GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

# PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-21-602 (R-6081-0A0) GTRC/~~GIT~~ DATE 1/ 23/ 86

Project Director: J. Schlag School/~~Lab~~ EE

Sponsor: Control Data Corporation
Bloomington, MN 55420

Type Agreement: CDC Proj. No. 85G101

Award Period: From 10/1/85 To 9/30/87 (Performance) ~~9/30/87~~ 3/31/88 (Reports)

Sponsor Amount:

| | This Change | Total to Date |
|---|---|---|
| Estimated: | $ | $ |
| Funded: | $ 100,000 | $ 100,000 |

Cost Sharing Amount: $ N/A Cost Sharing No: N/A

Title: Microcomputer/Data Service Network Protocols

## ADMINISTRATIVE DATA

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Defense Priority Rating: ______ Military Security Classification: N/A
(or) Company/Industrial Proprietary: N/A

## RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Sponsor - However none is proposed.

## COMMENTS:

See "Sponsored Research Projects Guidelines and Practices" handbook for Control Data Corp. Policies & Procedures.

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GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

## SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 5/11/88

Project No. E-21-602 — School/Lab EE

Includes Subproject No.(s) A-4431/Schlag

Project Director(s) J. Schlag — GTRC/[redacted]

Sponsor Control Data Corporation Bloomington, MN 55420

Title Microcomputer/ Data Service Network ~~Protocals~~ Protocols

Effective Completion Date: 9/30/87 (Performance) 3/31/88 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Copy of Last Invoice Serving as Final
- [ ] Release and Assignment
- [ ] Final Report of Inventions and/or Subcontract: Patent and Subcontract Questionnaire sent to Project Director [ ]
- [ ] Govt. Property Inventory & Related Certificate
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K-21-602

# Standardized Protocols Between Microcomputers and Data Service Networks

## Introduction

The rapid growth of computer applications coupled with the development of inexpensive, small computer systems has made drastic changes in the role of the large mainframe computer service network. These changes have been produced primarily by the shift of computer intelligence from the main host to the user-based systems. This shift has precipitated a need for changes in many of the other computer functions such as data base management, application programs, data security and communication protocols. This effort addresses issues within the single area of computer communication protocols in the computer service network and the impact of modern computer networks on the protocol requirements. Of particular interest to this project will be the areas of communication hardware, data transmission structure, error detection, error correction, encryption, data base security, data format exchange, and data base management command exchange.

To understand the need for new user/computer service communication protocols, it is useful to understand the evolutionary trends occuring in the entire network. The user in a service computer network in the 1970 time frame was a simple CRT terminal or hard copy device with no local processing or data storage capability. The user communicated with the host computer over a commercial grade telephone line using a standard RS232 protocol at a speed of 300 BAUD. The data was transmitted in standard, ASCII form with no communication security, data encryption, error detection or error correction. This communication was handled by a communication adapter at the host site which could have been as simple as a telephone switching network. The communication adapter connected the user to the central operating system which in turn called up the particular application program that was requested by the user. The application program handles the great majority of all of the user/host controlling inputs and outputs to the user, inputs and outputs to the host data base, input and output formats, data security, data encryption, error detection, and error correction. Many of these application programs were executed in a Batch Mode and supplied little, if any, direct communication with the remote user. Interaction operation was also limited by the extremely slow communication speed between the user and the host. In this type of system the application program served as the center of both processing and control of the computer operation.

During the early 1980 period the service networks developed a large variety of computer communication networks to effectively handle larger volumes of more sophisticated data transmissions. These networks effectively removed the communication demands from the central computer but did not remove the host application programs as the center of processing activity.

With the development of inexpensive personal and business computers, the large service computer network is undergoing a number of organizational changes. The typical user in 1990 time frame will be a small business or personal computer with local application programs and mass storage capability. The majority of the interactive applications processing will be performed at the local user level with the computer service network supplying access to large data bases for portions of the processing information. The bulk of the user/host communication will still be handled via commercial telephone connections, but at considerably higher transmissions rates (4800, 9600 BAUD). The information to and from the local user will be processed by a much more sophisticated communications adapter which can connect the user into different segments of the operating system or possibly even direct access to the host data base. The operating system can access a variety of application programs which would normally be extremely large programs that could not be executed on the local computer or specialized data base management systems which are tailored to make specific types of operation on the host data base. The operating system level mightalso allow a direct contact between the remote user and the data base itself. The data bases will be extremely large and more likely to be shared between a number of users than the data bases of the 1970's.

A major problem in a system of the 1990's will be to keep the executable files on remote updated by the host system in a timely and cost effective manner. To better understand the issues involved in solving this problem, it is useful to examine the block-level diagrams illustrated in Figures 1-4 of the segments a typical 1990 data transfer system. The management system segment, common to all four segments, will have the role of coordinating the four modules that in turn generate the updates to modify an old file into a new version, transport the updates through the various elements of two communication systems, and finally reconstructing a new file from the old and incorporating the transmitted updates. A summary of the system elements being examined is offered below.

The data generation system, illustrated in Figure 1, consists of eight elements. Four of these simply represent the old and new source files and their corresponding executable files, which serve as inputs to the download file generator. The function of the download file generator is to generate, based on a scheme to be described later, a file with information for decomposing an old executable file and reconstructing it to mirror the new executable file. The generated file will be dependent upon the instruction set about which information is available through the instruction table. Ideally, information in the instruction table will be the output of the automatic instruction table generator which will be a program, probably based on artificial intelligence, to take an instruction set and extract information about it necessary for use in the download file generator. The new download file is the output of the download file generator and the input to the data communication system illustrated in Figure 2. In this system, there are four blocks, the first of which is labeled "packet convert" and which accurately describes its function. For checking and error detection purposes it is more efficient to send data in packets. The data packets are

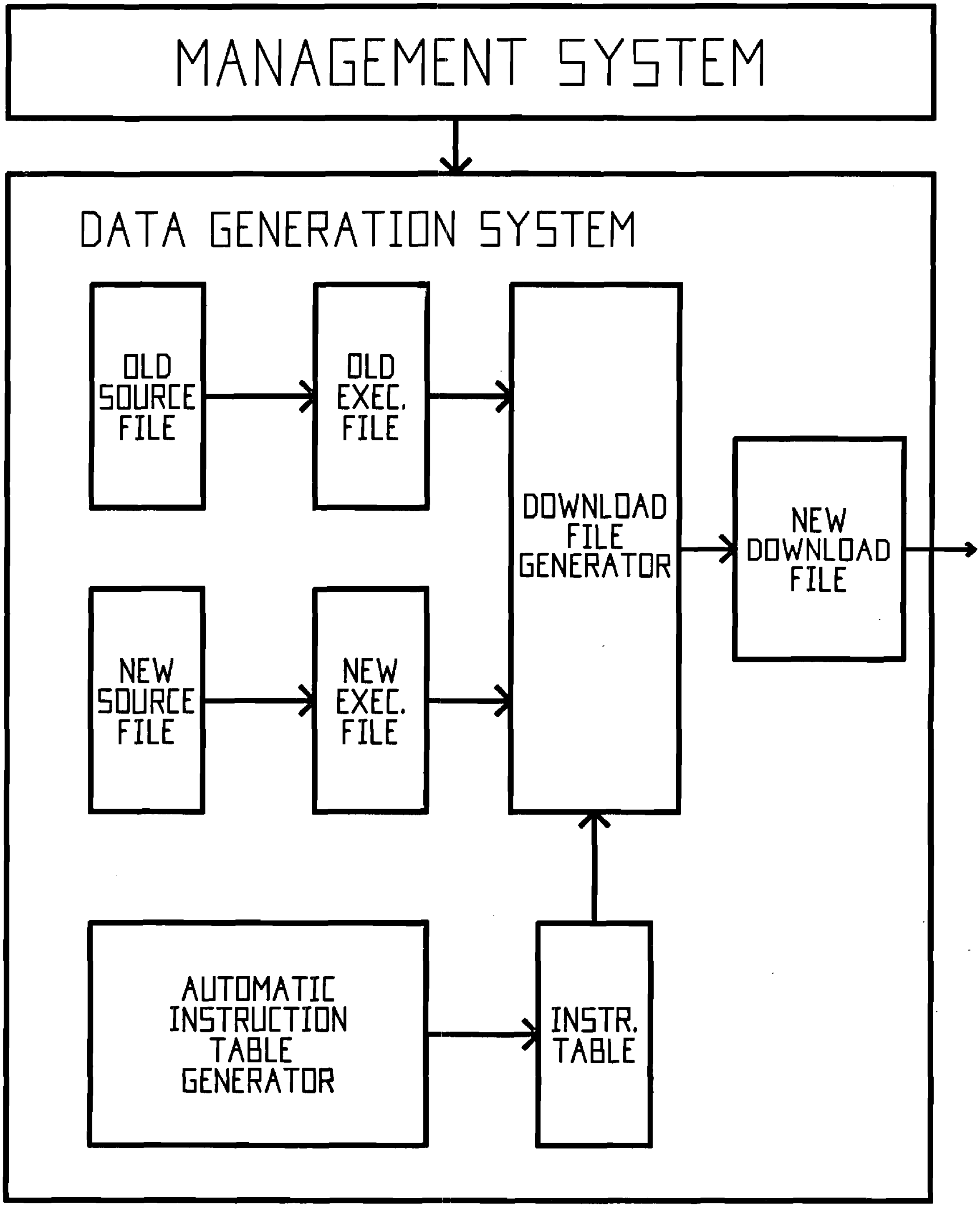


FIGURE 1

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION<br>DATA COMMUNICATION SYSTEM | | |
| CDCC1 | J.H. SCHLAG | 3/86 |

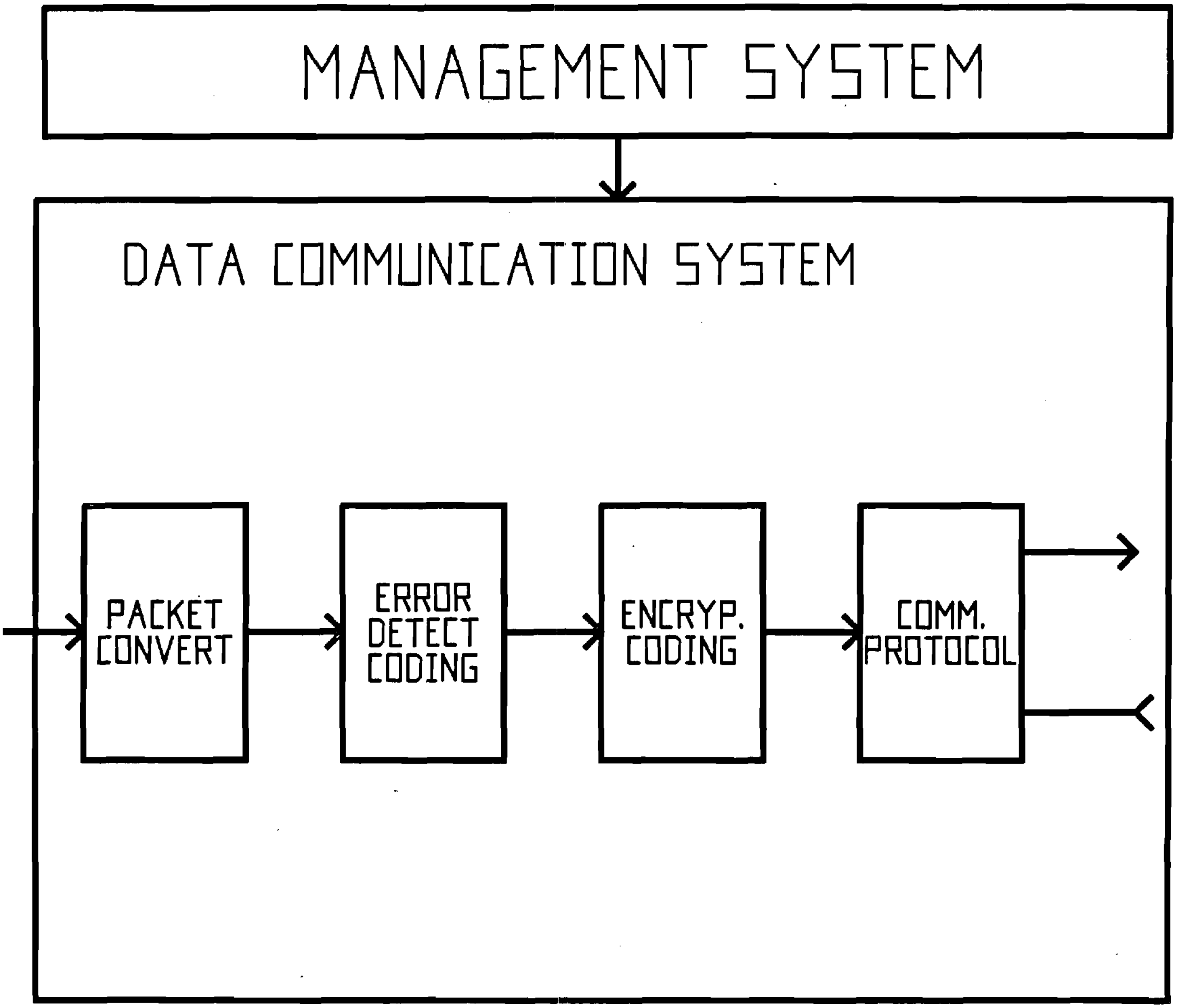


FIGURE 2

| | | |
|---|---|---|
| GEORGIA INSTITUTE OF TECHNOLOGY | | |
| CONTROL DATA CORPORATION<br>DATA COMMUNICATION SYSTEM | | |
| CDCC2 | J.H. SCHLAG | 3/86 |

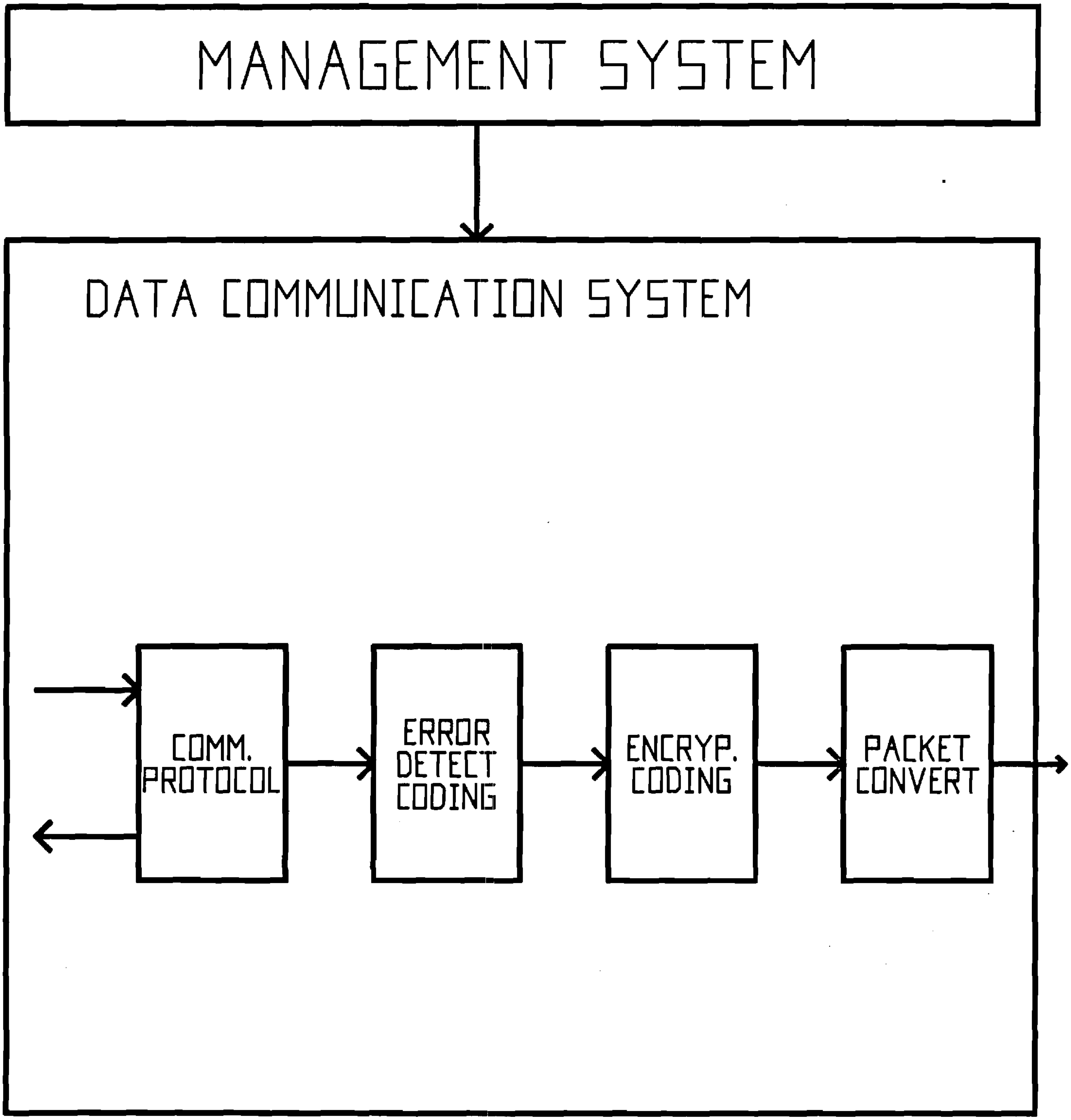


FIGURE 3

GEORGIA INSTITUTE OF TECHNOLOGY

CONTROL DATA CORPORATION
DATA COMMUNICATION SYSTEM

CDCC3 | J.H. SCHLAG | 3/86

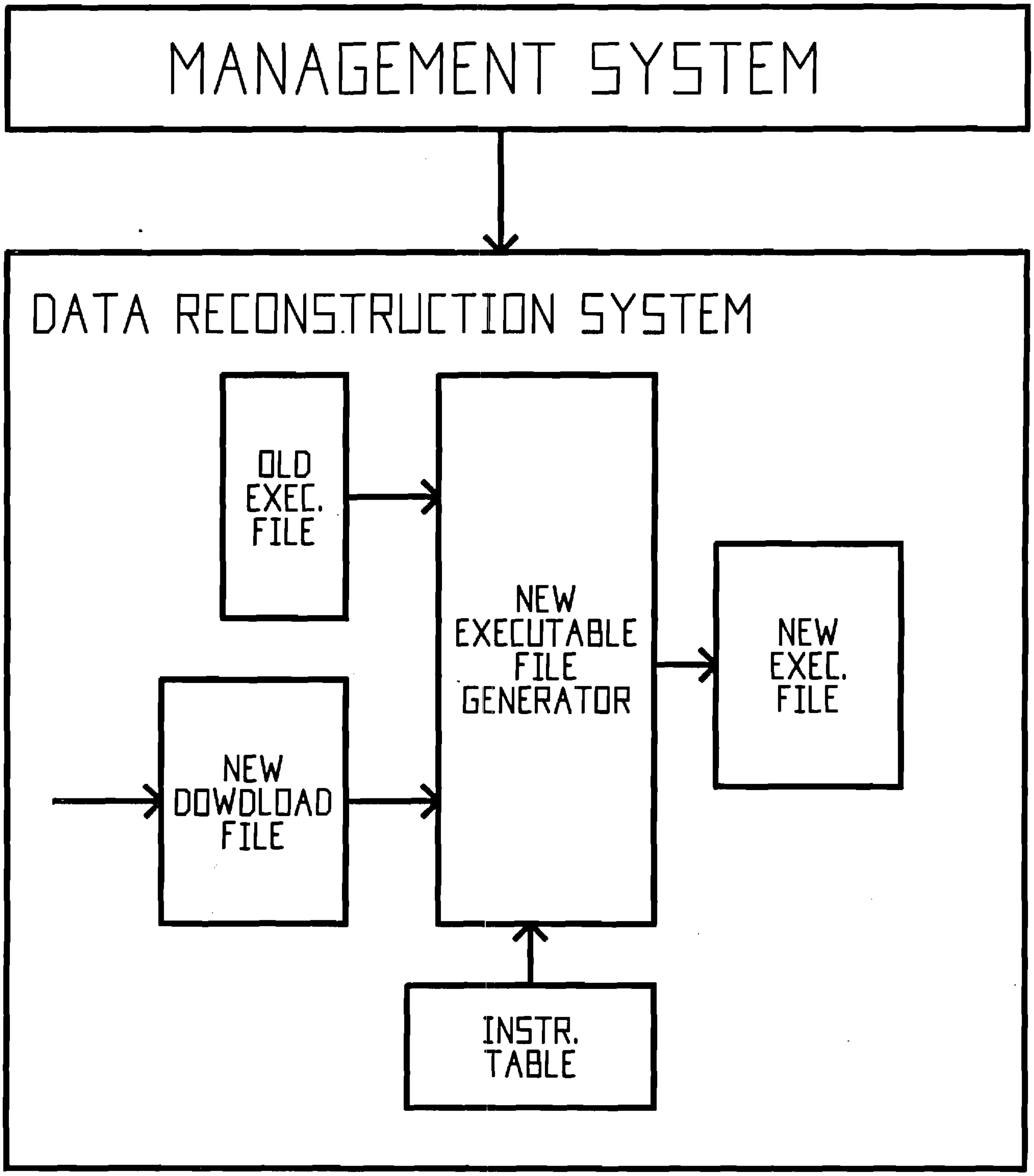


FIGURE 4

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION DATA COMMUNICATION SYSTEM | | |
| CDCC4 | J.H. SCHLAG | 3/86 |

then subject to error detection and correction and to encryption for security as indicated by the next two blocks in Figure 2.

The need for higher BAUD rates over commercial telephone lines will increase the probability of data transmission errors, but the use of packet protocols will increase the probability that these errors can be detected. The technique used for error detection will most likely be a vertical or possibly vertical and horizontal cyclic redundancy code. Certain single and multiple bit errors can be corrected using packet protocols and particular coding schemes such as the Hamming code.

A number of factors will increase the need for encrypting data between the user and the host service network. With little or no application program on the host computer, the data transmitted will more likely be the essential data base unfiltered by application programs at the host. The use of shared data bases will tend to make companies more security conscious. New regulations such as the Privacy Act will increase the responsibility of companies to maintain secure data.

Even though proper encryption can maintain the security of the data transmitted between the host and user, additional steps must be provided to keep unauthorized users from accessing or changing specific areas of the data base. As more of the applications programs are moved to the user system, more responsibility for data base security will fall on the communication system.

Data packets, having been error corrected and encrypted for security, pass to the fourth block, the communication protocol block in the system. Definite protocols need to be established between host and system including packet acknowledgement and retransmission. Through these protocols data is transmitted from host to remote use. Figure 3 is mirror image of Figure 2 and represents the fact the the functions of the data communication systems of the remote system in Figure 3 mirror those of the host system in Figure 2.

The data reconstruction system is illustrated in Figure 4. The new download file contains the packets of data produced by the data communication system of the remote system. This input along with the old executable file that resides at the remote site are submitted to the new executable file generator which, with information from the instruction table, reconstructs the old executable to a new executable file identical to that in Figure 1. Details of the schemes developed for the download file generator of Figure 1 and the new executable file generator are presented later. As was noted earlier, to make sure that all the modules described interact properly, all are controlled by a management system. Through the management system the host makes program changes and sends them to all the remote users who are eligible to receive them. By the same system the remote user advises the host when updates have been completed successfully. When the remote signs on, the host should request that an update be made automatically; the remote user can then respond with his desires. The management system keeps account of which systems have been updated.

Each of the system elements and their interrelation will be areas of changing needs related to communication protocols between the host and the user. Each of these areas has proved to be fertile ground for researchers. Publications with results of work in the areas have been assembled in a library both for assessment of the current status and for future reference. A bibliography of these publications is included as an appendix.

The issues described above relate to the broad context of the problem of keeping the executable file on the remote terminals updated by the host. For the initial effort a narrower focus was taken with a concentration on a scheme for downloading the file generator and new file generation.

To date, the schemes available to keep update files available at the remote terminals have been compacting schemes that assumed no a priori information at the receiver and involved sending entire new files, but in as compact and efficient manner as possible. In contrast, the new scheme that is the subject of this report assumes that an old file exists at the remote and needs merely to be updated. The new scheme involves examining the changes that need to be made and sending only the information necessary to make the changes.

New Update Scheme

The basic idea in the new update scheme that is being developed is to begin with an old executable file that requires an update and that exists both at the remote and the host systems. An update to the old file is made at the host. The objective is to transmit the update to the remote system. In the new scheme this is done by decomposing the old file at the remote and reconstructing it with update information to in fact make a replica of the new executable at the remote system.

This update process will by nature mean that the instructions from the old executable file will be located in a different position in the new executable file. In order to implement the changes in an existing code, it is useful to examine first the types of information fields involved in an instruction and then the ways these fields change with changes of position.

Four Types of Information Fields

1. OP code fields specify the type of instruction, such as "MOV", that is to be executed and by its very nature is position independent.

2. A second type of position independent fields is a general class of position independent fields, other than OP code fields (e.g. fieldsthat specify registers).

3. Relative position dependent fields specify information such that if moved from one position to another, the value of the number in the field will be changed by the amount relative to the amount it moved.

4. Absolute position dependent fields are fields specifying values whose magnitude changes according to its absolute position in memory.

Four Ways to Transfer Data

1. Absolute position valid data packets involves moving groups of instructions that are independent of position as illustrated in Figure 5 and as follows:

   a. remove n bytes of data from the old executable file starting at the old file data pointer

   b. place n bytes of data in new file starting at the new file data pointer with no changes to the data packet

   c. add n to both old and new pointers

2. Offset position valid data packet involves receiving a command that identifies the type of move and the value of n, as well as two offset values, both relative and absolute, as illustrated in Figure 6 and as follows:

   a. remove n bytes of data from the old executable file starting at the old file data pointer

   b. add current relative offset value to all relative dependent fields

   c. place data packet back in new executable file

   d. add n to old and new data pointers

3. Delete Data Packet from the old executable file by supplying the value of n and then add n to old data pointer as illustrated in Figure 7.

4. Add Data Packet involves receiving n bytes of new data from communication channel (host) as illustrated in Figure 8 and as follows:

   a. place n bytes of new data starting at the data pointer in the new executable file

   b. add n to new file data pointer

# ABSOLUTE POSITION DATA PACKET

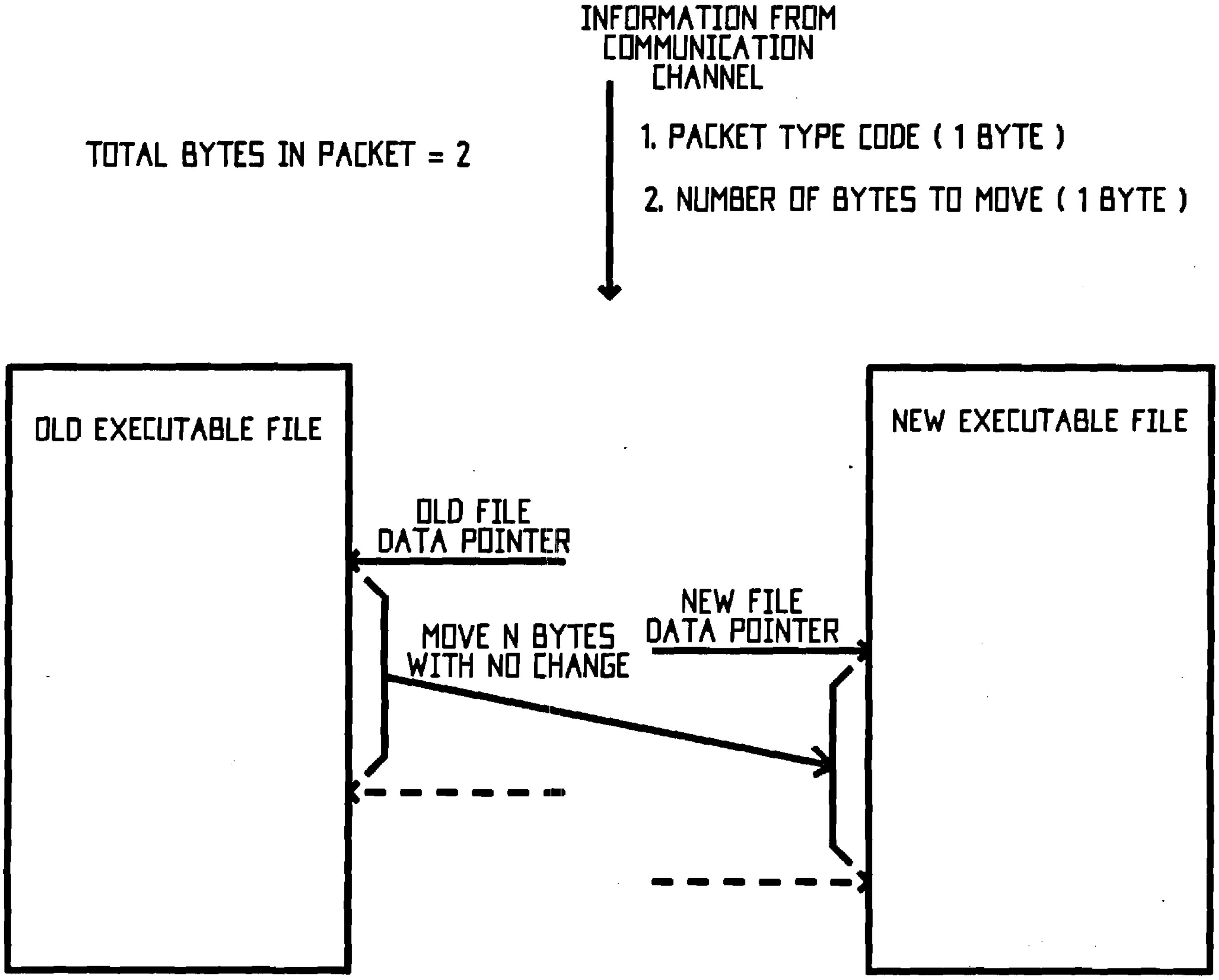


FIGURE 5

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION<br>ABSOLUTE POSITION DATA PACKET | | |
| CDCC5 | J.H. SCHLAG | 3/86 |

# OFFSET POSITION DATA PACKET

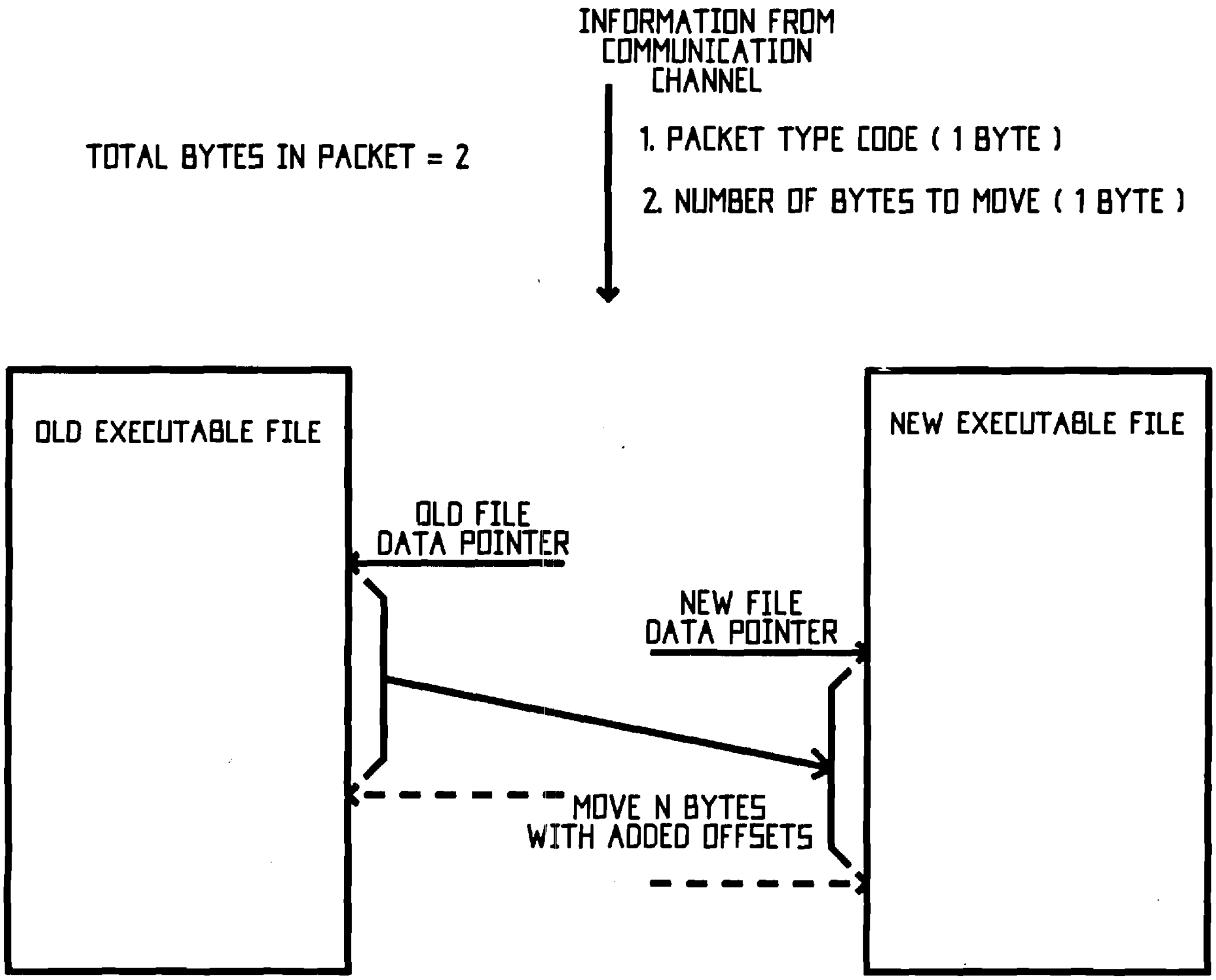


FIGURE 6

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION<br>OFFSET POSITION DATA PACKET | | |
| CDCC6 | J.H. SCHLAG | 3/86 |

# DELETE
# DATA PACKET

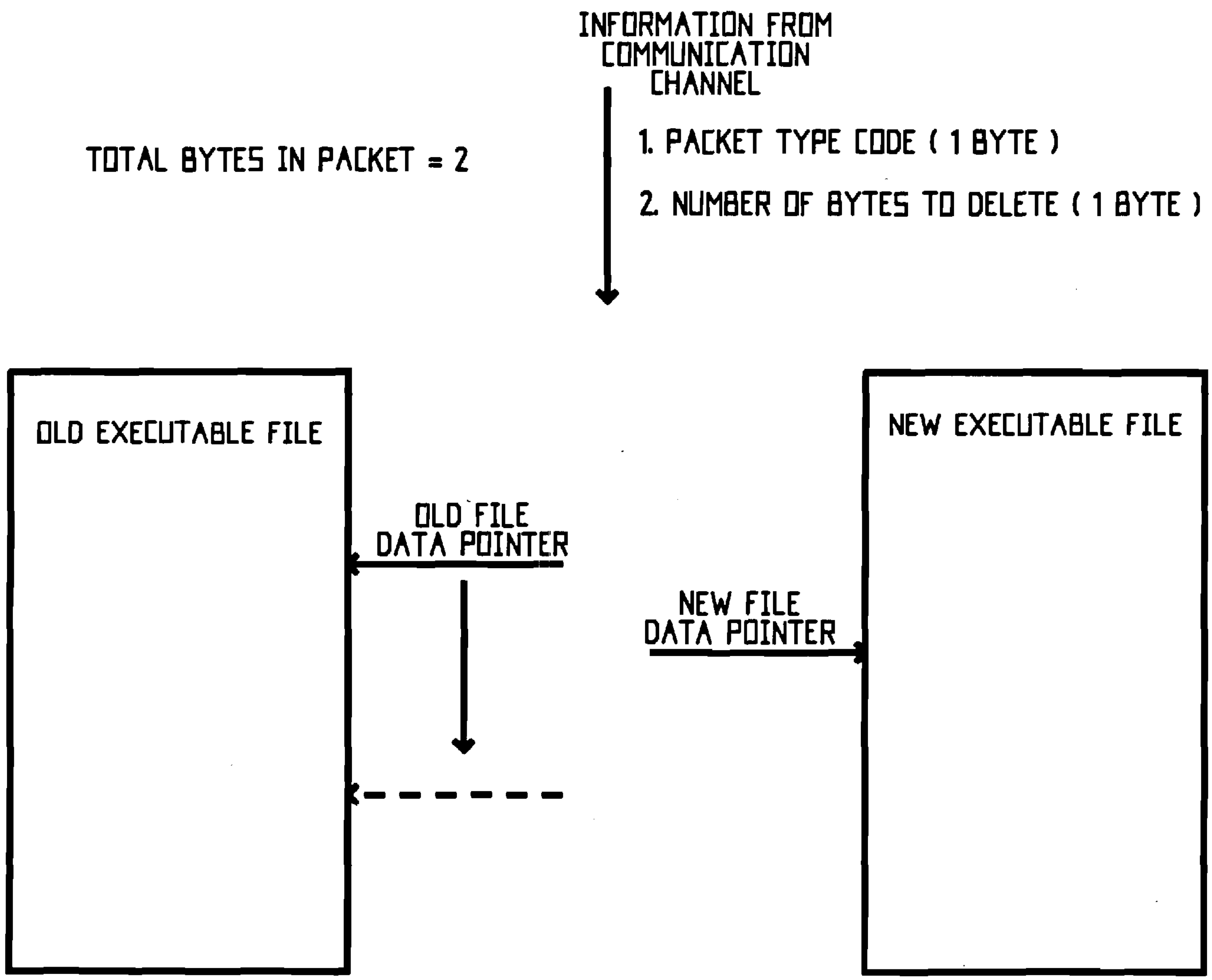


FIGURE 7

GEORGIA INSTITUTE OF TECHNOLOGY

CONTROL DATA CORPORATION
DELETE DATA PACKET

| | | |
|---|---|---|
| CDCC7 | J.H. SCHLAG | 3/86 |

# ADD
# DATA PACKET

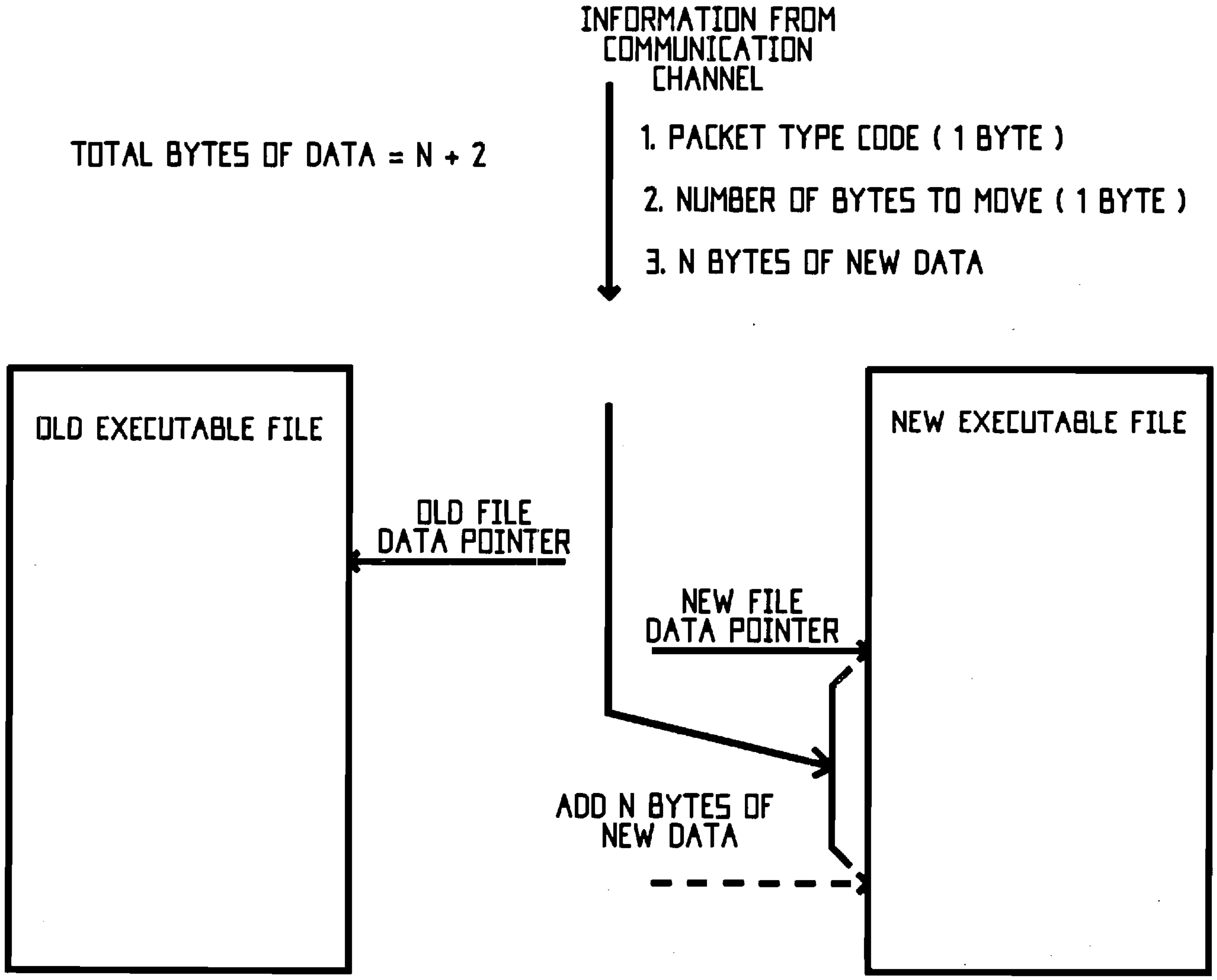


FIGURE 8

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION<br>ADD DATA PACKET | | |
| CDCC7 | J.H. SCHLAG | 3/86 |

In the worst case, by exercising data transfers types 3 & 4, the old file will be completely replaced by a new executable file, in much the same way as is currently done. When the changes are extensive, it may be the most efficient way to proceed. In many other instances, when the changes are minor, considerable savings in time and money could be realized with the new scheme.

## A Trial Scheme

Based on the information presented above a trial scheme has been devised and is illustrated in following example.

A sample assembly language program was selected at random ( Duke University Computer Science homework problem number 4). An additional instruction was added to the program and it was re-assembled. The old and new code were printed and the proposed scheme was manually applied to indicate the degree of saving in download efficiency. The following indicates the bytes that would be sent in the download file.

Download codes for sample program

| Data | Number of bytes |
|---|---|
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 133 | 1 byte |
| Add data code | 1 byte |
| 1 | 1 byte |
| B8 | 1 byte |
| Position offset code | 1 byte |
| Relative position offset | 1 byte |
| Absolute position offset | 1 byte |
| 215 | 1 byte |
| Total | 19 bytes |

Analysis of sample program using proposed download scheme

Total bytes in program = 1373 bytes

Types of data fields / bytes per field:

Position independent fields = 1157 bytes

Absolute position dependent fields = 215

Number of bytes required to transmit each field type:

Position independent data = 10 bytes

Added data = 3 bytes

Absolute position dependent data = 6 bytes

Total number of bytes required for transmission = 19 bytes

Ratio of direct download to proposed scheme = 72.3

Instruction Set Investigation

To investigate the validity of the new trial scheme, an example of a machine language instruction is selected to check the following:

1. to see if using this format, does there exist data that cannot be taken apart and put back together again,

2. to check on the efficiency of the scheme, that is can you have as few variations as possible and still be effective.

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# STANDARDIZED PROTOCOLS BETWEEN MICROCOMPUTERS AND DATA SERVICE NETWORKS

by

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School of Electrical Engineering

Georgia Institute of Technology

March 16,1987

prepared for

Control Data Corporation

Standardized Protocols Between
Microcomputers and Data Service Networks

## Introduction

This report is the annual report covering the first year of a two year effort to investigate standardized protocols between microcomputers and data service networks. The first half of this report was presented earlier as a semi-annual report. The second half is a continuation of that report and is a discussion of the work that has been done during the remainder of that year.

The rapid growth of computer applications coupled with the development of inexpensive, small computer systems has made drastic changes in the role of the large mainframe computer service network. These changes have been produced primarily by the shift of computer intelligence from the main host to the user-based systems. This shift has precipitated a need for changes in many of the other computer functions such as data base management, application programs, data security and communication protocols. This effort addresses issues within the single area of computer communication protocols in the computer service network and the impact of modern computer networks on the protocol requirements. Of particular interest to this project will be the areas of communication hardware, data transmission structure, error detection, error correction, encryption, data base security, data format exchange, and data base management command exchange.

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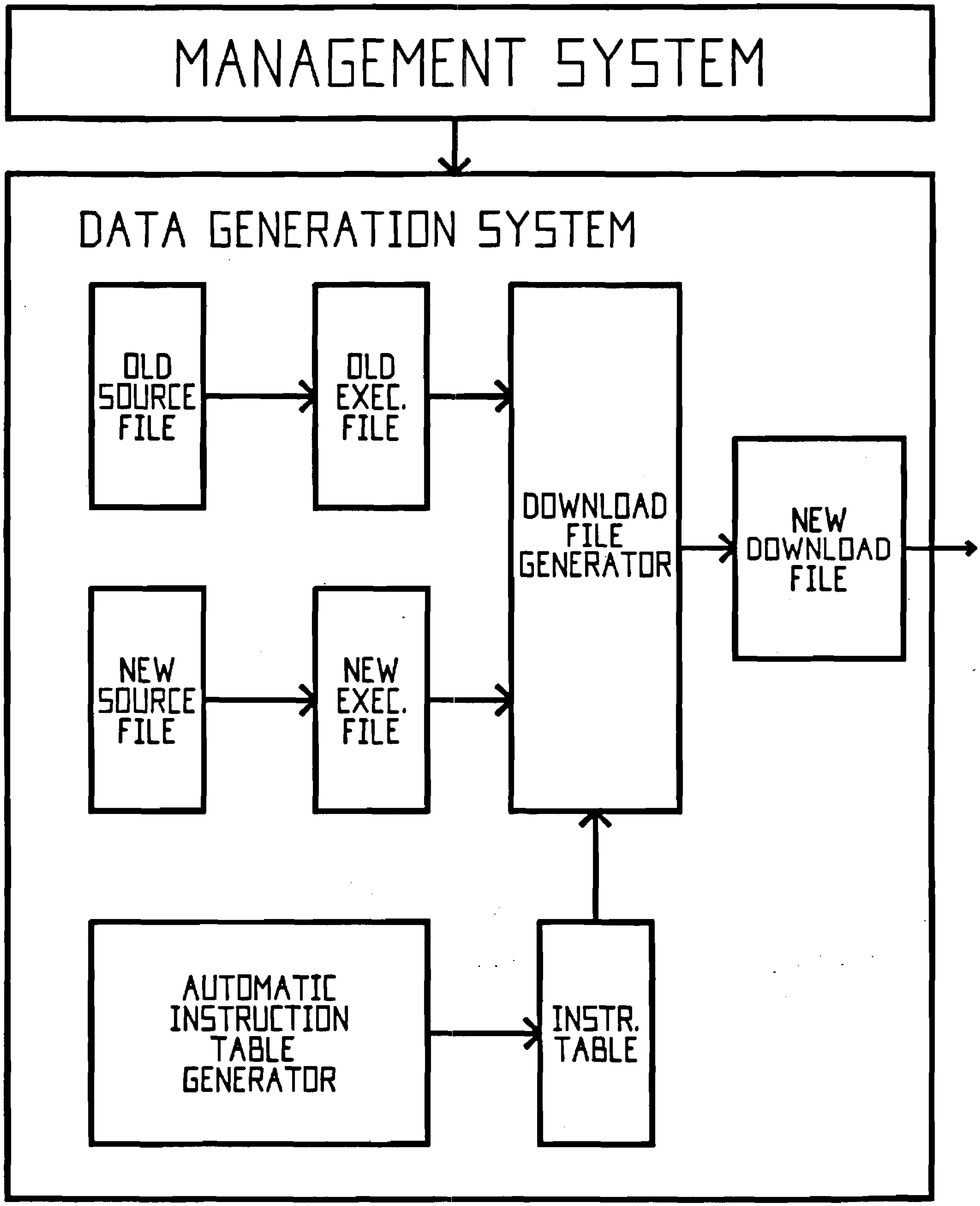


FIGURE 1

| | | |
|---|---|---|
| GEORGIA INSTITUTE OF TECHNOLOGY | | |
| CONTROL DATA CORPORATION<br>DATA COMMUNICATION SYSTEM | | |
| CDCC1 | J.H. SCHLAG | 3/86 |

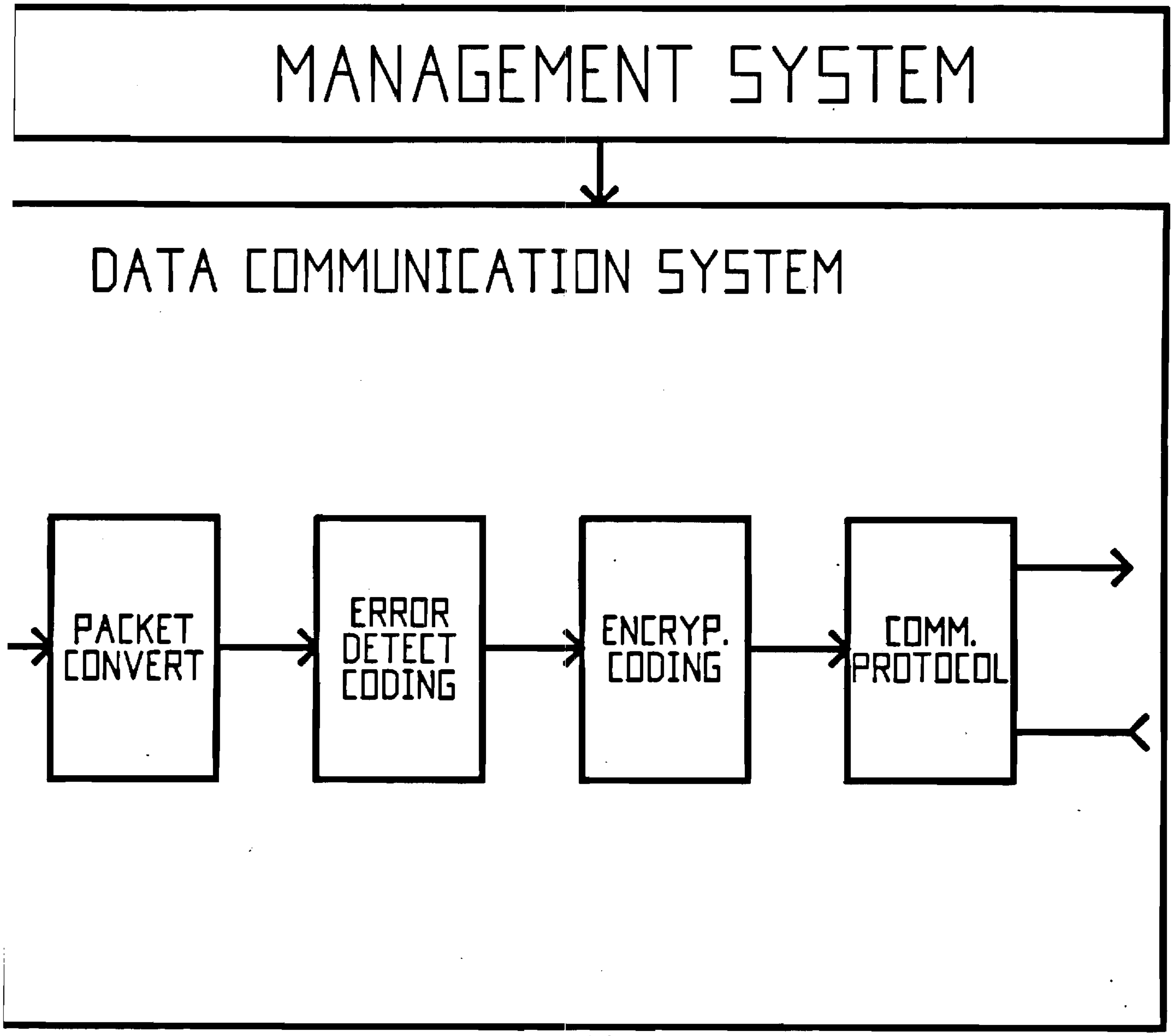


FIGURE 2

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION<br>DATA COMMUNICATION SYSTEM | | |
| CDCC2 | J.H. SCHLAG | 3/86 |

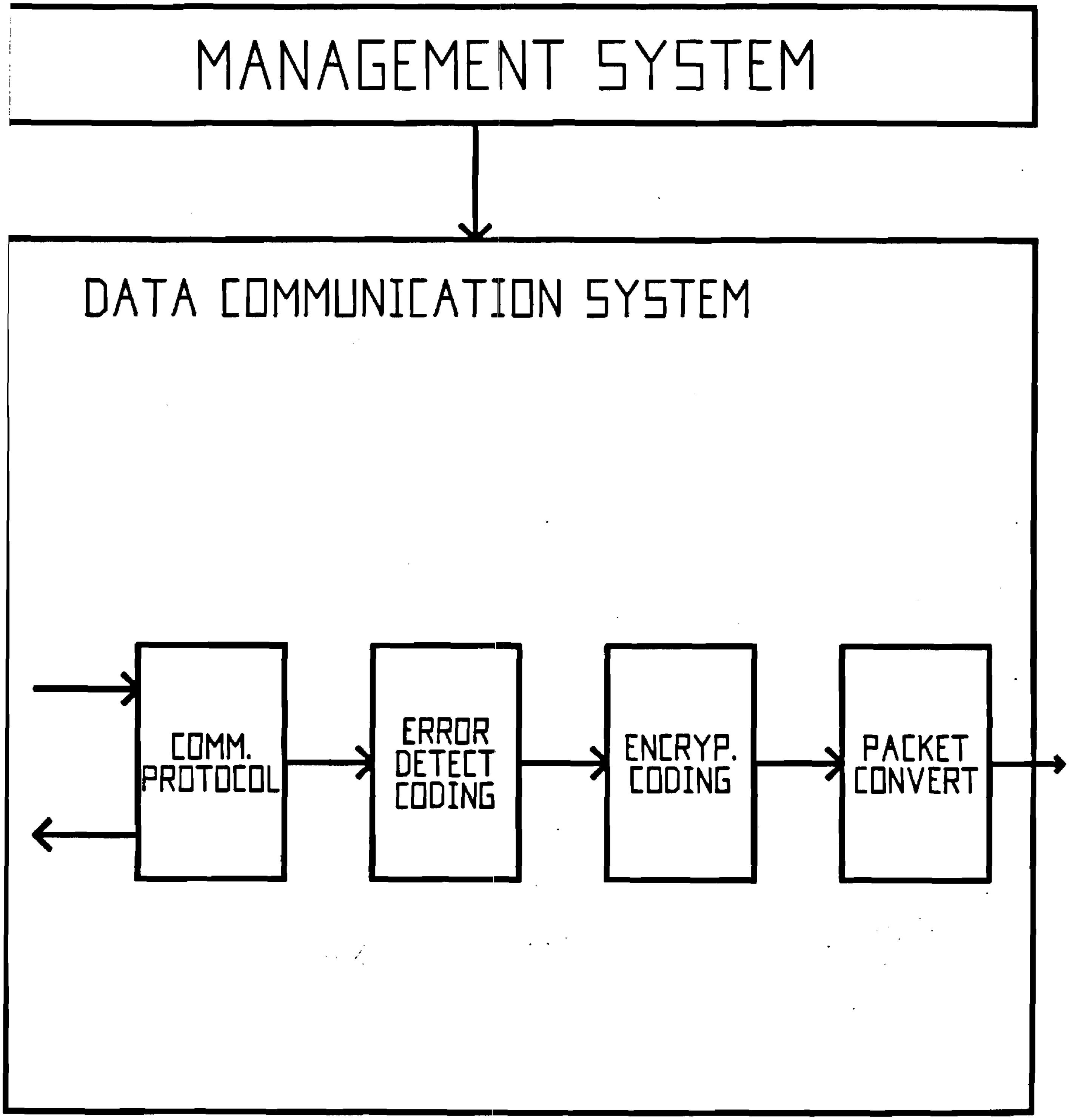


FIGURE 3

| | | |
|---|---|---|
| GEORGIA INSTITUTE OF TECHNOLOGY | | |
| CONTROL DATA CORPORATION<br>DATA COMMUNICATION SYSTEM | | |
| CDCC3 | J.H. SCHLAG | 3/86 |

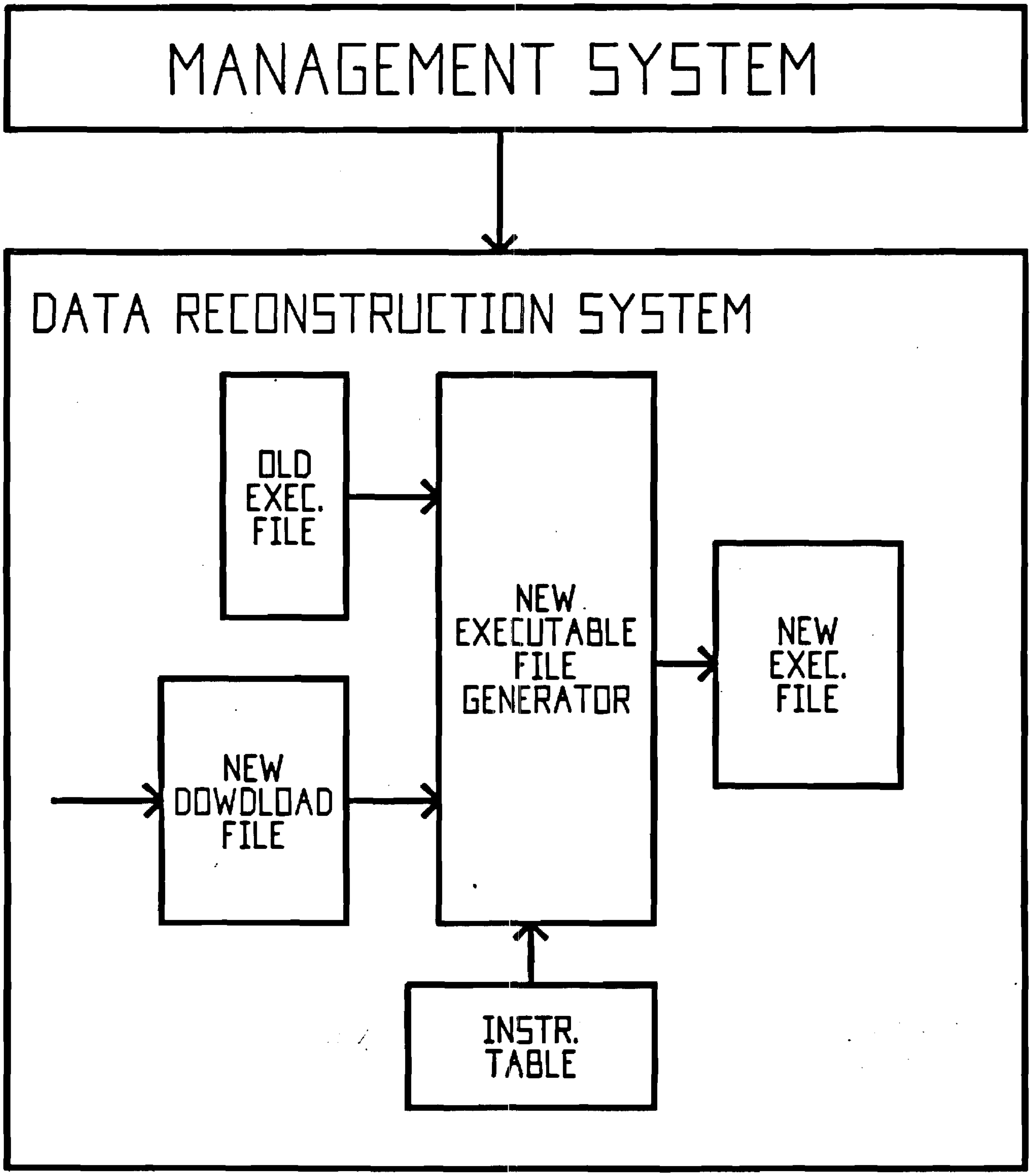


FIGURE 4

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION DATA COMMUNICATION SYSTEM | | |
| CDCC4 | J.H. SCHLAG | 3/86 |

information about it necessary for use in the download file generator. The new download file is the output of the download file generator and the input to the data communication system illustrated in Figure 2. In this system, there are four blocks, the first of which is labeled "packet convert" and which accurately describes its function. For checking and error detection purposes it is more efficient to send data in packets. The data packets are then subject to error detection and correction and to encryption for security as indicated by the next two blocks in Figure 2.

The need for higher BAUD rates over commercial telephone lines will increase the probability of data transmission errors, but the use of packet protocols will increase the probability that these errors can be detected. The technique used for error detection will most likely be a vertical or possibly vertical and horizontal cyclic redundancy code. Certain single and multiple bit errors can be corrected using packet protocols and particular coding schemes such as the Hamming code.

A number of factors will increase the need for encrypting data between the user and the host service network. With little or no application program on the host computer, the data transmitted will more likely be the essential data base unfiltered by application programs at the host. The use of shared data bases will tend to make companies more security conscious. New regulations such as the Privacy Act will increase the responsibility of companies to maintain secure data.

Even though proper encryption can maintain the security of the data transmitted between the host and user, additional steps must be provided to keep unauthorized users from accessing or changing specific areas of the data base. As more of the applications programs are moved to the user system, more responsibility for data base security will fall on the communication system.

Data packets, having been error corrected and encrypted for security, pass to the fourth block, the communication protocol block in the system. Definite protocols need to be established between host and system including packet acknowledgement and retransmission. Through these protocols data is transmitted from host to remote use. Figure 3 is mirror image of Figure 2 and represents the fact the the functions of the data communication systems of the remote system in Figure 3 mirror those of the host system in Figure 2.

The data reconstruction system is illustrated in Figure 4. The new download file contains the packets of data produced by the data communication system of the remote system. This input along with the old executable file that resides at the remote site are submitted to the new executable file generator which, with information from the instruction table, reconstructs the old executable to a new executable file identical to that in Figure 1. Details of the schemes developed for the download file generator of Figure 1 and the new executable file generator are presented later. As was noted earlier, to make sure that all the modules described interact properly, all are controlled by a management system. Through the management system the host makes program changes and sends them to all the remote users who are eligible to receive them. By the same system the remote user advises the host when updates have been completed successfully. When the remote signs on, the host should request that an update be made automatically; the remote user can then respond with his desires. The management system keeps account of which systems have been updated.

Each of the system elements and their interrelation will be areas of changing needs related to communication protocols between the host and the user. Each of these areas has proved to be fertile ground for researchers. Publications with results of work in the areas have been assembled in a library both for assessment of the current status and for future reference. A bibliography of these publications is included as an appendix.

The issues described above relate to the broad context of the problem of keeping the executable file on the remote terminals updated by the host. For the initial effort a narrower focus was taken with a concentration on a scheme for downloading the file generator and new file generation.

To date, the schemes available to keep update files available at the remote terminals have been compacting schemes that assumed no a priori information at the receiver and involved sending entire new files, but in as compact and efficient manner as possible. In contrast, the new scheme that is the subject of this report assumes that an old file exists at the remote and needs merely to be updated. The new scheme involves examining the changes that need to be made and sending only the information necessary to make the changes.

## New Update Scheme

The basic idea in the new update scheme that is being developed is to begin with an old executable file that requires an update and that exists both at the remote and the host systems. An update to the old file is made at the host. The objective is to transmit the update to the remote system. In the new scheme this is done by decomposing the old file at the remote and reconstructing it with update information to in fact make a replica of the new executable at the remote system.

This update process will by nature mean that the instructions from the old executable file will be located in a different position in the new executable file. In order to implement the changes in an existing code, it is useful to examine first the types of information fields involved in an instruction and then the ways these fields change with changes of position.

## Four Types of Information Fields

1. OP code fields specify the type of instruction, such as "MOV", that is to be executed and by its very nature is position independent.

2. A second type of position independent fields is a general class of position independent fields, other than OP code fields (e.g. fields that specify registers).

3. Relative position dependent fields specify information such that if moved from one position to another, the value of the number in the field will be changed by the amount relative to the amount it moved.

4. Absolute position dependent fields are fields specifying values whose magnitude changes according to its absolute position in memory.

<u>Four Ways to Transfer Data</u>

1. Position independent data packets involve moving groups of instructions that are independent of position as illustrated in Figure 5 and as follows:

   a. remove n bytes of data from the old executable file starting at the old file data pointer

   b. place n bytes of data in new file starting at the new file data pointer with no changes to the data packet

   c. add n to both old and new pointers

2. Offset position valid data packet involves receiving a command that identifies the type of move and the value of n, as well as two offset values, both relative and absolute, as illustrated in Figure 6 and as follows:

   a. remove n bytes of data from the old executable file starting at the old file data pointer

   b. add current relative offset value to all relative dependent fields

   c. change all absolute fields to reflect the new code position

   d. place data packet back in new executable file

   e. add n to old and new data pointers

3. Delete Data Packet from the old executable file by supplying the value of n and then add n to old data pointer as illustrated in Figure 7.

# ABSOLUTE POSITION DATA PACKET

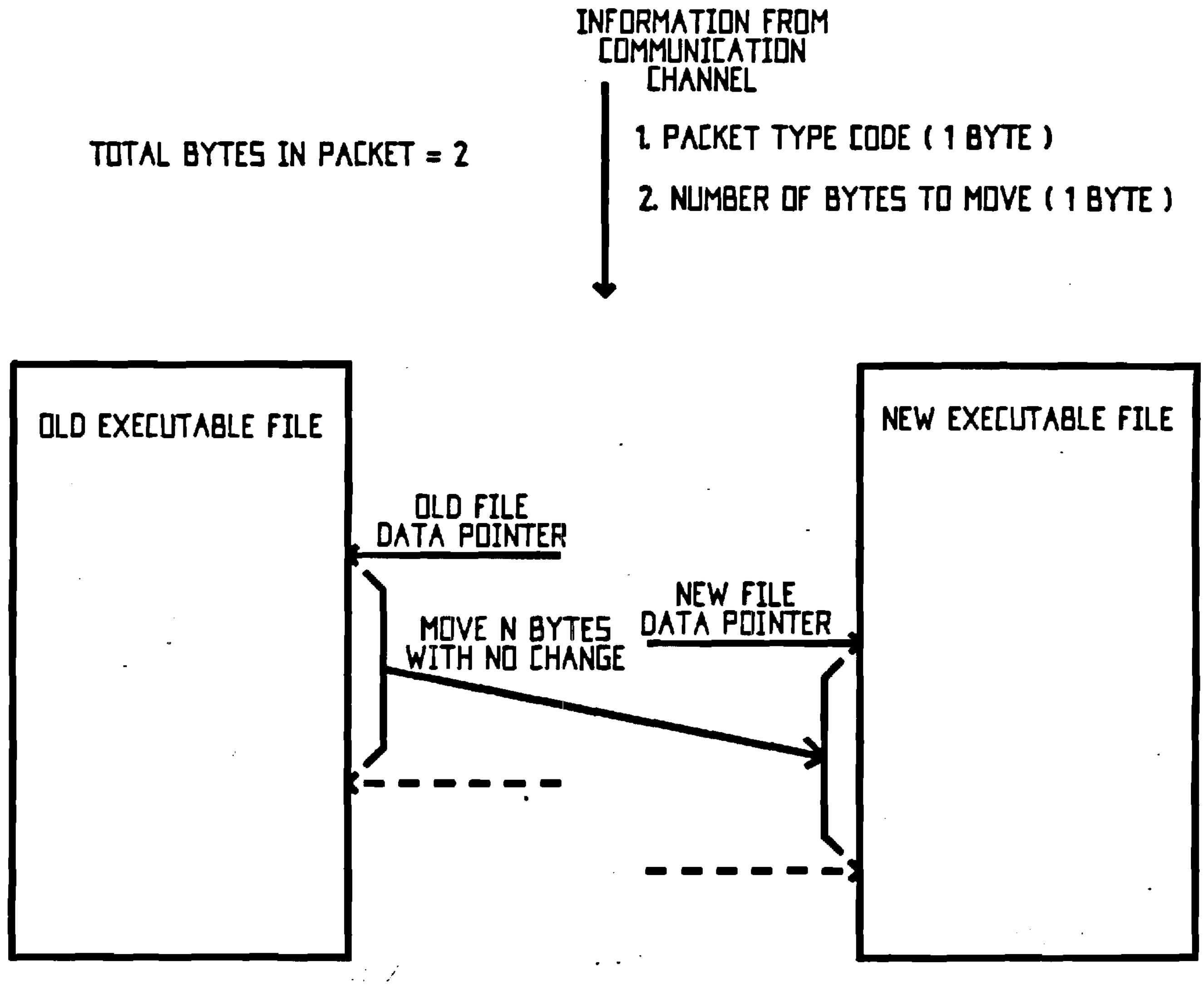


FIGURE 5

| | | |
|---|---|---|
| GEORGIA INSTITUTE OF TECHNOLOGY | | |
| CONTROL DATA CORPORATION ABSOLUTE POSITION DATA PACKET | | |
| CDCCS | J.H. SCHLAG | 3/86 |

# OFFSET POSITION DATA PACKET

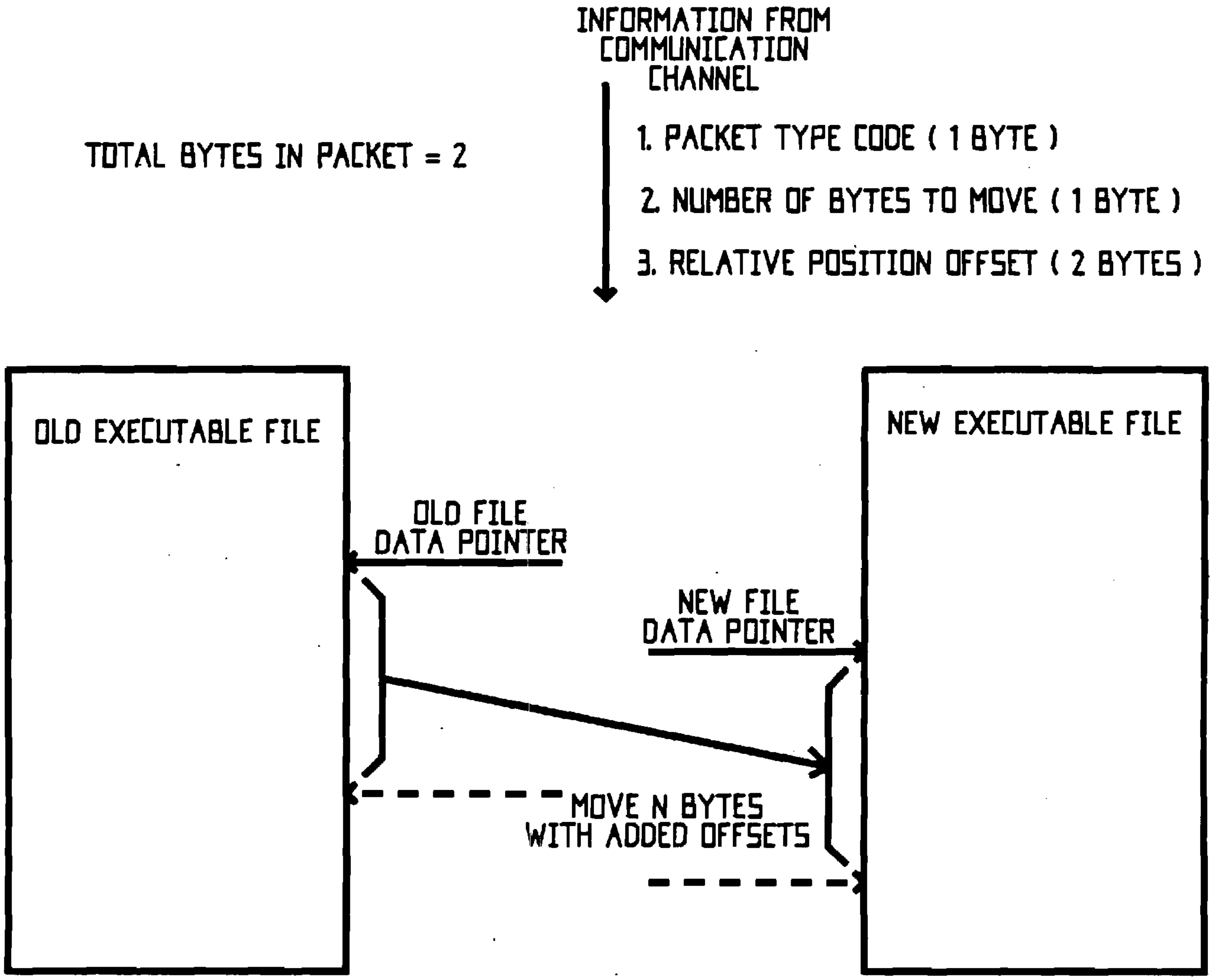


FIGURE 6

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION OFFSET POSITION DATA PACKET | | |
| CDCC6 | J.H. SCHLAG | 3/86 |

# DELETE
# DATA PACKET

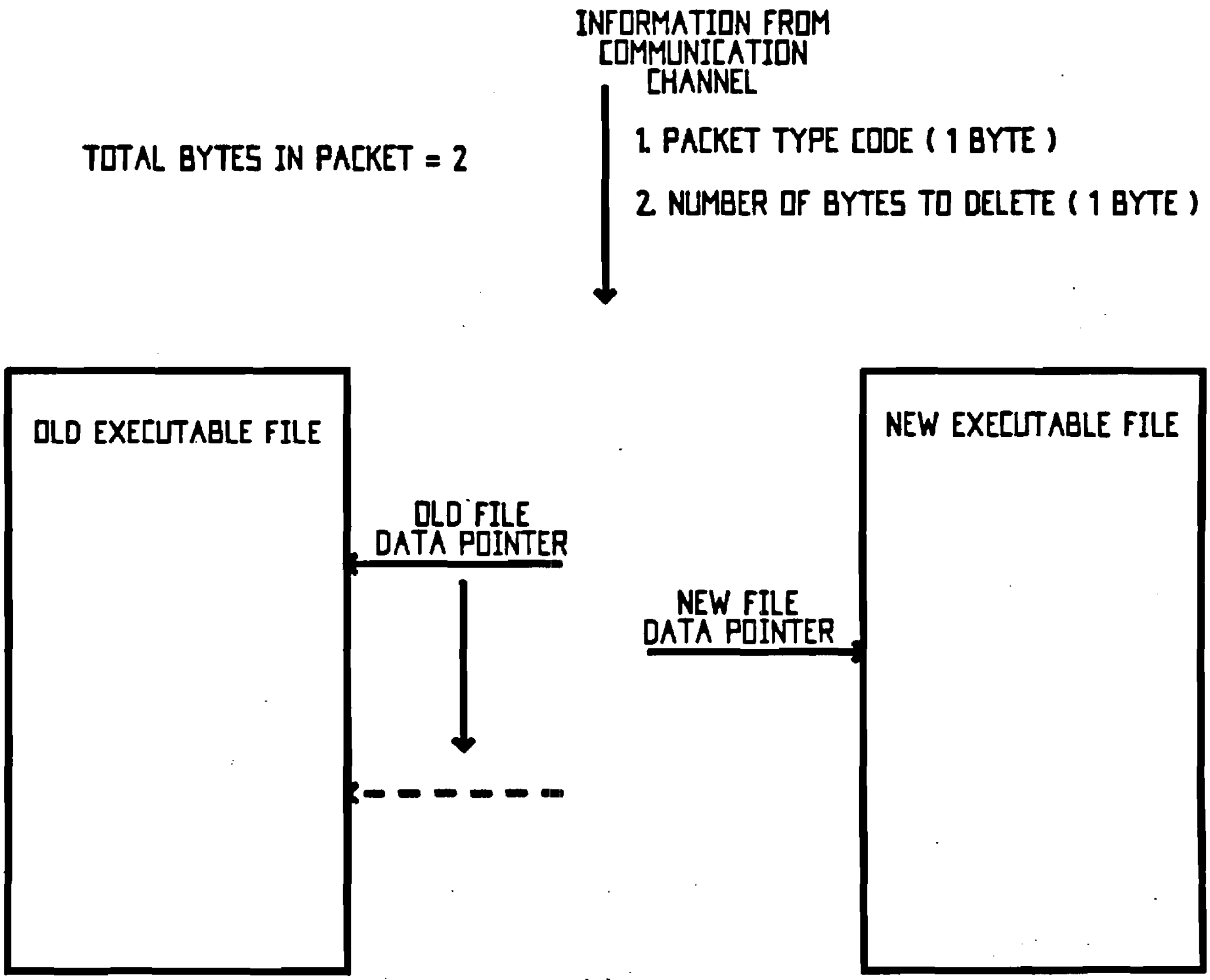


FIGURE 7

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION<br>DELETE DATA PACKET | | |
| CDCC7 | J.H. SCHLAG | 3/86 |

# ADD
# DATA PACKET

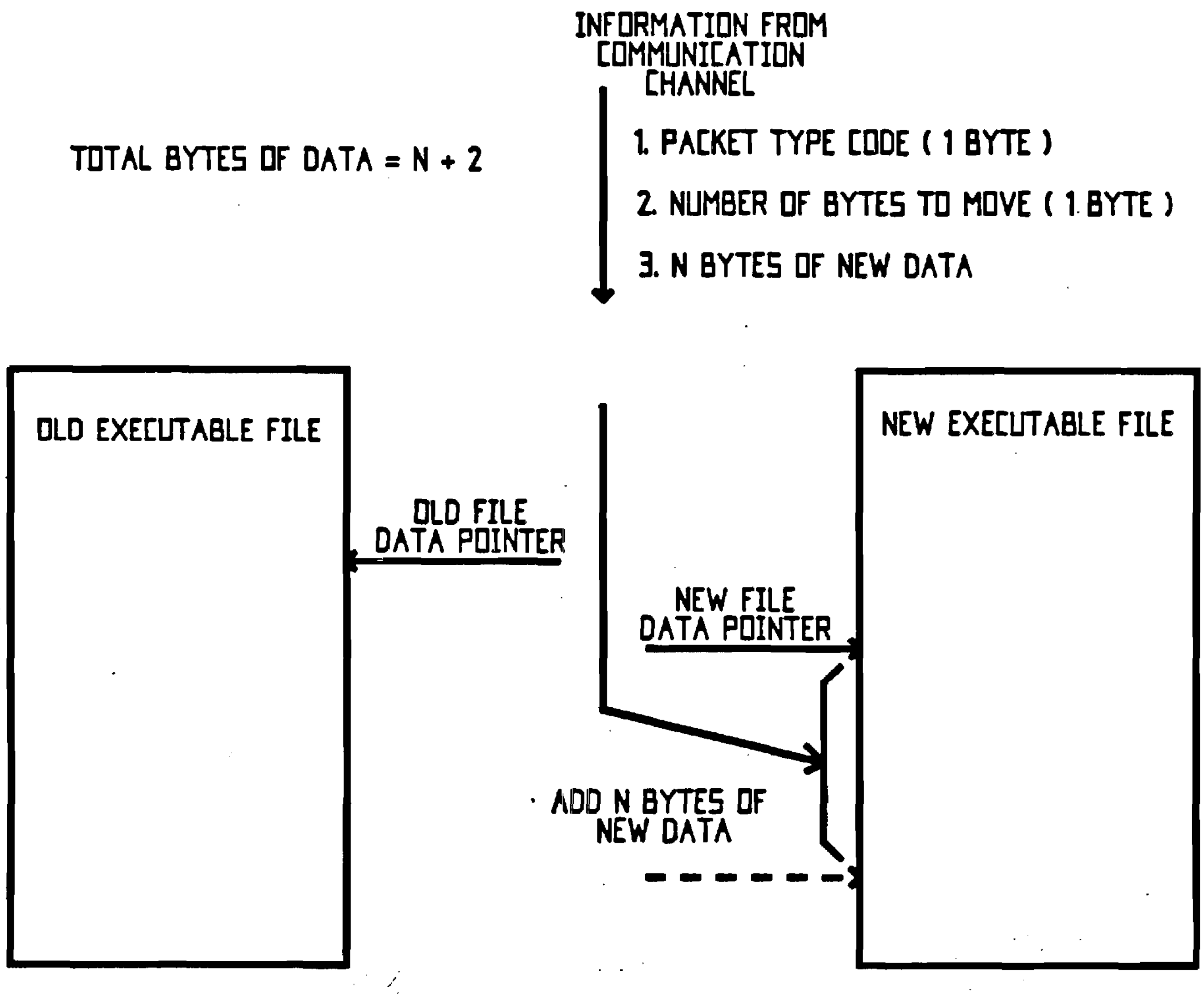


FIGURE 8

| GEORGIA INSTITUTE OF TECHNOLOGY | | |
|---|---|---|
| CONTROL DATA CORPORATION<br>ADD DATA PACKET | | |
| CDCC7 | J.H. SCHLAG | 3/86 |

4. Add Data Packet involves receiving n bytes of new data from communication channel (host) as illustrated in Figure 8 and as follows:

   a. place n bytes of new data starting at the data pointer in the new executable file

   b. add n to new file data pointer

In the worst case, by exercising data transfers types 3 & 4, the old file will be completely replaced by a new executable file, in much the same way as is currently done. When the changes are extensive, it may be the most efficient way to proceed. In many other instances, when the changes are minor, considerable savings in time and money could be realized with the new scheme.

A Trial Scheme

Based on the information presented above a trial scheme has been devised and is illustrated in the following example.

A sample assembly language program was selected at random ( Duke University Computer Science homework problem number 4). An additional instruction was added to the program and it was re-assembled. The old and new code were printed and the proposed scheme was manually applied to indicate the degree of saving in download efficiency. The following indicates the bytes that would be sent in the download file.

Download codes for sample program

| Data | Number of bytes |
|---|---|
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 256 | 1 byte |
| Position independent code | 1 byte |
| 133 | 1 byte |
| Add data code | 1 byte |
| 1 | 1 byte |
| B8 | 1 byte |
| Position offset code | 1 byte |
| Relative position offset | 2 byte |
| 215 | 1 byte |
| Total | 17 bytes |

## Analysis of sample program using proposed download scheme

Total bytes in program = 1372 bytes

Types of data fields / bytes per field:

Position independent fields = 1157 bytes

Absolute position dependent fields = 215

Number of bytes required to transmit each field type:

Position independent data = 10 bytes

Added data = 3 bytes

Absolute position dependent data = 4 bytes

Total number of bytes required for transmission = 17 bytes

Ratio of direct download to proposed scheme = 1372/17= 80.7

## Instruction Set Investigation

To investigate the validity of the new trial scheme, an example of a machine language instruction is selected to check the following:

1. to see if using this format, does there exist data that cannot be taken apart and put back together again,

2. to check on the efficiency of the scheme, that is, can you have as few variations as possible and still be effective.

## Second Six Months Effort

The objectives for the second six months of effort include the following. The first objective was to classify a subset of the 8086 language into the field structure proposed to the communication scheme and to build an instruction table for that subset. A second objective was to install two compilers on the IBM personal computer; in fact, compilers for three high-level languages, "C", Pascal, and Fortran, were installed. The third objective was to run several examples of inserting and deleting lines from each of these compiler-level languages. The fourth objective was to compare the machine language code before and after the changes to calculate the efficiency that would result from using the proposed communication scheme. The fifth objective was to identify the problem features of the DOS COM1 communication port. The work involved in reaching each of these objectives is discussed below.

### Instructions Classified by Field Structure

To classify a subset of the 8086 language into the field structure proposed to the communication scheme described earlier, some example instructions were examined in detail so that the effect of a position change on each field in that instruction could be evaluated. Fields that are position independent require no adjustment in the update scheme. Fields that are either relative or absolute position dependent will require an adjustment in the update situation. The appropriate adjustments will be made based on information in an instruction table. This instruction table will be based on information gained through the analysis of position dependencies of various fields.

The first instruction to be examined is

MOV destination,source

which transfers a byte or a word from the source operand to the destination operand. This instruction was chosen as an example for discussion because it has the potential for many different combinations of fields. This instruction comprises a set of seven instructions each characterized by the nature of the operands involved. The first of those seven involves a memory or register operand to/from a register operand. The encoding of this combination of operands can be described as

| 100010 | d | w | mod | reg | r/m | disp-lo | disp-hi |
|---|---|---|---|---|---|---|---|
| I | I | I | I | I | I | R/I | R/I |

if d=1 then SRC=EA,DEST=REG,else SRC=REG,DEST=EA, where SRC=source,DEST=destination,REG=register,EA=effective address,and disp-l and disp-h are the displacement, lower and higher order bits, respectively. Note that w=0 or 1 to indicate a register width of one or two bytes, respectively. The fields into which the bytes of the instruction have been separated for analysis are indicated by vertical dotted lines. The character of the position dependencies of each field is indicated by: I = position independent, including OPeration codes, R = relative position dependent, and A = absolute position dependent. As indicated above, The first three fields that comprise the first byte are position independent, as is the second field of the second byte. The first field of the first byte is an OP code, which is always position independent. The values of d, indicating the direction of the move, w, indicating the width of the data to be moved, and reg, specifying the register involved in the move, once set for an instruction, would not change with a change in position. The mod and r/m fields in the second byte are used in combination to indicate the addressing mode when one of the operands is in memory, as indicated in Table 1. Since one of a number of these combinations would be assigned for a particular instruction, and since many of the combinations correspond to operand effective addresses that would be relative position dependent, it would be necessary to examine these fields for a particular instruction; however, once an addressing mode has been set for an instruction, changing the position of the instruction will not change the addressing mode, so the mod and r/m fields are themselves position independent. The last two bytes, which are optional, are used to specify the displacement of the data from the beginning of the data stack. In the update process, if lines of code are inserted that refer to data which simultaneously is inserted in the stack, but after the data referred to by the instruction in question, then the values in the displacement fields would not change with position. However, when lines of code are inserted which add data in the stack above data referenced by the instruction in question, the value of the displacement will change by an amount corresponding to the amount of data that was inserted. In this case, the fields containing displacement information are considered to be relative position dependent. For these reasons, the displacement fields could be either relative position dependent or independent.

Using the logic described above, the other MOV instructions were analyzed. The field characterizations are summarized below.

Immediate Operand to Memory or Register Operand:

| 1100011 | w | mod | 000 | r/m | disp-lo | disp-hi | data | data if w=1 |
|---|---|---|---|---|---|---|---|---|
| I | I | I | I | I | R/I | R/I | I | I |

where SRC=data, DEST=EA.

In this case all fields are position independent, except the third and fourth bytes which indicate displacement. These fields, for the reasons noted above, are relative position dependent or independent.

Immediate Operand to Register:

| 1011 | w | reg | data | data if w=1 |
|---|---|---|---|---|
| I | I | I | I | I |

SRC = data, DEST=REG.

In this case all fields are position independent.

Memory Operand to Accumulator:

| | | | |
|---|---|---|---|
| 1010000 | w | addr-low | addr-high |
| I | I | R/I | R/I |

if w=0 then SRC=addr,DEST=AL
else SRC=addr+1:addr,DEST=AX.

The first two fields are position independent. Moving data in memory to the accumulator involves only the direct addressing mode, which means that the address is equivalent to displacement; therefore, like displacement fields, these address fields are either relative position dependent or independent.

Accumulator to Memory Operand:

| | | | |
|---|---|---|---|
| 10100001 | w | addr-low | addr-high |
| I | I | R/I | R/I |

if w=0 then SRC=AL, DEST=addr
else SRC=AX,DEST=addr+1:addr.

Like the previous instruction, the first two fields are position independent, and the address fields are either relative position dependent or independent.

Memory or Register Operand to Segment Register:

| | | | | | | |
|---|---|---|---|---|---|---|
| 10001110 | mod | 0 | reg | r/m | disp-lo | disp-hi |
| I | I | I | I | I | R/I | R/I |

if reg not equal 01 then SRC=EA, DEST=REG
else undefined operation.

As usual, the OP code in the first byte is a position independent field. The second byte is divided into four fields. The first and fourth are independent for reasons noted above. The second field contains one bit,is equal to 0 and is position independent. The third field in the second byte is two bits long, specifies a segment register, and is, therefore, position independent.

Segment Register to Memory or Register Operand:

| | | | | | | |
|---|---|---|---|---|---|---|
| 10001100 | mod | 0 | reg | r/m | disp-lo | disp-hi |
| I | I | I | I | I | R/I | R/I |

SRC=REG,DEST=EA

As in the instruction described above, the OP code in the first byte and field is position independent, as is the zero bit and field in the second byte. The field in the second byte specifying the segment register is also position independent. The fields denoted by mod and r/m are independent. The displacement fields that are the third and fourth bytes are relative position dependent or independent.

Turning now to an instruction other than ones related to MOV, consider the following:

NOP

NOP (No Operation) causes the CPU to do nothing. NOP does not affect any flags. It is encoded as

| 10010000 |
|---|
| I |

This single byte is one field which is an OP code and is position independent.

Based on the analysis presented above, an instruction table was prepared and is presented as Table 2.

## Installation of Compilers

To evaluate the effect that a high-level language compiler would have on the field dependencies described above, three compilers were installed on the IBM personal computer. The three high-level languages whose compilers were installed are "C",PASCAL, and FORTRAN. They were installed on the IBM XT personal computer with 640K of memory and a 10 megabyte hard disk. The installation was complex and time consuming, but the installation documentation was adequate. The parameters associated with each is listed below.

Microsoft FORTRAN 77 Compiler Rev 3.30
Microsoft PASCAL Compiler Rev. 3.31
Microsoft C Compiler Rev. 4.00

## Evaluation of Effect of Code Insertion and Deletion

For each of the high-level language compilers installed, a sample program was coded and compiled , generating the associated assembly code. For the "C" compiler, a sample program was selected from The "C" Programming Language, by Brian W. Kernighan and Dennis M. Ritchie, page 26. A copy of the program and associated assembly language code is included as Appendix A. A new line of code, adding a new variable, "min", was inserted into the original program. The program was then recompiled, generating new assembly code. The new program and associated assembly code are included as Appendix

TABLE 1 MOD AND R/M PARAMETERS

FIRST OPERAND CHOICE DEPENDS ON ADDRESSING MODE

1. FIRST OPERAND IN MEMORY

A. INDIRECT ADDRESSING

MOD = 00 => DISP = 0
MOD = 01 => DISP = DISP-LO SIGN EXTENDED
MOD = 10 => DISP = DISP-HI, DISP-LO

| R/M | OPERAND EFFECTIVE ADDRESS |
|---|---|
| 000 | (BX) + (SI) + DISP |
| 001 | (BX) + (DI) + DISP |
| 010 | (BP) + (SI) + DISP |
| 011 | (BP) + (DI) + DISP |
| 100 | (SI) + DISP |
| 101 | (DI) + DISP |
| 110 | (BP) + DISP |
| 111 | (BX) + DISP |

B. DIRECT ADDRESSING

MOD = 00
R/M = 110
OPERAND EFFECTIVE ADDRESS = DISP-HI, DISP-LO

2. FIRST OPERAND IN REGISTER

MOD = 11

| R/M | REGISTER | |
|---|---|---|
| | 8-BIT (W=0) | 16-BIT (W=1) |
| 000 | AL | AX |
| 001 | CL | CX |
| 010 | DL | DX |
| 011 | BL | BX |
| 100 | AH | SP |
| 101 | CH | BP |
| 110 | DH | SI |
| 111 | BH | DI |

TABLE 2 INSTRUCTION TABLE FORMAT

General instruction Table

Starting bit of OPCODE
Ending bit of OPCODE
OPCODE value
Starting bit of d parameter
Starting bit of w parameter
Starting bit of mod parameter
Starting bit of reg parameter
Starting bit of r/m parameter
Starting bit of data value
Number of data bits
Starting bit of disp value
Number of disp bits
Starting bit of address value
Number of address bits

Notes:
1. If the starting bit is zero then the parameter is not used
2. If the number of bits is indicated as a W, then the number of bits is controlled by the W parameter

MOV instruction Table Example
Memory or Register Operand to/from Register Operand:

| | |
|---|---|
| Starting bit of OPCODE | 1 |
| Ending bit of OPCODE | 6 |
| OPCODE value | 100010 |
| Starting bit of d parameter | 7 |
| Starting bit of w parameter | 8 |
| Starting bit of mod parameter | 9 |
| Starting bit of reg parameter | 12 |
| Starting bit of r/m parameter | 0 |
| Starting bit of data value | 0 |
| Number of data bits | 0 |
| Starting bit of disp value | 18 |
| Number of disp bits | W |
| Starting bit of address value | 0 |
| Number of address bits | 0 |

MOV instruction Table Example
Memory Operand to Accumulator

| | |
|---|---|
| Starting bit of OPCODE | 1 |
| Ending bit of OPCODE | 7 |
| OPCODE value | 101000 |
| Starting bit of d parameter | 0 |
| Starting bit of w parameter | 8 |
| Starting bit of mod parameter | 0 |
| Starting bit of reg parameter | 0 |

| | |
|---|---|
| Starting bit of r/m parameter | 0 |
| Starting bit of data value | 0 |
| Number of data bits | 0 |
| Starting bit of disp value | 0 |
| Number of disp bits | 0 |
| Starting bit of address value | 9 |
| Number of address bits | 16 |

B. A similar procedure was followed for each of the other two compilers. The FORTRAN results are included as Appendices C and D. The PASCAL results are included as Appendices E and F. The efficiency of the proposed download scheme is illustrated in Table 3. In each case the file size ratio of the direct download file to the proposed download scheme was over 100. For example in the C program example a conventional direct download would require 6558 bytes and the download with the proposed scheme would require 62 bytes.

TABLE 3 COMPARISION OF RESULTS FROM PROPOSED DOWNLOAD SCHEME

C Program Example

Total Program Size = 6558

| Data Section | Number of Bytes | Download Type | Download Bytes |
|---|---|---|---|
| Before Insert | 14 | Pos. Indep. | 2 |
| Added Code | 6 | Add Data | 8 |
| After Insert | 216 | Rel. Dep. | 2 |
| Run Time Library | 6342 | Rel. Dep. | 50 |
| Total | 6558 | | 62 |

Ratio of direct download to proposed scheme = 105.7

FORTRAN Program Example

Total Program Size = 31054

| Data Section | Number of Bytes | Download Type | Download Bytes |
|---|---|---|---|
| Before Insert | 200 | Pos. Indep. | 2 |
| Added Code | 22 | Add Data | 24 |
| After Insert | 1005 | Rel. Dep. | 8 |
| Run Time Library | 29828 | Rel. Dep. | 234 |
| Total | 31054 | | 268 |

Ratio of direct download to proposed scheme = 115.8

PASCAL Program Example

Total Program Size = 37314

| Data Section | Number of Bytes | Download Type | Download Bytes |
|---|---|---|---|
| Before Insert | 36 | Pos. Indep. | 2 |

| | | | |
|---|---|---|---|
| Added Code | 16 | Add Data | 18 |
| After Insert | 561 | Rel. Dep. | 6 |
| Run Time Library | 36701 | Rel. Dep. | 288 |
| | ------ | | ---- |
| Total | 37314 | | 314 |

Ratio of direct download to proposed scheme = 118.8

Protocol of the COM1 communication port on the IBM personal computer

The protocol for the IBM personal computer COM1 communication port has a number of features that make computer-to-computer communications difficult when operating under DOS. These features involve both the hardware and software of the communication port. This section of the report describes the problem features, and it documents a group of assembly language subroutines that have been written to control the port directly from a higher-level language.

Problem Features of the DOS COM1 Communication Port

The following hardware and software features create problems in communicating between two computers under DOS:

1. If a character has arrived at the COM1 communication port prior to the operating system accessing the port, the system declares the receiver-full status to be a device error and will cause a run-time error.

2. When the communication port is initialized to receive data, the clear-to-send line is set high, but the data terminal ready line is set low. If the full hardware handshake lines are implemented between two COM1 communication ports, the receiving port will inhibit the sending port and no data will be transmitted.

3. The software termination for a DOS input on the COM1 port is a control Z character, but the output protocol traps the transmission of a control Z on output so that the output protocol is not compatible with the input protocol.

4. The software protocol automatically sends both a carriage return and a line feed at the end of a string output, but the input only requires a carriage return to terminate the string input. This extra line feed character sent on the output usually ends up as a character left in the receiver register at the end of a transmission, which results in a run-time error as described in item 1.

The following assembly language programs were written to allow a user to access the COM1 port directly from a high-level program.

IC1LS - Reads the line status of the COM1 port

IC1MS - Reads the modem status of the COM1 port

IC1INT - Initializes the COM1 port configuration

IC1MCO - Set the value of the COM1 port modem control lines

IC1TD - Sends one character to the COM1 port

IC1TDW - Sends one character to the COM1 port after the transmitter buffer is empty

IC1RD - Reads one character from the COM1 port with a null indicating no character is available

IC1RDW - Reads one character from the COM1 port after a character becomes available

The following FORTRAN subroutines were written to supplement the assembly language routines.

C1RSTR - Read a string of characters into a character array from the COM1 port.

C1SSTR - Send a string of characters from a character array to the COM1 port.

# APPENDIX A

## C COMPILER LISTINGS

```
#define  MAXLINE  1000  /* maximum input line size */

main()   /* find longest line */
{
     int len; /* current line length */
     int max; /* maximum length seen so far */
     char line[MAXLINE]; /* current input line */
     char save[MAXLINE]; /* longest line, saved */

     max = 0;
     while ((len = getline(line, MAXLINE)) >0)
          if (len > max) {
               max = len;
               copy(line, save);
          }
     if (max > 0)   /* there was a line */
          printf("%s", save);
}

getline(s, lim)   /* get a line into s, return length */
char s[];
int lim;
{
    int c, i;

    for (i=0; i<lim-1 && (c=getchar()) && c!='\n'; ++i)
         s[i] = c;
    if (c == '\n') {
         s[i] = c;
         ++i;
    }
    s[i] = '\0';
    return(i);
}

copy(s1, s2)   /* copy s1 to s2; assume s2 big enough */
char s1[], s2[];
{
    int i;

    i = 0;
    while ((s2[i] = s1[i]) != '\0')
        ++i;
}
```

Line# Source Line                    Microsoft C Compiler Version 4.00

```

        #define  MAXLINE  1000  /* maximum input line size */

        main()   /* find longest line */
        {
             int len; /* current line length */
             int max; /* maximum length seen so far */
             char line[MAXLINE]; /* current input line */
             char save[MAXLINE]; /* longest line, saved */

             max = 0;
             while ((len = getline(line, MAXLINE)) >0)
                  if (len > max) {
                       max = len;
                       copy(line, save);
                  }
             if (max > 0)   /* there was a line */
                  printf("%s", save);
        }
```

main Local Symbols

| Name | Class | Offset | Register |
|---|---|---|---|
| max . . . . . . . . . . . . . . . . | auto | -07d4 | |
| line. . . . . . . . . . . . . . . . | auto | -07d2 | |
| save. . . . . . . . . . . . . . . . | auto | -03ea | |
| len . . . . . . . . . . . . . . . . | auto | -0002 | |

```

        getline(s, lim)   /* get a line into s, return length */
        char s[];
        int lim;
        {
            int c, i;

            for (i=0; i<lim-1 && (c=getchar()) && c!='\n'; ++i)
                 s[i] = c;
            if (c == '\n') {
                 s[i] = c;
                 ++i;
            }
            s[i] = '\0';
            return(i);
```

getline Local Symbols

| Name | Class | Offset | Register |
|---|---|---|---|
| i . . . . . . . . . . . . . . . . . . | auto | -0004 | |
| c . . . . . . . . . . . . . . . . . . | auto | -0002 | |
| s . . . . . . . . . . . . . . . . . . | param | 0004 | |
| lim . . . . . . . . . . . . . . . . . | param | 0006 | |



Line# Source Line                                Microsoft C Compiler Version 4.00

```
        }

        copy(s1, s2)   /* copy s1 to s2; assume s2 big enough */
        char s1[], s2[];
        {
            int i;

            i = 0;
            while ((s2[i] = s1[i]) != '\0')
                ++i;
        }
```

copy  Local Symbols

| Name | Class | Offset | Register |
|---|---|---|---|
| i . . . . . . . . . . . . . . . . . . | auto | -0002 | |
| s1. . . . . . . . . . . . . . . . . . | param | 0004 | |
| s2. . . . . . . . . . . . . . . . . . | param | 0006 | |

Global Symbols

| Name | Type | Size | Class | Offset |
|---|---|---|---|---|
| copy. . . . . . . . . . . . . . . . . | near function | *** | global | 00bd |
| getchar . . . . . . . . . . . . . . . | near function | *** | extern | *** |
| getline . . . . . . . . . . . . . . . | near function | *** | global | 0061 |
| main. . . . . . . . . . . . . . . . . | near function | *** | global | 0000 |
| printf. . . . . . . . . . . . . . . . | near function | *** | extern | *** |

Code size = 00e7 (231)
Data size = 0003 (3)
Bss size  = 0000 (0)

No errors detected

# APPENDIX B

## C COMPILER LISTINGS
## WITH INSTRUCTION ADDED

```
#define  MAXLINE  1000  /* maximum input line size */

main()   /* find longest line */
{
     int len; /* current line length */
     int max; /* maximum length seen so far */
     int min; /* --- new variable added */
     char line[MAXLINE]; /* current input line */
     char save[MAXLINE]; /* longest line, saved */

     max = 0;

     min = 123;           /* new line added */

     while ((len = getline(line, MAXLINE)) >0)
          if (len > max) {
               max = len;
               copy(line, save);
          }
     if (max > 0)   /* there was a line */
          printf("%s", save);
}

getline(s, lim)   /* get a line into s, return length */
char s[];
int lim;
{
    int c, i;

    for (i=0; i<lim-1 && (c=getchar()) && c!='\n'; ++i)
         s[i] = c;
    if (c == '\n') {
         s[i] = c;
         ++i;
    }
    s[i] = '\0';
    return(i);
}

copy(s1, s2)   /* copy s1 to s2; assume s2 big enough */
char s1[], s2[];
{
    int i;

    i = 0;
    while ((s2[i] = s1[i]) != '\0')
        ++i;
}
```

Line# Source Line                                   Microsoft C Compiler Version 4.00

```

#define  MAXLINE  1000  /* maximum input line size */

main()   /* find longest line */
{
     int len; /* current line length */
     int max; /* maximum length seen so far */
     int min; /* --- new variable added */
     char line[MAXLINE]; /* current input line */
     char save[MAXLINE]; /* longest line, saved */

     max = 0;

     min = 123;          /* new line added */

     while ((len = getline(line, MAXLINE)) >0)
          if (len > max) {
               max = len;
               copy(line, save);
          }
     if (max > 0)   /* there was a line */
          printf("%s", save);
}
```

main Local Symbols

| Name | Class | Offset | Register |
|---|---|---|---|
| max . . . . . . . . . . . . . . . . | auto | -07d6 | |
| line. . . . . . . . . . . . . . . . | auto | -07d4 | |
| min . . . . . . . . . . . . . . . . | auto | -03ec | |
| save. . . . . . . . . . . . . . . . | auto | -03ea | |
| len . . . . . . . . . . . . . . . . | auto | -0002 | |

```

getline(s, lim)   /* get a line into s, return length */
char s[];
int lim;
{
    int c, i;

    for (i=0; i<lim-1 && (c=getchar()) && c!='\n'; ++i)
         s[i] = c;
    if (c == '\n') {
         s[i] = c;
         ++i;
```

```
        }
        s[i] = '\0';
        return(i);
```

getline Local Symbols

| Name | Class | Offset | Register |
|---|---|---|---|

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Line# Source Line Microsoft C Compiler Version 4.00

| Name | Class | Offset | Register |
|---|---|---|---|
| i . . . . . . . . . . . . . . . . . | auto | -0004 | |
| c . . . . . . . . . . . . . . . . . | auto | -0002 | |
| s . . . . . . . . . . . . . . . . . | param | 0004 | |
| lim . . . . . . . . . . . . . . . | param | 0006 | |

```
}

copy(s1, s2)   /* copy s1 to s2; assume s2 big enough */
char s1[], s2[];
{
    int i;

    i = 0;
    while ((s2[i] = s1[i]) != '\0')
        ++i;
}
```

copy Local Symbols

| Name | Class | Offset | Register |
|---|---|---|---|
| i . . . . . . . . . . . . . . . . . | auto | -0002 | |
| s1. . . . . . . . . . . . . . . . . | param | 0004 | |
| s2. . . . . . . . . . . . . . . . . | param | 0006 | |

Global Symbols

| Name | Type | Size | Class | Offset |
|---|---|---|---|---|
| copy. . . . . . . . . . . . . . . | near function | *** | global | 00c3 |
| getchar . . . . . . . . . . . . . | near function | *** | extern | *** |
| getline . . . . . . . . . . . . . | near function | *** | global | 0067 |
| main. . . . . . . . . . . . . . . | near function | *** | global | 0000 |
| printf. . . . . . . . . . . . . . | near function | *** | extern | *** |

```
Code size = 00ed (237)
Data size = 0003 (3)
Bss size  = 0000 (0)

No errors detected
```

# APPENDIX C

## FORTRAN COMPILER LISTINGS

```
C
C     TELEPHONE NUMBER PROGRAM
C
1000  FORMAT(5X,'TELEPHONE/ADDRESS PROGRAM REV 1.0')
1001  FORMAT(5X,'ENTER NAME STRING')
1002  FORMAT(70A)
1003  FORMAT(1X,70A)
1004  FORMAT(/,5X,'TO CONTINUE TYPE C, ELSE SPACE')
1005  FORMAT(1A)
1006  FORMAT(/,5X,'SORRY I CAN NOT MATCH THAT AT ALL !!!')
1007  FORMAT(/,5X,'SORRY CAN NOT FIND ANY MORE NAMES TO MATCH')
C
      CHARACTER*70 IN,ITL
      CHARACTER*1 IC
C
      WRITE(*,1000)
      WRITE(*,1001)
      READ(*,1002) IN
C
C     FIND END OF LINE
C
      DO 20 I=1,69
      LEN = 70 - I
      ICT = IN(LEN:LEN)
      IF(ICT.NE.' ') GO TO 50
20    CONTINUE
C
C     SEARCH FOR NAME
C
50    IFF = 0
      ICF = 0
      OPEN(150,FILE='\UTIL\TNUM')
100   READ(150,1002,END=400) ITL
110   ICT = ITL(1:1)
      IF(ICT.EQ.':') GO TO 300
      IF(ICT.EQ.' ') GO TO 100
C
C     CHECK FOR PERSON MATCH
C
      DO 150 I=1,LEN
      IF(IN(I:I).NE.ITL(I:I)) GO TO 100
150   CONTINUE
C
C     PERSON MATCHES
C
      IFF = 1
170   WRITE(*,1003) ITL
      READ(150,1002,END=400) ITL
      ICT = ITL(1:1)
      IF(ICT.EQ.' ') GO TO 170
      ICF = 0
200   WRITE(*,1004)
      READ(*,1005) IC
      IF(IC.NE.'C') STOP
```

```
      IF(IC.EQ.0) GO TO 110
      GO TO 100
C
C     CHECK FOR COMPANY MATCH
C
300   DO 350 I=1,LEN
      J=I+1
      IF(IN(I:I).NE.ITL(J:J)) GO TO 100
350   CONTINUE
C
C     COMPANY MATCHES
C
      IFF = 1
      ICF = 1
370   WRITE(*,1003) ITL
      READ(150,1002,END=400) ITL
      ICT = ITL(1:1)
      IF(ICT.NE.'#') GO TO 370
      GO TO 200
C
C     END OF FILE
C
400   IF(IFF.EQ.0) WRITE(*,1006)
      IF(IFF.EQ.1) WRITE(*,1007)
      CLOSE(150)
      STOP
      END
```

# APPENDIX D

## FORTRAN COMPILER LISTINGS WITH INSTRUCTION ADDED

```
C
C     TELEPHONE NUMBER PROGRAM
C
1000  FORMAT(5X,'TELEPHONE/ADDRESS PROGRAM REV 1.0')
1001  FORMAT(5X,'ENTER NAME STRING')
1002  FORMAT(70A)
1003  FORMAT(1X,70A)
1004  FORMAT(/,5X,'TO CONTINUE TYPE C, ELSE SPACE')
1005  FORMAT(1A)
1006  FORMAT(/,5X,'SORRY I CAN NOT MATCH THAT AT ALL !!!')
1007  FORMAT(/,5X,'SORRY CAN NOT FIND ANY MORE NAMES TO MATCH')
C
      CHARACTER*70 IN,ITL
      CHARACTER*1 IC
C
      WRITE(*,1000)
      WRITE(*,1001)
      READ(*,1002) IN
C
C     FIND END OF LINE
C
      DO 20 I=1,69
      LEN = 70 - I
      ICT = IN(LEN:LEN)
      IF(ICT.NE.' ') GO TO 50
20    CONTINUE
C
C ********************************************************************
C
C       INSTRUCTION ADDED
C
C ********************************************************************
C
        J = I * I
C
C     SEARCH FOR NAME
C
50    IFF = 0
      ICF = 0
      OPEN(150,FILE='\UTIL\TNUM')
100   READ(150,1002,END=400) ITL
110   ICT = ITL(1:1)
      IF(ICT.EQ.':') GO TO 300
      IF(ICT.EQ.' ') GO TO 100
C
C     CHECK FOR PERSON MATCH
C
      DO 150 I=1,LEN
      IF(IN(I:I).NE.ITL(I:I)) GO TO 100
150   CONTINUE
C
C     PERSON MATCHES
C
      IFF = 1
```

```
170    WRITE(*,1003) ITL
       READ(150,1002,END=400) ITL
       ICT = ITL(1:1)
       IF(ICT.EQ.' ') GO TO 170
       ICF = 0
200    WRITE(*,1004)
       READ(*,1005) IC
       IF(IC.NE.'C') STOP
       IF(IC.EQ.0) GO TO 110
       GO TO 100
C
C      CHECK FOR COMPANY MATCH
C
300    DO 350 I=1,LEN
       J=I+1
       IF(IN(I:I).NE.ITL(J:J)) GO TO 100
350    CONTINUE
C
C      COMPANY MATCHES
C
       IFF = 1
       ICF = 1
370    WRITE(*,1003) ITL
       READ(150,1002,END=400) ITL
       ICT = ITL(1:1)
       IF(ICT.NE.'#') GO TO 370
       GO TO 200
C
C      END OF FILE
C
400    IF(IFF.EQ.0) WRITE(*,1006)
       IF(IFF.EQ.1) WRITE(*,1007)
       CLOSE(150)
       STOP
       END
```

# APPENDIX E

## PASCAL COMPILER LISTINGS

```
program hmwrkl;

   var
      x, d : array[0..16] of real;
      b, n, i, k, j : integer;
      z, v : real;

   begin

     n := 16;
     z := 0.96;

     { Instruction added }
     z := 0.96;

      {the array x will be filled with nodal points, the element d[i] will
       contain f[x(i)]}
     for i := 0 to n do
       begin
         x[i] := -1 + (i/8);
         d[i] := 1/(1 + sqr(100*x[i]));
       end;

      {fill the array d such that element d[i] contains f[x(i),...,x(n)]}
     for k := 1 to n do
       begin
         b := n - k;
         for i := 0 to b do
           d[i] := (d[i+1] - d[i])/(x[i+k] - x[i]);
       end;

      {calculate Newton form with ceneters x(n)...x(1)}
     v := d[0];
     for j := 1 to n do
       v := d[j] + ((z - x[j])*v);

      {print the result}
     writeln('The answer is ',v);
  end.
```

# APPENDIX F

## PASCAL COMPILER LISTINGS WITH INSTRUCTION ADDED

```
program hmwrk1;

   var
      x, d : array[0..16] of real;
      b, n, i, k, j : integer;
      z, v : real;

   begin

     n := 16;
     z := 0.96;

      {the array x will be filled with nodal points, the element d[i] will
       contain f[x(i)]}
     for i := 0 to n do
       begin
         x[i] := -1 + (i/8);
         d[i] := 1/(1 + sqr(100*x[i]));
       end;

      {fill the array d such that element d[i] contains f[x(i),...,x(n)]}
     for k := 1 to n do
       begin
         b := n - k;
         for i := 0 to b do
           d[i] := (d[i+1] - d[i])/(x[i+k] - x[i]);
       end;

      {calculate Newton form with ceneters x(n)...x(1)}
     v := d[0];
     for j := 1 to n do
       v := d[j] + ((z - x[j])*v);

      {print the result}
     writeln('The answer is ',v);
  end.
```

Final Report

# STANDARDIZED PROTOCOLS BETWEEN MICROCOMPUTERS AND DATA SERVICE NETWORKS

By
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Mr. Henry Owen
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February, 1988

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# STANDARDIZED PROTOCOLS BETWEEN MICROCOMPUTERS AND DATA SERVICE NETWORKS

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1 February 1988

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# SECTION 1

# INTRODUCTION

The rapid growth of computer applications coupled with the development of inexpensive, small computer systems has drastically changed the role of the mainframe computer service network, primarily because computer intelligence has shifted from the main host to the user-based systems. This shift has precipitated a need for changes in many other computer functions such as data base management, applications programs, data security and communication protocols. Control Data Corporation initiated a two-year effort with Georgia Tech to address issues within the single area of computer communication protocols in the computer service network and the impact of modern computer networks on the protocol requirements. Of particular interest are the areas of communication hardware, data transmission structure, error detection, error correction, encryption, data base security, data format exchange, and data base management command exchange. The main thrust of this effort has been to develop of an efficient algorithm to keep the executable files on a remote computer updated by the host system and to investigate the related issues.

This report is the final report on that two-year effort. An annual report was submitted covering the work done in the first year. Included in that report are the results of a literature search with results of recent work in the above referenced areas of interest, both for the assessment of the current status and for future reference; a description of the system elements involved in updating an executable file on the remote from the host system; a discussion of the proposed new update scheme including an analysis of the information fields in an instruction and methods of transferring data; the results of trial data in each of several compiler-level languages processed with the new update scheme and the efficiency that would result from using the new scheme; and a discussion of the problem features of the DOS COM1 communication port. Those results will not be repeated here, but will be summarized where necessary for clarity and continuity. The reader is referred to the annual report for details.

# SECTION 2

# BACKGROUND

During the 1970 time frame the user in a service computer network was a simple CRT terminal or hard-copy device with no local processing or data storage capability. During the early 1980 period the service networks developed a large variety of computer communication networks to effectively handle larger volumes of more sophisticated data transmissions. These networks effectively removed the communication demands from the central computer but did not remove the host application programs as the center of processing activity. With the development of inexpensive personal and business computers, the typical user will require local application programs and mass storage, with the computer service network supplying access to large data bases for portions of the processing information. A major problem in a system of the 1990's will be to keep the executable files on a remote computer updated by the host system in a timely and cost effective manner. Currently when an application program is changed on the host system, the new executable file is transmitted in toto to the remote user to replace the old executable file. This process is both time consuming and costly. The new update scheme compares at the host system both the old and new executable files. Any differences in the files, including different offsets from change in position, additional data, and information from deleted data, are incorporated into a file, hopefully much smaller than the new executable file, that is transmitted to the remote user. Information in this file is then used to reconstruct the old executable file at the remote into a new executable file that matches the one at the host system. If the changes have been minor, there is the potential to save a great deal of time and money.

To design an algorithm to realize this kind of update scheme, a number of considerations must be taken into account. During the first year of this effort Georgia Tech examined several issues and made some preliminary estimates of the efficiencies that might be realized. The results were promising. More specifically, Georgia Tech examined four types of information fields that comprise machine-level instructions for the impact that changes in a program would have on them, as well as four ways to transfer data packets to properly account for that impact. During the second year project personnel used new insights gained in the areas of information fields and data transfer to examine the instruction formats, header segments and data segments, and the file comparison algorithms that might be used or modified to detect the differences between the old and new executable files. Results from these examinations will be presented in Section 3 below. Section 4 is devoted to a description of the update algorithm that was designed. Section 5 is a discussion of future directions that are recommended for the refinement and expansion of the update approach developed during this effort.

# SECTION 3

## ALGORITHM CONSIDERATIONS

To develop an algorithm that will update an executable file using as much of the old file as possible as the building blocks for the new file, Georgia Tech personnel carefully examined a number of issues believed to be critical to the initial development of the update algorithm investigated. The results, presented below, were incorporated into the algorithm outlined in Section 4. The detailed study of some of the remaining issues are outside the scope of this effort, but are identified and discussed briefly in this report as future directions for this program.

The algorithm must identify the instructions that are common between various versions of the program. In identifying these instructions, the algorithm must recognize identical instructions which have different offsets in their data, displacement, or address fields. In order to search an executable file for instructions, the header and data segments must be removed from consideration, since these segments do not contain instructions. The header and data segments are handled separately, with their transmission algorithms being different from the code segment.

### INSTRUCTION FORMAT DECODING

The INTEL 8086/8088 instruction set is made up of many different instruction formats. The "iAPX 86/88, 186/188 Users' Manual", 1985, lists the formats for each instruction type in Table 1-22. The instructions are made up of subfields which are summarized in Table 1-21. When an instruction is relocated in a program, subfields within the instructions change to reflect the new instruction location. By examining the subfields in each instruction as shown in Table 1-22, the bytes in an instruction format that may change upon relocation may be identified. The above referenced tables are include as Appendix A of this report. A summary of those fields which may change upon instruction relocation includes the following bytes in the instructions:

| | |
|---|---|
| DISP-LO | Lower-order byte of an unsigned displacement |
| DISP-HI | Higher-order byte of an unsigned displacement |
| IP-LO | Lower-order byte of a new instruction pointer value |
| IP-HI | Higher-order byte of a new instruction pointer value |
| CS-LO | Lower-order byte of a new code segment |
| CS-HI | Higher-order byte of a new code segment |
| IP-INC8 | 8-bit signed increment to instruction pointer |
| IP-INC-LO | Lower-order byte of signed 16-bit instruction pointer increment |
| IP-INC-HI | Higher-order byte of signed 16-bit instruction pointer increment |
| ADDR-LO | Lower-order byte of direct address (offset) of memory operand |
| ADDR-HI | Higher-order byte of direct address (offset) of memory operand |
| DATA-LO | Lower-order byte of data |
| DATA-HI | Higher-0rder byte of data |

For a given instruction, it is necessary to identify the fields that may change upon instruction relocation. By examining Table 1-22, sixteen different cases may be identified. These sixteen different cases are shown in Figure 1. In this figure, only those bytes which are underlined may change upon relocation

In order to determine the format for a given instruction, several bit fields within a given instruction must be examined. The first field is the most significant eight bits (the first byte) of the instruction. For all instructions which do not contain displacements, the format is now determined. For instructions which may have displacements, the number of displacement bytes must be determined. These are determined from the MOD field bits which are the two most significant bits in the second byte of an instruction. For MOD=11 there are no displacement bytes, for MOD=10 there are two displacement bytes, and for MOD=01 there is one displacement byte. If MOD=00 and also R\M=110 then two displacement bytes follow. The R\M field is located in the three least significant bits in the second byte of an instruction.

There are two special cases in which the OPCODE must be used in conjunction with the register field to determine the instruction format. The register field consists of of third, fourth, and fifth bits of the second instruction byte as counted from MSB to LSB. For OPCODE Hex F6 and REG=000, one data byte will be contained at the end of the instruction. For OPCODE Hex F7 and REG=000, two data bytes will be contained at the end of the instruction.

The flow chart for determining the instruction format is shown in Figure 2. The result of this format algorithm is an assigned instruction format type for every possible instruction. It should be noted that the first eight bits of all instructions are not always sufficient to determine the instruction type. Every instruction is assigned an initial instruction type based on the first eight bits and a table look-up scheme; then by examining additional bits in those cases where it is necessary, the correct instruction format assignment is always obtained. The initial instruction format assignment is made from Figure 3. Figure 3 represents all of the 256 possible initial assignments based upon the first eight bits of an instruction. The table is read by referencing the position in the table and equating this position to the corresponding first eight entries of

| TYPE | INSTRUCTION FORMAT | | | | | |
|---|---|---|---|---|---|---|
| 1 | BYTE 1 | BYTE 2 | | | | |
| 2 | BYTE 1 | BYTE 2 | DISP-LO | | | |
| 3 | BYTE 1 | BYTE 2 | DISP-LO | DISP-HI | | |
| 4 | BYTE 1 | BYTE 2 | DATA-LO | DATA-HI | | |
| 5 | BYTE 1 | BTYE 2 | DISP-LO | DATA-LO | DATA-HI | |
| 6 | BYTE 1 | BYTE 2 | DISP-LO | DISP-HI | DATA-LO | DATA-HI |
| 7 | BYTE 1 | BYTE 2 | BYTE 3 | | | |
| 8 | BYTE 1 | BYTE 2 | DISP-LO | BYTE 4 | | |
| 9 | BYTE 1 | BYTE 2 | DISP-LO | DISP-HI | BYTE 5 | |
| 10 | BYTE 1 | DATA-LO | DATA-HI | | | |
| 11 | BYTE 1 | BYTE 2 | | | | |
| 12 | BYTE 1 | ADDR-LO | ADDR-HI | | | |
| 13 | BYTE 1 | | | | | |
| 14 | BYTE 1 | IP-INC-LO | IP-INC-HI | | | |
| 15 | BYTE 1 | IP-LO | IP-HI | CS-LO | CS-HI | |
| 16 | BYTE 1 | IP-INC8 | | | | |

Figure 1 Instruction Format Types

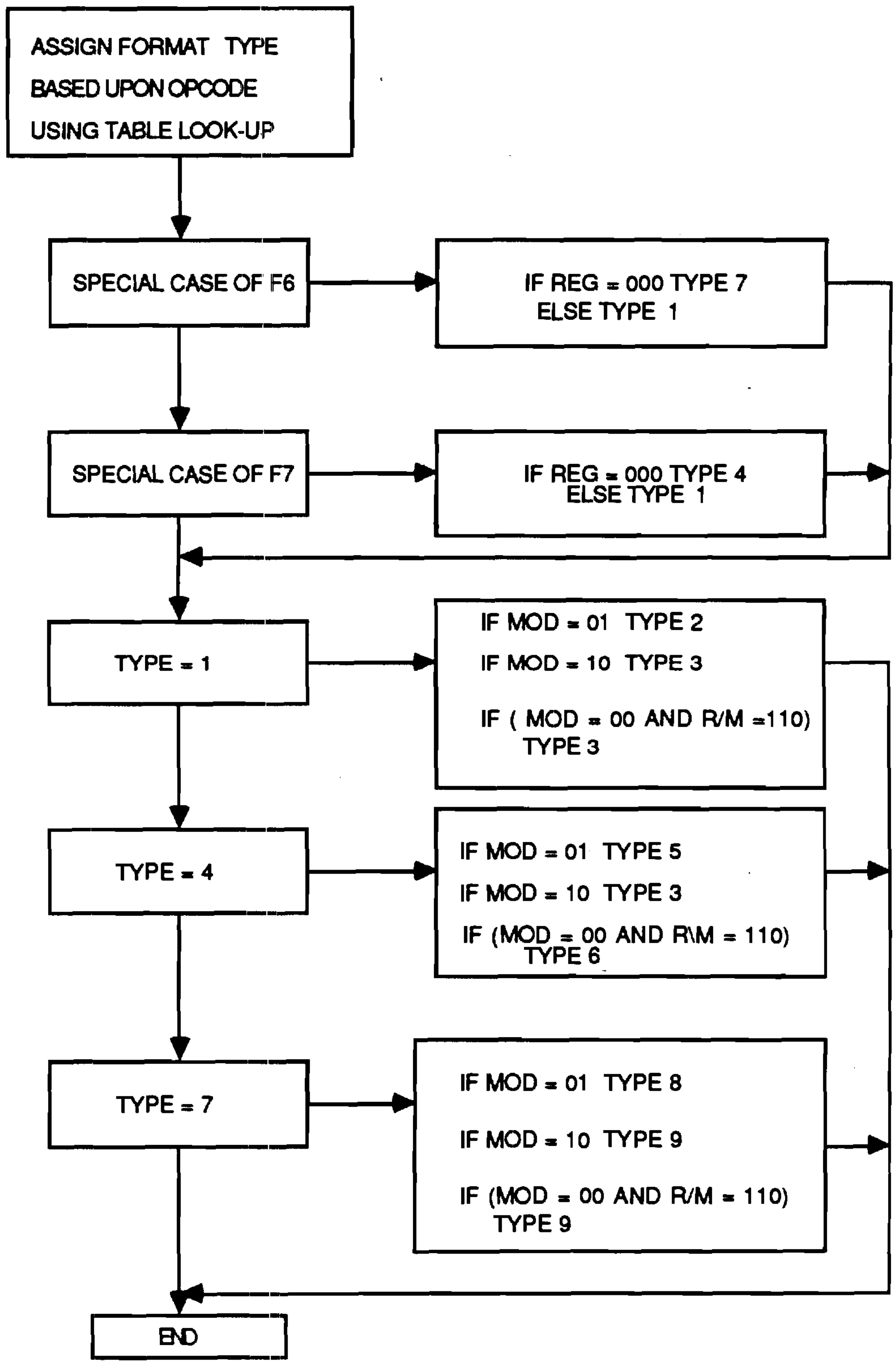


Figure 2 Algorithm Flow Chart

| INSTRUCTION FIRST BYTE | INSTR. TYPE |
|---|---|
| 00 | 1 |
| 01 | 1 |
| 02 | 1 |
| 03 | 1 |
| 04 | 11 |
| 05 | 10 |
| 06 | 13 |
| 07 | 13 |
| 08 | 1 |
| 09 | 1 |
| 0A | 1 |
| 0B | 1 |
| 0C | 11 |
| 0D | 10 |
| 0E | 13 |
| 0F | 13 |
| 10 | 1 |
| 11 | 1 |
| 12 | 1 |
| 13 | 1 |
| 14 | 11 |
| 15 | 10 |
| 16 | 13 |
| 17 | 13 |
| 18 | 1 |
| 19 | 1 |
| 1A | 1 |
| 1B | 1 |
| 1C | 11 |
| 1D | 10 |
| 1E | 13 |
| 1F | 13 |
| 20 | 1 |
| 21 | 1 |
| 22 | 1 |
| 23 | 1 |
| 24 | 11 |
| 25 | 10 |
| 26 | 13 |
| 27 | 13 |
| 28 | 1 |
| 29 | 1 |
| 2A | 1 |
| 2B | 1 |
| 2C | 11 |
| 2D | 10 |
| 2E | 13 |
| 2F | 13 |

Figure 3. 256 Possible TYPE Assignments Based on First Byte

| INSTRUCTION FIRST BYTE | INSTR. TYPE |
|---|---|
| 30 | 1 |
| 31 | 1 |
| 32 | 1 |
| 33 | 1 |
| 34 | 11 |
| 35 | 10 |
| 36 | 13 |
| 37 | 13 |
| 38 | 1 |
| 39 | 1 |
| 3A | 1 |
| 3B | 1 |
| 3C | 11 |
| 3D | 10 |
| 3E | 13 |
| 3F | 13 |
| 40 | 13 |
| 41 | 13 |
| 42 | 13 |
| 43 | 13 |
| 44 | 13 |
| 45 | 13 |
| 46 | 13 |
| 47 | 13 |
| 48 | 13 |
| 49 | 13 |
| 4A | 13 |
| 4B | 13 |
| 4C | 13 |
| 4D | 13 |
| 4E | 13 |
| 4F | 13 |
| 50 | 13 |
| 51 | 13 |
| 52 | 13 |
| 53 | 13 |
| 54 | 13 |
| 55 | 13 |
| 56 | 13 |
| 57 | 13 |
| 58 | 13 |
| 59 | 13 |
| 5A | 13 |
| 5B | 13 |
| 5C | 13 |
| 5D | 13 |
| 5E | 13 |
| 5F | 13 |

Figure 3. Continued

| INSTRUCTION FIRST BYTE | INSTR. TYPE |
|---|---|
| 60 | 13 |
| 61 | 13 |
| 62 | 13 |
| 63 | 13 |
| 64 | 13 |
| 65 | 13 |
| 66 | 13 |
| 67 | 13 |
| 68 | 13 |
| 69 | 13 |
| 6A | 13 |
| 6B | 13 |
| 6C | 13 |
| 6D | 13 |
| 6E | 13 |
| 6F | 13 |
| 70 | 16 |
| 71 | 16 |
| 72 | 16 |
| 73 | 16 |
| 74 | 16 |
| 75 | 16 |
| 76 | 16 |
| 77 | 16 |
| 78 | 16 |
| 79 | 16 |
| 7A | 16 |
| 7B | 16 |
| 7C | 16 |
| 7D | 16 |
| 7E | 16 |
| 7F | 16 |
| 80 | 7 |
| 81 | 4 |
| 82 | 7 |
| 83 | 7 |
| 84 | 1 |
| 85 | 1 |
| 86 | 1 |
| 87 | 1 |
| 88 | 1 |
| 89 | 1 |
| 8A | 1 |
| 8B | 1 |
| 8C | 1 |
| 8D | 1 |
| 8E | 1 |
| 8F | 1 |

Figure 3. Continued

| INSTRUCTION FIRST BYTE | INSTR. TYPE |
|---|---|
| 90 | 13 |
| 91 | 13 |
| 92 | 13 |
| 93 | 13 |
| 94 | 13 |
| 95 | 13 |
| 96 | 13 |
| 97 | 13 |
| 98 | 13 |
| 99 | 13 |
| 9A | 15 |
| 9B | 13 |
| 9C | 13 |
| 9D | 13 |
| 9E | 13 |
| 9F | 13 |
| A0 | 12 |
| A1 | 12 |
| A2 | 12 |
| A3 | 12 |
| A4 | 13 |
| A5 | 13 |
| A6 | 13 |
| A7 | 13 |
| A8 | 11 |
| A9 | 10 |
| AA | 13 |
| AB | 13 |
| AC | 13 |
| AD | 13 |
| AE | 13 |
| AF | 13 |
| B0 | 11 |
| B1 | 11 |
| B2 | 11 |
| B3 | 11 |
| B4 | 11 |
| B5 | 11 |
| B6 | 11 |
| B7 | 11 |
| B8 | 10 |
| B9 | 10 |
| BA | 10 |
| BB | 10 |
| BC | 10 |
| BD | 10 |
| BE | 10 |
| BF | 10 |

Figure 3. Continued

| INSTRUCTION FIRST BYTE | INSTR. TYPE |
|---|---|
| C0 | 13 |
| C1 | 13 |
| C2 | 10 |
| C3 | 13 |
| C4 | 1 |
| C5 | 1 |
| C6 | 7 |
| C7 | 4 |
| C8 | 13 |
| C9 | 13 |
| CA | 10 |
| CB | 13 |
| CC | 13 |
| CD | 11 |
| CE | 13 |
| CF | 13 |
| D0 | 1 |
| D1 | 1 |
| D2 | 1 |
| D3 | 1 |
| D4 | 11 |
| D5 | 11 |
| D6 | 13 |
| D7 | 13 |
| D8 | 11 |
| D9 | 1 |
| DA | 1 |
| DB | 1 |
| DC | 1 |
| DD | 1 |
| DE | 1 |
| DF | 11 |
| E0 | 16 |
| E1 | 16 |
| E2 | 16 |
| E3 | 16 |
| E4 | 11 |
| E5 | 11 |
| E6 | 11 |
| E7 | 11 |
| E8 | 14 |
| E9 | 14 |
| EA | 15 |
| EB | 11 |
| EC | 13 |
| ED | 13 |
| EE | 13 |
| EF | 13 |

Figure 3. Continued

| INSTRUCTION FIRST BYTE | INSTR. TYPE |
|---|---|
| F0 | 13 |
| F1 | 13 |
| F2 | 13 |
| F3 | 13 |
| F4 | 13 |
| F5 | 13 |
| F6 | 7 |
| F7 | 4 |
| F8 | 13 |
| F9 | 13 |
| FA | 13 |
| FB | 13 |
| FC | 13 |
| FD | 13 |
| FE | 1 |
| FF | 1 |

Figure 3. Continued

an instruction. As an example the first eight entries of Figure 3 are repeated below with the corresponding first instruction byte:

| First Byte | Type |
|---|---|
| 00 | 1 |
| 01 | 1 |
| 02 | 1 |
| 03 | 1 |
| 04 | 11 |
| 05 | 10 |
| 06 | 13 |
| 07 | 13 |

The table entries are determined from Table 1-23 by assuming that the instructions contain no displacements and a type is assigned on that basis. The table type value is then changed later in the algorithm as shown in the flow chart (Figure 2) based upon the MOD bits. The complete table contains an initial type assignment for each of the 256 possible cases for the first byte of an instruction.

The format types contained in the table contain types which appear to be redundant. For example, Type 1 and Type 11 appear the same. The difference is that Types 1,4, and 7 are types that require that the MOD field be examined to determine the number of displacement bytes that are included in the instruction. All other types are not affected by the MOD bits. The algorithm uses Types 1,4, and 7 to signify that the algorithm must examine the MOD bits to make a final determination of the format of the instruction.

Once the instruction format type is known, the number of bytes for that instruction is known, as well as the location of the bytes in the instruction that may change upon instruction relocation. This information is critical in determining which bytes to ignore during a file comparison so as to determine when two segments of code are identical except for instruction relocation offsets.

## HEADER IDENTIFICATION

An executable program consists of two parts. The first part is a header record that contains control and relocation information. The second part is the actual load module. The header record contains information about the size of the executable module, where it is to be loaded into memory, and relocation offsets to be inserted into incomplete machine addresses. The header fields and their explanation are shown in Figure 4.

The size of the header may be determined by the following procedure. In the executable file, obtain the hex values in the ninth and tenth bytes of the file. (Count the first hex byte as one, not zero.) The tenth byte is most significant, the ninth byte is least significant. This hex value should be converted to decimal and then multiplied by 16 since the header size is given in 16-byte increments. This is the size of the header in bytes.

## CODE SEGMENT IDENTIFICATION

The code segment may be located by using the " .map" output of the linker. The beginning of the code segment in the output from the Micrsoft PASCAL compiler is located two bytes after the header; therefore, the first code segment's location, relative to the start of the executable file, is at a an offset value equal to the size of the header plus two bytes. The end of the code segment is determined from the " .map" file, which is an output from the linker. The procedure for determining the end of the code segment is as follows. In the " .map" file as output by the linker, find the class of "encode" shown in the "class" column. In the column "start" is shown the end of the code segment. This value is relative to the header size and must be added to the header size which is determined from the header as discussed above. After adding the header size to the code segment value, the end of the code segment's location, relative to the beginning of the executable file, is now known.

## DATA SEGMENT IDENTIFICATION

The start of the data segment is determined from the end of the code

| Relative Hex Position: | Field: |
|---|---|
| 00 | Hex 4D5A. The Linker inserts this code to identify the file as a valid EXE file |
| 02 | Reserved |
| 04 | Size of the file including the header, in 512-byte increments ("pages") |
| 06 | Number of relocation table items following the formatted portion of the header |
| 08 | Size of the header in 16-byte increments. The purpose of this field is to help locate the start of the executable module that follows this header |
| 0A | Reserved |
| 0C | High/low loader switch. You decide at the start of LINK whether your program is to load for execution at a low (the usual) or a high memory address. Hex 0000 indicates high and hex FFFF indicates low |
| 0E | Offset location in the executable module of the Stack Segment |
| 10 | Address that the Loader is to insert in the SP register when transferring control to the executable module |
| 12 | Checksum value – the sum of all the words in the file (ignoring overflows) used as a validation check for lost data |
| 14 | The offset that the Loader is to insert in the IP register when transferring control to the executable module |
| 16 | The offset location in the executable module of the Code Segment |
| 18 | The offset of the first relocation item in this file |
| 1A | Reserved |
| 1B | Relocation table containing a variable number of relocation items, as identified at offset 06 |

Figure 4 Header Fields and their Explanations

segment. The data segment begins at the end of the code segment and continues to the end of the executable file. This may not always be true, but it is true for all Microsoft Pascal examples run during this effort.

EXAMPLE OF SEGMENT IDENTIFICATION

To illustrate the procedure for determining the locations of the various segments in an executable file, the following example is provided. The required input information is the " .map" file from the linker, and the " .exe" file. An example " .map" file is shown in Figure 5, and an example header portion for the same example is shown in Figure 6.

The procedure to identify the segments is as follows:

Step 1: In the " .exe" file obtain the hex values in the ninth and tenth bytes of the file. In this example the values are 60 and 00, respectively.

Step 2: Convert this value to decimal and multiply the result by 16. In this example, this is 96 times 16, indicating a header size of 1536 bytes.

Step 3: Determine the beginning of the code segment by adding two bytes to the size of the header; therefore, the code segment in this example begins at 1538 bytes into the file.

Step 4: In the " .map" file as output by the linker, find the class of "encode" shown in the "class" column. In the column "start" is shown the hex location of the end of the code segment. In this example, this value is 0436E hex.

Step 5: Add the header size to the value obtained in step 2. The result is the end of the code segment and the beginning of the data segment. In this example, this value is 1536 + 17262, which yields 18798 bytes.

The summary of the results from this example are:

Header begins at 0 and ends 1536 bytes into the file
Code begins at 1538 and ends 18798 bytes into the file
Data begins at 18799 and ends at the end of the file

```
********
**
**       *****     *****    *****
**         *       *        *
********           ****     ****
           *       *        *
           *       *****    *****
```

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7/13/1987 17:48:16
FILENAME = c:\pascal\prog\simple1.map

| Start | Stop | Length | Name | Class |
|---|---|---|---|---|
| 00000H | 0004BH | 0004CH | SIMPLE1 | CODE |
| 0004CH | 01295H | 0124AH | _TEXT | CODE |
| 01296H | 01FCAH | 00D35H | FILFQQ_CODE | CODE |
| 01FCCH | 0249FH | 004D4H | ORDFQQ_CODE | CODE |
| 024A0H | 0284FH | 003B0H | STRFQQ_CODE | CODE |
| 02850H | 02872H | 00023H | EXIT_TEXT | CODE |
| 02874H | 02A15H | 001A2H | CONUXU_CODE | CODE |
| 02A16H | 03693H | 00C7EH | FILUQQ_CODE | CODE |
| 03694H | 038D6H | 00243H | ERREQQ_CODE | CODE |
| 038D8H | 039BBH | 000E4H | HEAHQQ_CODE | CODE |
| 039BCH | 039EDH | 00032H | MISOQQ_CODE | CODE |
| 039EEH | 03AEDH | 00100H | PASUXU_CODE | CODE |
| 03AEEH | 03CD4H | 001E7H | COUCQQ_CODE | CODE |
| 03CD6H | 03DA2H | 000CDH | MISHQQ_CODE | CODE |
| 03DA4H | 04183H | 003E0H | LONCQQ_CODE | CODE |
| 04184H | [illegible] | [illegible] | MISYQQ_CODE | CODE |
| [illegible] | [illegible] | [illegible] | [illegible]_TEXT | CODE |
| 043AEH | 043AEH | 00000H | C_ETEXT | ENDCODE |
| [illegible] | [illegible] | 0000CH | __FBSS | FAR_BSS |
| 04370H | 043BEH | 0004FH | NULL | BEGDATA |
| 043C0H | 04FD7H | 00C18H | _DATA | DATA |
| 04FD8H | 04FD8H | 00000H | COMADS | DATA |
| 04FD8H | 04FD8H | 00000H | XIB | DATA |
| 04FD8H | 04FDBH | 00004H | XI | DATA |
| 04FDCH | 04FDCH | 00000H | XIE | DATA |
| 04FDCH | 04FDCH | 00000H | XCB | DATA |
| 04FDCH | 04FDFH | 00004H | XC | DATA |
| 04FE0H | 04FE0H | 00000H | XCE | DATA |
| 04FE0H | 04FE0H | 00000H | P1IB | DATA |
| 04FE0H | 04FE3H | 00004H | P1I | DATA |
| 04FE4H | 04FE4H | 00000H | P1IE | DATA |
| 04FE4H | 04FE4H | 00000H | P2IB | DATA |
| 04FE4H | 04FE4H | 00000H | P2I | DATA |
| 04FE4H | 04FE4H | 00000H | P2IE | DATA |
| 04FE4H | 04FE4H | 00000H | P3IB | DATA |
| 04FE4H | 04FE7H | 00004H | P3I | DATA |
| 04FE8H | 04FE8H | 00000H | P3IE | DATA |
| 04FE8H | 04FE8H | 00000H | P1CB | DATA |
| 04FE8H | 04FEBH | 00004H | P1C | DATA |
| 04FECH | 04FECH | 00000H | P1CE | DATA |
| [illegible] | 04FECH | [illegible] | [illegible] | DATA |

Figure 5 Example of " .map " File

```
4FECH 04FECH 00000H P2C                    DATA
4FECH 04FECH 00000H P2CE                   DATA
4FECH 04FECH 00000H P3CB                   DATA
4FECH 04FEFH 00004H P3C                    DATA
4FF0H 04FF0H 00000H P3CE                   DATA
4FF0H 04FF[illegible] 0000EH CDATA                  DATA
4FFEH 0918[illegible] 0018CH CONST                  CONST
0518AH 0518AH 00000H EDATA                  ENDDATA
0518AH 0518AH 00000H EEND                   ENDBSS
0518AH 0518AH 00000H _BSS                   BSS
05190H 0598FH 00800H STACK                  STACK

Origin    Group
0487:0    DGROUP

rogram entry point at 0004:06F0
```

Figure 5 Example of " .map " File
(continued)

```
4D \ IDENTIFIES FILE AS A VALID .EXE FILE
5A /
8A
01
2C \ 002C IS SIZE OF FILE IN 512 BYTE INCREMENTS
00 /    2CH * 512 = 22528
6A \ NUMBER OF RELOCATION TABLE ITEMS FOLLOWING HEADER
01 /    016AH = 362
60 \ SIZE OF HEADER IN 16 BYTE INCREMENTS
00 /    0060H * 16 = 1536
81
00
FF
FF
19 \ OFFSET LOCATION IN .EXE MODULE OF STACK SEGMENT
05 /      0519H
00
08
F5
08
F0
06
04 \ OFFSET LOCATION IN .EXE MODULE OF CODE SEGMENT
00 /      0004H
IE
00
00
00
 .
 .
 .
 .
 .
 .
 .
 .
 .
 .
```

Figure 6. Example of a Header File

FILE- COMPARISON APPROACHES

In a typical situation only minor changes have been made to the update program. In that case many, perhaps most of the instructions will be the same except for minor differences. The minor differences include different offsets in the data, displacements, or address fields. The approach to compare these files must be able to recognize matching instruction pairs that are either identical or different only in the minor ways mentioned above and explained later and to account for these minor changes in the transmission process so that the new file can be reconstructed from the old with the correct modifications.

To this end a number of existing file-compare algorithms were examined to see if existing software could be used or adapted for this application. Notable among the papers found in the literature were: "A Fast Algorithm for Computing Longest Common Subsequence," by James Hunt of Standford University and Thomas G. Szymanski, Communications of ACM, Volume 20, No. 5, May 1977; "Algorithms for the Longest Common Subsequence Problem," by Daniel S. Hirschberg of Princeton University, Journal of the Association for Computing Machinery, Volume 24, No. 4, October 1977, pages 664-675; and " File Comparison Algorithms," by Tom Steppe, Dr. Dobb's Journal of Software Tools, September 1987, pages 28-33 and 54-60. Of these three, the last proved to be most useful since it reviewed several types of algorithms including the longest common subsequence type referenced in the first two articles. Copies of the articles are included as Appendix B.

Basically, file-compare algorithms look for line matches, then report lines not included as matches as differences. The differences are usually expressed as insertions, deletions and changes that must be made to make the files match. Algorithms are evaluated to answer the questions: Is it efficient? Is it robust? Can it let differences go undetected? Can it let matches go undetected? Can it detect blocks of text that have been moved? There are several popular algorithms. The "scan until next match" algorithm starts at the tops of both files and matches as many lines as possible. When a difference is detected, the next M lines are scanned until at least N consecutive matches are found. The main advantages of this algorithm is time efficiency and minimal memory requirements; the main problem with this algorithm is that it is not robust over a variety of situations. A second type of algorithm is called the "longest common subsequence" algorithm. This algorithm finds the longest common, though not necessarily consecutive, sequence of lines in the two files. This type of algorithm often produces the best reports when comparing files that do not involve moved blocks of code, but it can be slow. A third type, called "extended unique matching" is based on the idea that a line that occurs once and only once in each file must be the same line. These pairs of "unique" lines determine the initial set of unmatched lines. Then, in each file, the lines adjacent to each match are examined and, if identical, are added to the set of matched lines, and the process is repeated. Though efficient in time and space, it is prone to detecting false differences. A fourth type of algorithm, developed by Steppe, is called the "recursive longest matching sequence." This method scans both files looking for the longest sequence of consecutive lines. This block then divides the files into top and bottom halves, each of which is then scanned. The process is repeated until no more matches can be found. The space for this algorithm is linear but the time is quadratic. A modification to the algorithm can reduce the time required. All of these algorithms were designed to handle text files, though many of the concepts apply to executable files as well.

An algorithm, based in part on some of these concepts, was conceived to address the special case of the executable file. The basic idea is to do an instruction by instruction comparison on the code sections of the old and new files where a file may have been padded at the end with "never match" code to make them the same size. On the first pass the largest block of consecutive matches will be identified and the size and location noted. The files will then be compared again with one of the files shifted by one line, as if the file were wrapped around to form a circle with the beginning and ending lines of each file touching. This is the reason the files must be made the same length. The process continues until the largest possible block of matches has been found. Note that a match is declared even if the offsets in their data, displacements, or address fields do not match. This block is, in effect, set aside and the whole process is repeated with the remainders of the files, which hopefully are much smaller. This process is continued until it is no longer feasible to search for matches; that is, when the remaining code segments or pieces are of a size that it is more cost effective to transmit the code in toto than to spend the overhead to form packets, etc. to follow the scheme outlined. The algorithm for the update scheme will incorporate the file compare approach just described.

# SECTION 4

# ALGORITHM

## Overview

There are two algorithms involved in the transmission of modified code. The host computer algorithm and the remote computer algorithm, run on the host and the remote computers, respectively.

The host computer algorithm requires a copy of the old host binary executable program (the unmodified program) as well as the new host binary executable program (the new version of the program). The host converts both of these binary program versions to hexadecimal representations and then compares the two programs. This comparison identifies the code segments that are identical in both the old and the new programs including those code segments that are different only by offset values in the various instruction subfields. The host algorithm generates a host update file which is decoded by the remote computer algorithm so as to generate the necessary changes to the remote computer's old remote binary executable file. This is accomplished in the remote computer by first converting the old remote binary executable program into an old remote hexadecimal executable program version. The new remote hexadecimal executable program is generated from the old executable program instructions, which are modified as necessary, and the instructions which are transmitted to the remote computer in the host update file. After the new remote hexadecimal executable program is generated, the program is converted into the new remote binary executable program. Figure 7 is an illustration of the files that the algorithm uses and the resulting files that are generated by the algorithm.

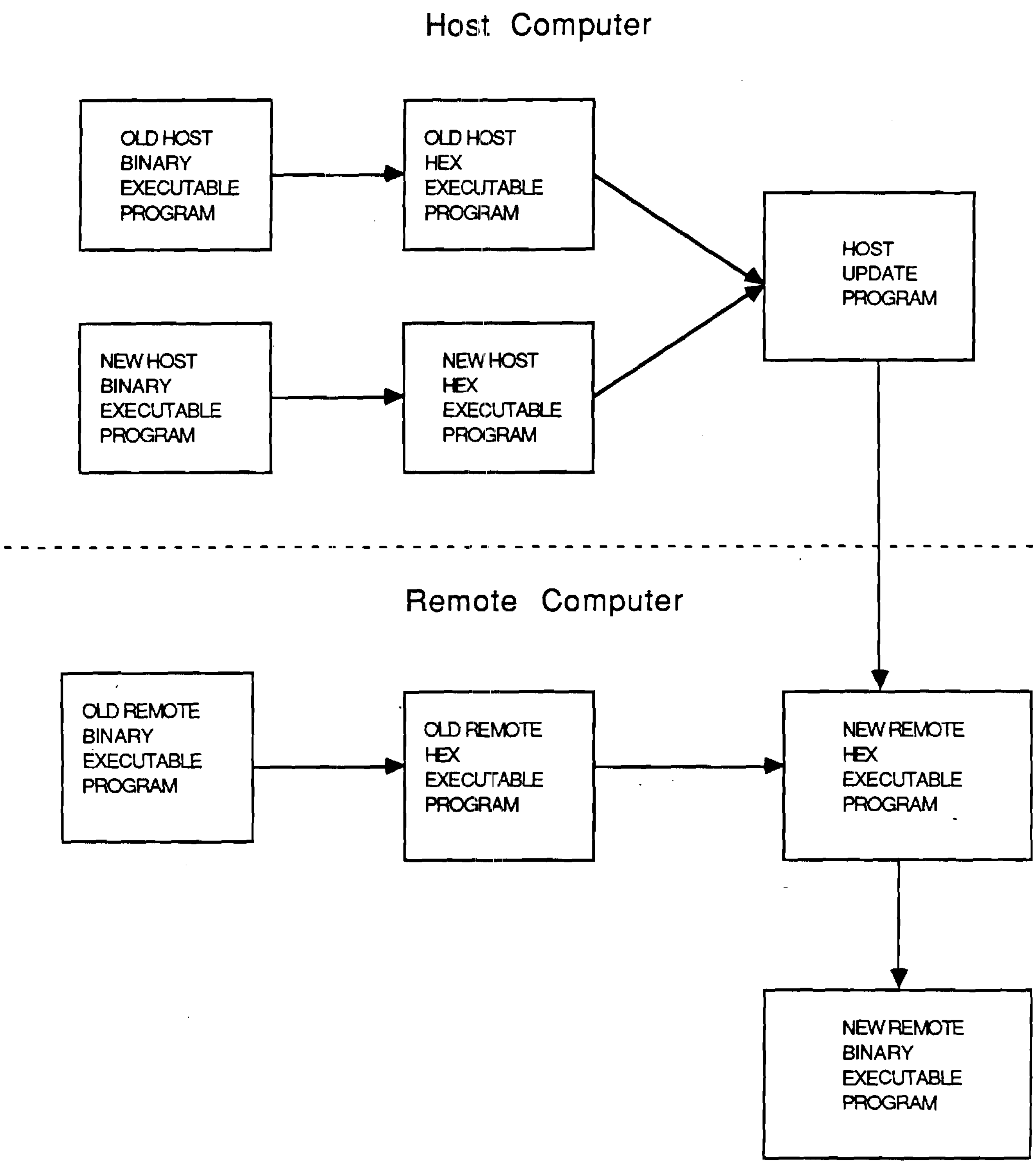


Figure 7 Programs Used by the Update Algorithms

## HOST UPDATE ALGORITHM

The host update algorithm is shown in Figure 8. The algorithm begins by converting the binary executable files of both the old and the new programs into hexadecimal representations. The hexadecimal representation of the new program is then used to determine the size of the new header.

The data section of the new executable file as determined from the new header and the " .map" output of the compiler is then identified and is stored in the host update file for transmission as a new packet.

In the next step of the algorithm, the old executable code segment is compared to the new executable code segment with all of the offset fields of each instruction nulled out. This nulling of all instruction offsets allows for the identification of code segments that are identical except for offsets. The offset fields that are nulled out are identified earlier in this report in the section entitled "INSTRUCTION FORMATS".

The compare algorithm orders the matching code segments with the largest matching code segment first. Each succeeding code segment is smaller in size.

Once the matching code segments have been identified, the lines in the new executable code which are not matches with the old code are identified. These code segments are to be transmitted to the remote computer as new packets.

After identifying the instructions in the new program which may be generated from the old program that resides in the remote computer, the process of determining the required offsets that may be added to the old resident code is initiated. During this process the actual transmission packets are formed. Using the matching code segment list, a pointer to the old executable code where the largest matching code segment is located is set to the corresponding value. These pointers will be transmitted to the remote computer to identify where to obtain the old code segments and where to place these offset modified instructions in the new code.

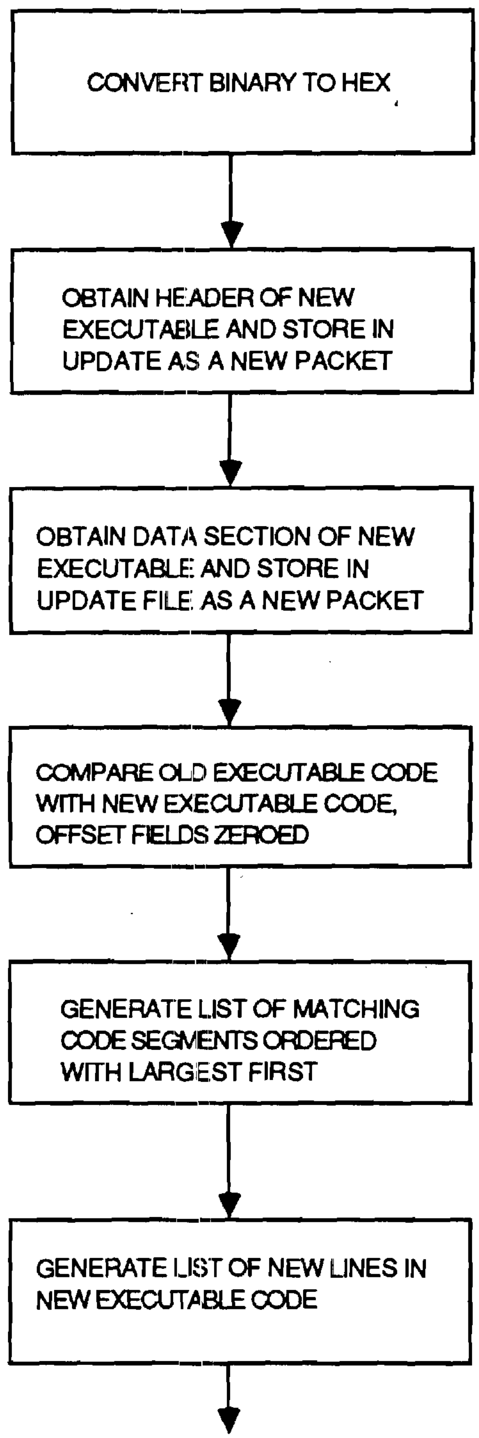


Figure 8 Host Update Algorithm

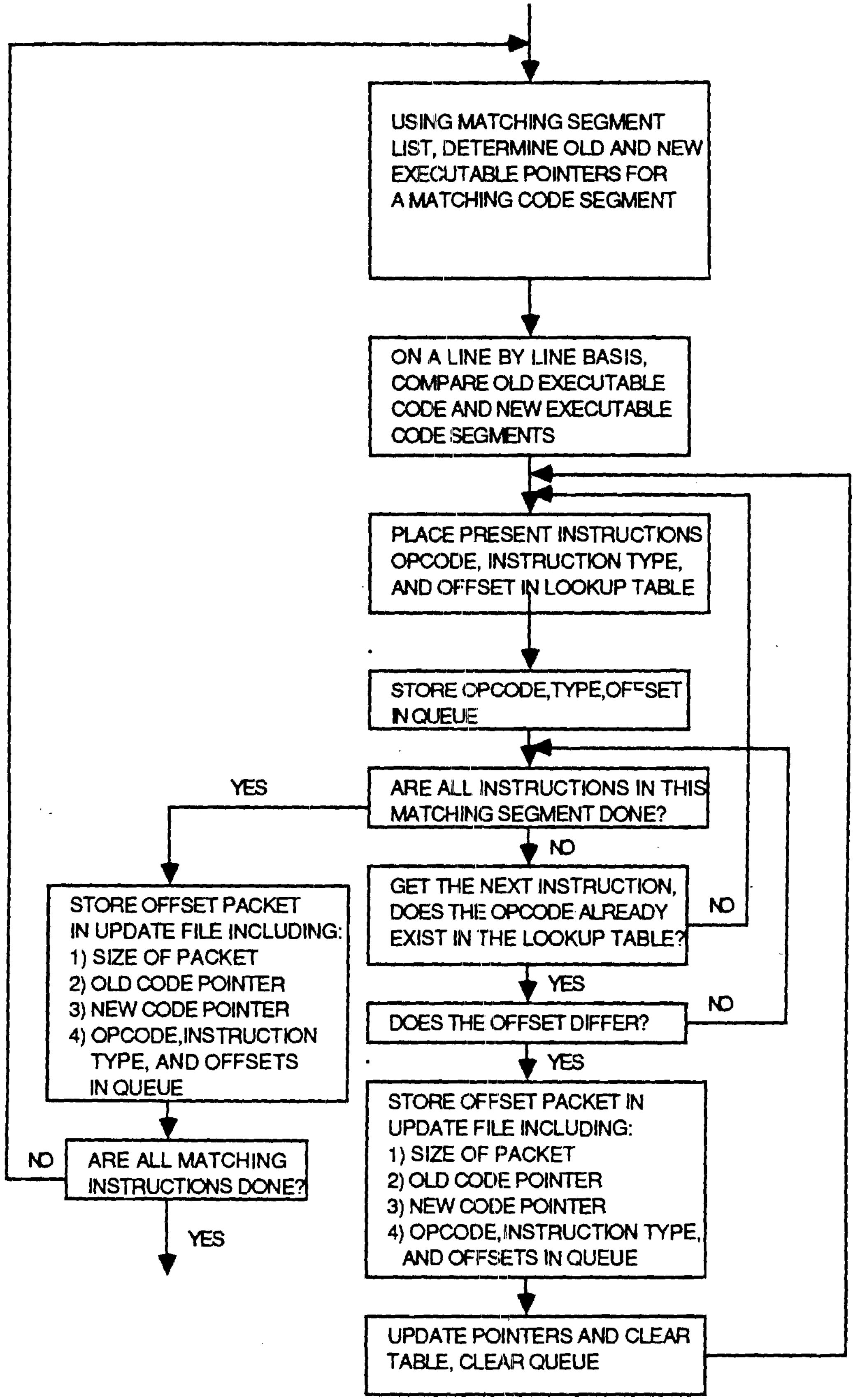


Figure 8 Host Update Algorithm (continued)

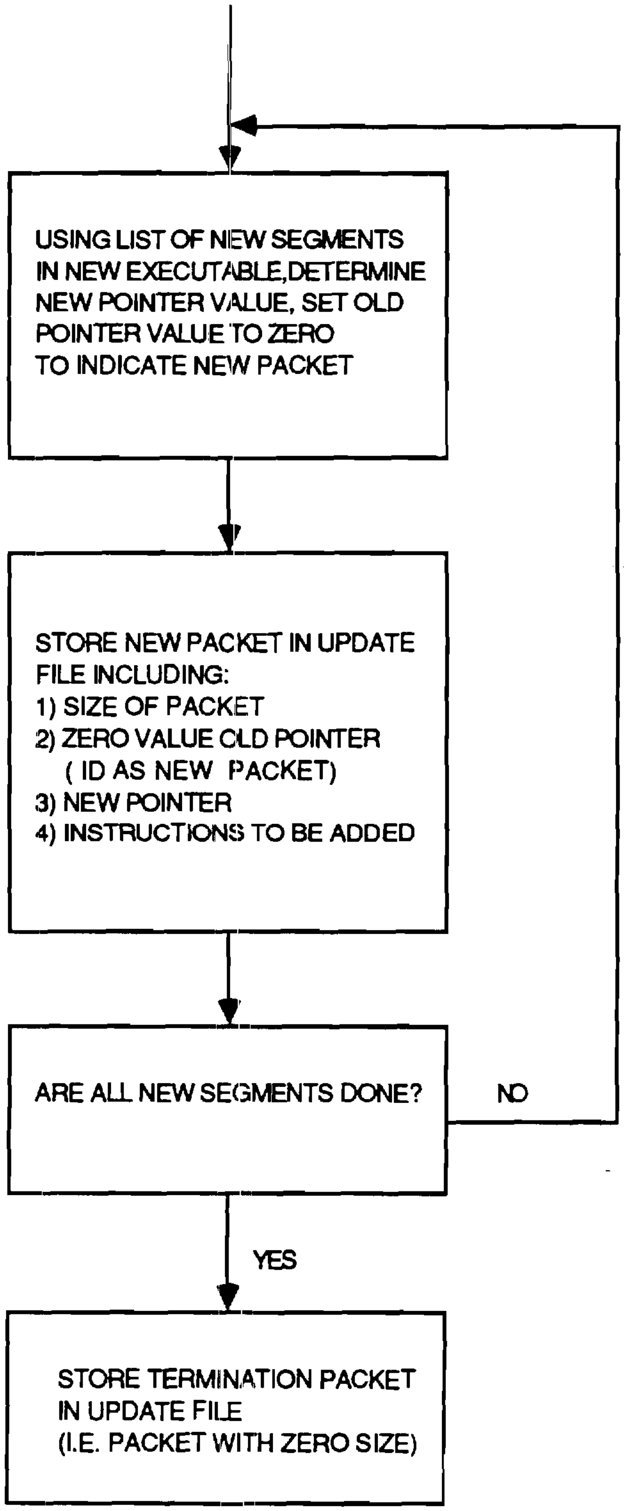


Figure 8 Host Update Algorithm (concluded)

On a line by line basis, the old executable instruction is compared to the new executable instruction. The opcodes are always the same since the compare algorithm used in previous steps has identified the matching segments (with the offsets nulled). The offsets are not nulled out in this portion of the algorithm, so any offset that differs from the instruction's old location and it's new location are identified. Each instruction that contains an offset field may have one, two ,three, or up to four bytes of offsets associated with it. The algorithm treats each byte independently and determines the value of an offset byte that is added to the respective instruction's offset byte to to obtain the new correct offset byte. The offsets that are required because of code relocation may be either a positive or negative offset. The algorithm always adds the offset byte ignoring any carry out that may be generated. This approach does not implement a signed addition, so that true addition or subtraction is carried out (i.e. not a two's complement type addition); however, a number can always be identified that may be added to obtain the correct final offset value.

Once the offset value for a given instruction is determined, the instruction's opcode, instruction format, and offset values are stored in a dynamic lookup table. The opcode and the instruction type identify how many offset fields are in the instruction and where they are located. For each different opcode and instruction type combination encountered, an entry in the offset table is made. For each instruction which is encountered in a given matching segment, a search in the offset table is made. If the instruction does not already exist in the offset table, it is added, even if all offsets in that instruction are zero. If an encountered instruction does exist in the offset table, the offset of the present version of the instruction must match the previous entry or else the present instruction cannot be included in the present packet. Once all of the instructions in a given matching code segment have been entered into the offset table, or in the event of an instruction that cannot be included in the present packet, the packet itself is formed and entered into the host update file.

A packet which is formed in this part of the algorithm is an offset packet which consists of the following information:

1) the size of the packet

2) the old code pointer which identifies where the old code is located in the old executable file

3) the new code pointer which identifies where the old code will be placed in the new executable file after the instructions are modified as specified in the offset lookup table

4) the offset lookup table for this packet of instructions. This included the opcode, the instruction format type, and the offsets for each different instruction contained in the packet.

Once a packet is formed, the offset table is cleared and the process is repeated for the next group of instructions until the groups of matching instructions are depleted.

At this point, the packets of new instructions must be formed. The output of the algorithm includes a list of the new code segments in the new executable file. This list is used to determine which instructions must be transmitted to the remote computer as new code. Using this list of new code segments, a pointer to the location in the new executable file is set, indicating where the new instructions will be placed. A new instruction packet is then formed. This new instruction packet contains the following:

1) the size of the packet

2) the old program pointer, which is set to a zero value since the new code does not come from any part of the old program and a zero value in the pointer allows the receiver algorithm to identify this packet as a new instruction packet

3) the new program pointer which indicates where in the new executable program the new instructions will be placed

4) the actual instructions which are to be placed in the new executable program

After all new instruction packets have been formed, the update file has a packet with zero size placed at the end to identify that the end of the file has been reached.

## UPDATE FILE FORMAT

The update file (as shown in Figure 9) consists of the following information in this order:

1) The new header information which is placed in the file as new instruction packets. This allows the new header to be transmitted as is with no modifications.

2) The new data segment information which is placed in the file as new instruction packets. This allows the new data segments to be transmitted as is with no modifications.

3) The offset packets which contain the locations of usable old instructions and the new offsets which should be used in the new version

4) The new instruction packets which contain those new instructions that are to be added to the new program

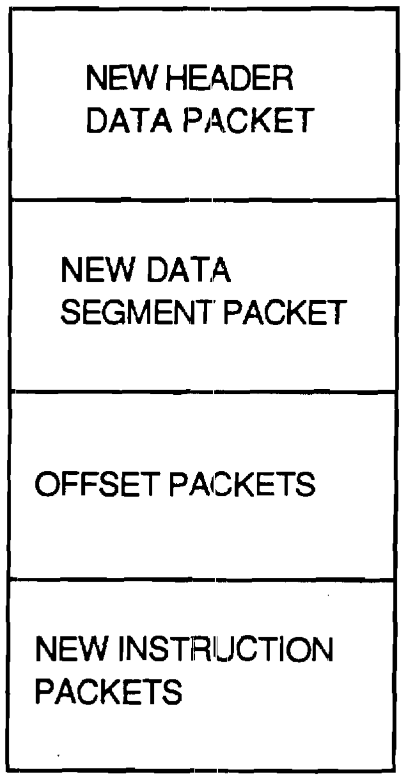


Figure 9 Update File Format

OFFSET PACKET FORMAT

The offset packets contain the size, pointers, and instruction offsets in the following order:

1) size of packet (2 bytes)

2) old pointer (4 bytes)

3) new pointer ( 4 bytes)

4) opcode, instruction type, offsets (variable size)

5) opcode, instruction type, offsets (variable size)

6) etc., until all different instructions in packet listed. Thus the size of the packet is variable depending upon the number of entries in the offset list

NEW PACKET FORMAT

The new packets contain the size, pointers, and instructions in the following order:

1) size of packet (2 bytes)

2) old pointer set to zero value (4 bytes)

3) new pointer (4 bytes)

4) complete instruction (variable size)

5) complete instruction (variable size)

6) etc., until all new code has been include

REMOTE UPDATE ALGORITHM

The remote computer algorithm accepts as input the update file which has been embedded in it the packets which are used to generate the new code on the remote computer. Thus, the inputs to the remote algorithm are the old remote executable file, and the new update file. The output of the remote algorithm is the new remote executable file. The remote algorithm is shown in Figure 10.

The remote algorithm begins by converting the old remote executable binary file to a hexadecimal representation. Portions of this executable file are used to generate the new executable file.

The update file is read next to identify a packet. The packet size is read to determine if the algorithm is completed. For a nonzero packet size, the old pointer value is read and a pointer is set to this location in the old remote executable file. The new pointer is read next, a pointer to indicate where the code will be placed in the new executable file set. If the old pointer is set to a zero value, the packet is a new instruction packet and all of the new instructions contained in the packet should be written to the new executable file as is.

In the event that the old pointer is equal to a zero value, the packet is an offset packet. The instruction opcodes, instruction type, and offsets are read in and used in a table lookup scheme to modify all instructions that are encountered in the old executable code segment that is being written into the new executable.

After the entire packet is written into the new executable file, the process is repeated until all packets have been transformed into the new code. The process ends when a zero size packet is encountered.

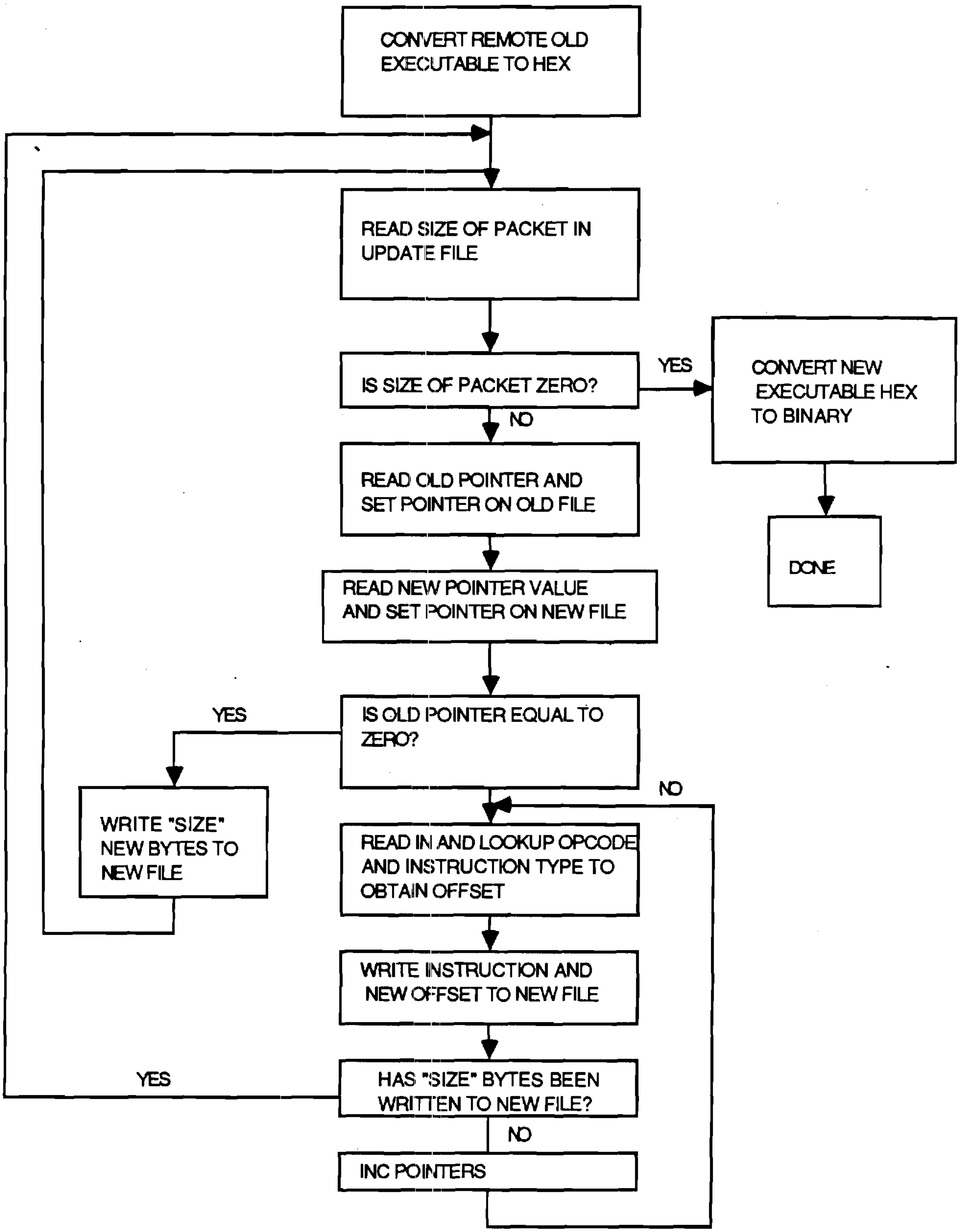


Figure 10 Remote Update Algorithm

## SECTION 5

## SOFTWARE DEVELOPMENT

An integral part of the design and and implementation of an algorithm is software development. Several programs were written both to implement and to test various parts of the algorithm. These programs are listed and described below and are illustrated in corresponding figures, Figures 11-17.

1. CDC Libraries

   CONVERT- converts binary integers to ASCII HEX for printing

   MODTYPE- imp'ements the algorithm in Figure 2 that modifies the instruction conversion table

   BLKDISP- finds the displacement fields in an instruction and makes the fields equal to zero

2. RDBIN.PAS

   This program is a byte by byte listing of any file in decimal and hexadecimal form. It is used as a debugging tool to look at headers and data segments.

   Inputs:
   File to be listed

   Outputs:
   Decimal listing
   Hexadecimal listing

CDC LIBRARY – CDC1.LIB

CONVERT

INTHEX

MODTYPE

BLKDISP

Figure 11 CDC Libraries

# READ BINARY – RDBIN.PAS

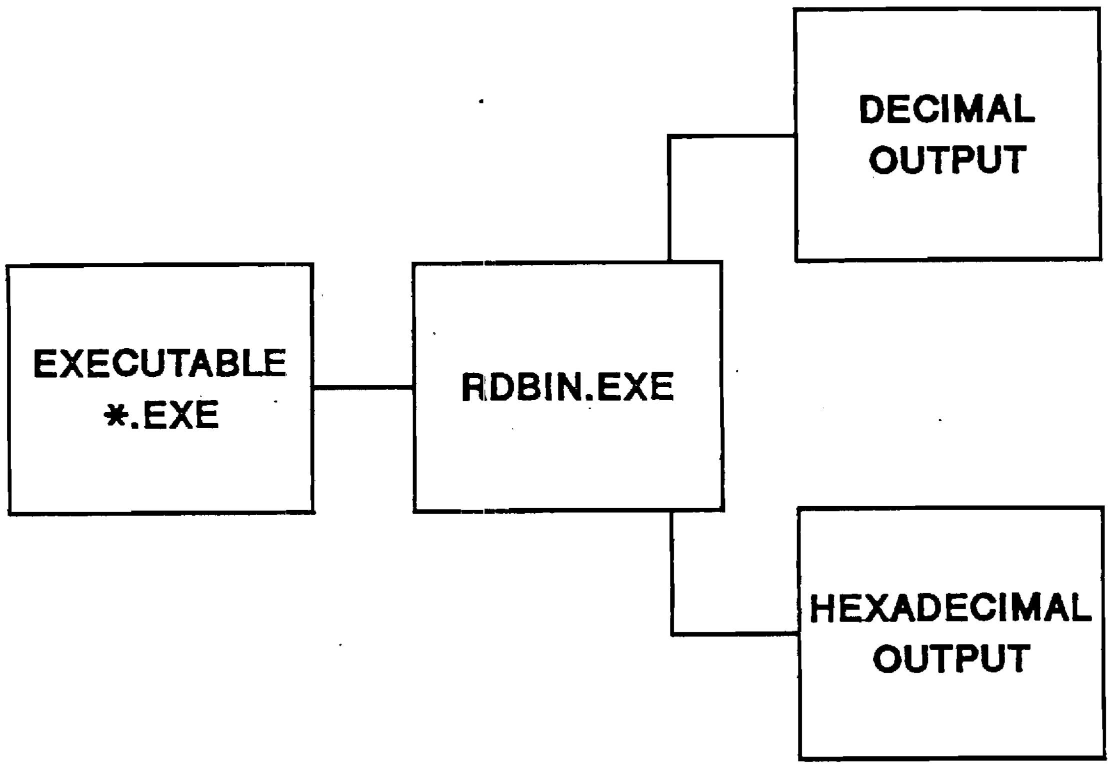


Figure 12 Flow Chart of RDBIN.PAS Program

# LIST EXECUTABLE - LEXEC5.EXE

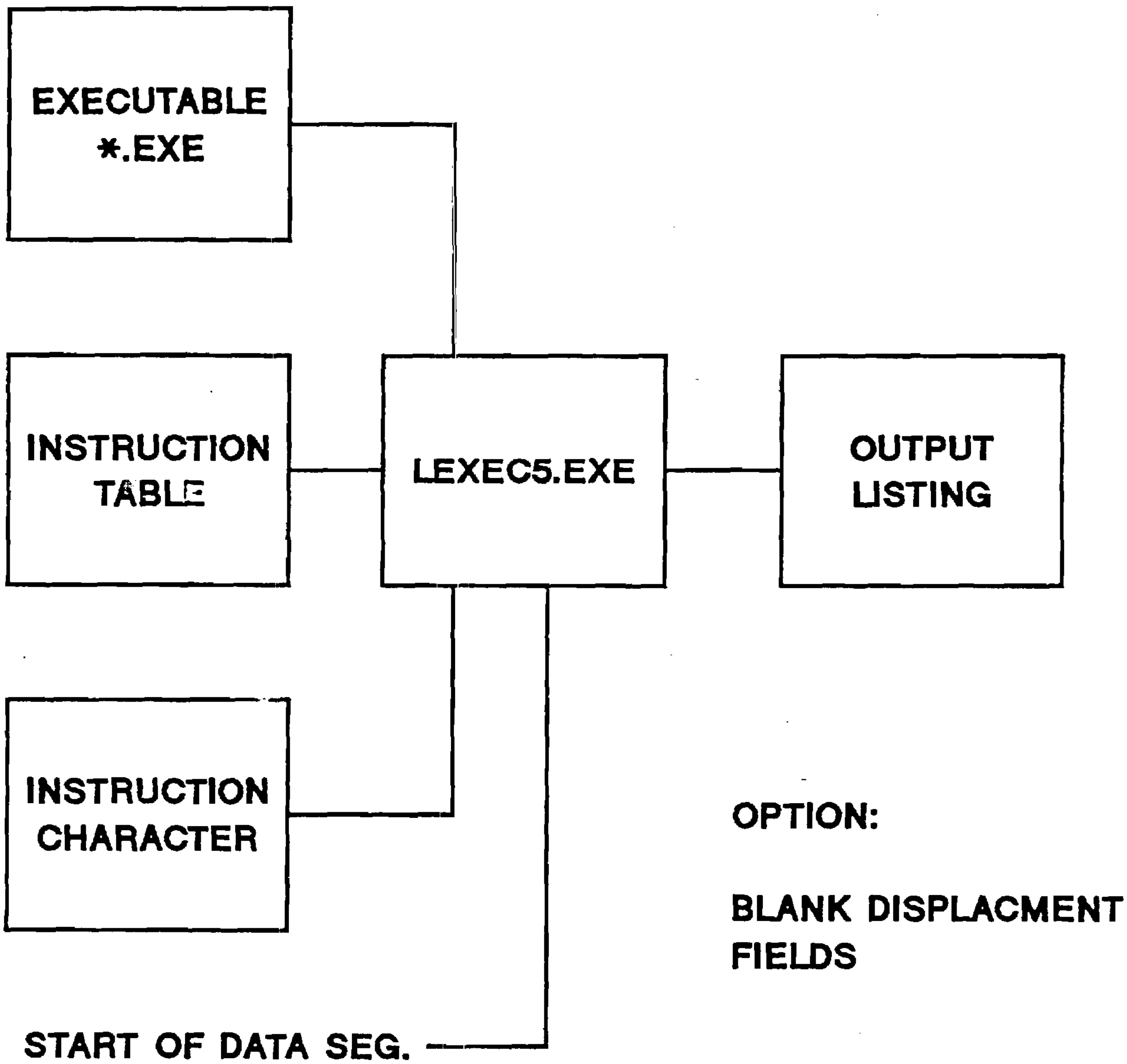


Figure 13 Flow Chart of LEXEC.PAS Program

# COMPARE EXECUTABLE – COMPEX.PAS

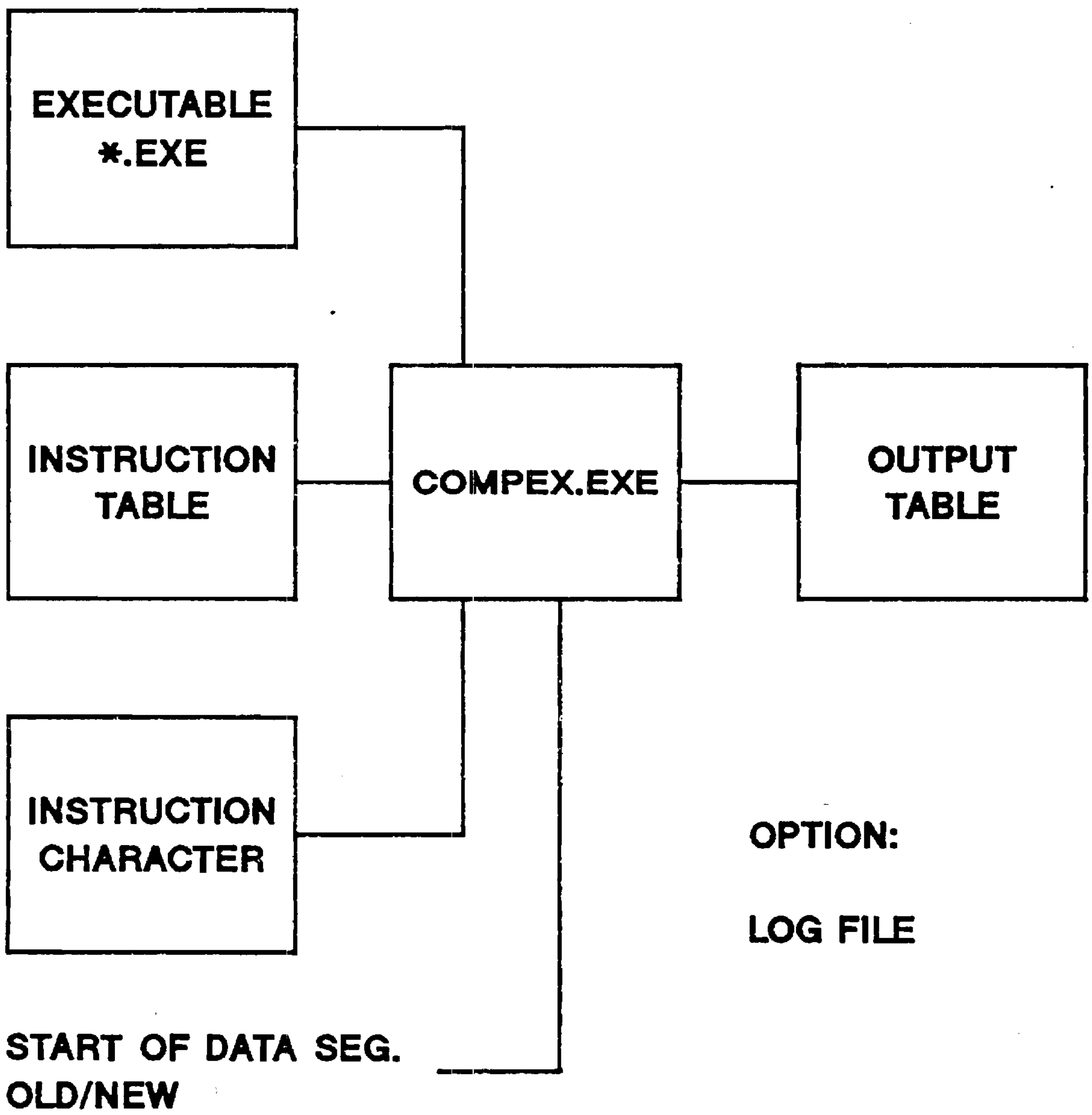


Figure 14 Flow Chart of COMPEX.PAS Program

# BUILD PACKETS – BPACK.PAS

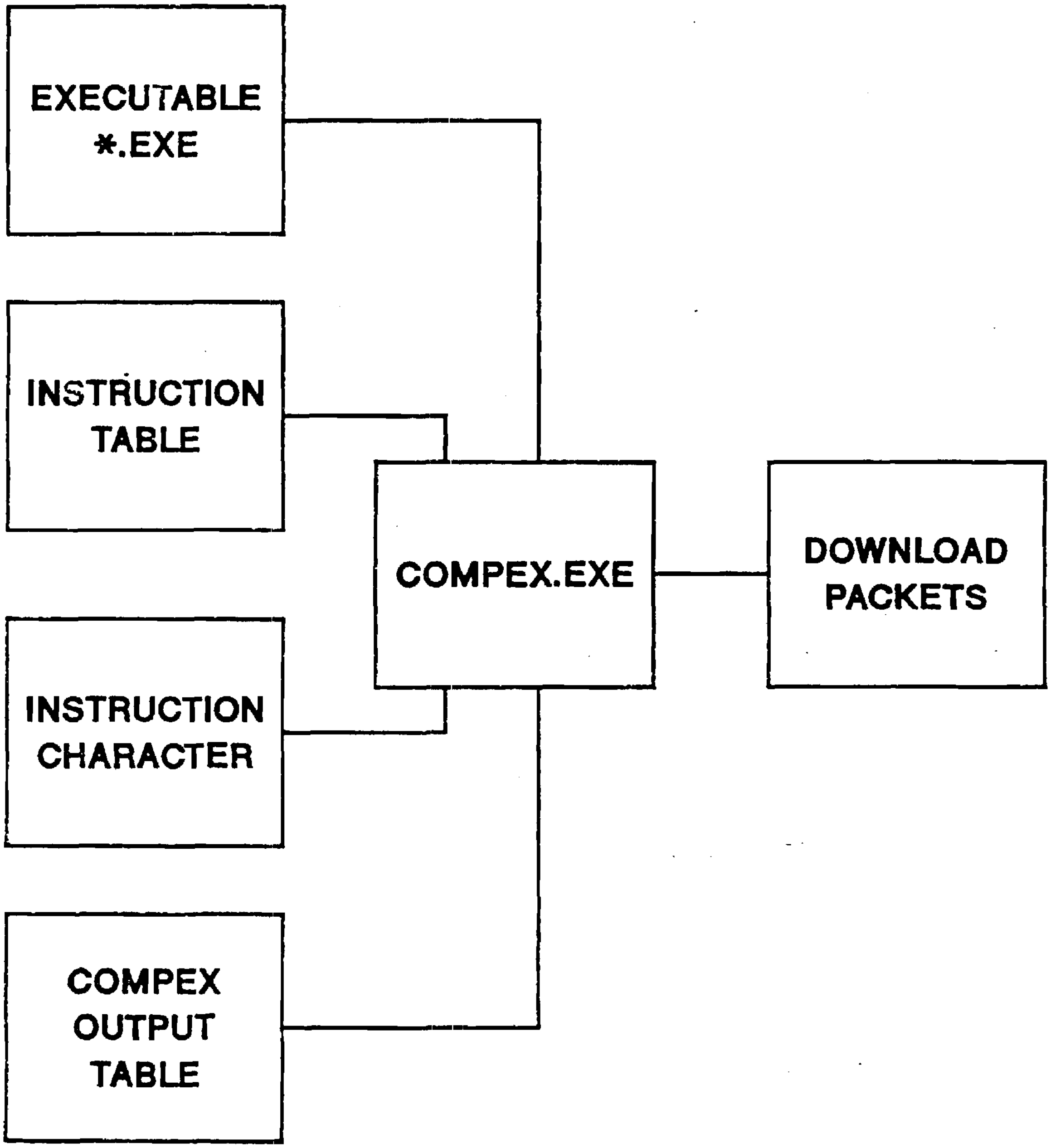


Figure 15 Flow Chart of BPACK.PAS Program

## COM1 PORT ACCESS
## ASSEMBLY LANGUAGE SUBROUTINES

**IC1LS – Read Line Status**

**IC1MS – Read Modem Status**

**IC1INT – Initialize Configuration**

**IC1MCO – Set Modem Control Lines**

**IC1TD – Send One Character**

**IC1TDW – Send One Charecter / Wait**

**IC1RD – Read One Character**

**IC1RDW – Read One Character / Wait**

Figure 16 List of Assembly Language Subroutines of COM1 Port Access

## COM1 PORT ACCESS
## FORTRAN SUBROUTINES

**C1RSTR – Read a String of Characters**

**C1SSTR – Send a String of Characters**

Figure 17 List of FORTRAN Subroutines of COM1 Port Access

3. LEXEC5.PAS

This program lists a file in instruction format and automatically finds the beginning of the code section from data in the header. The header and data segment are listed byte by byte in Hex form. The code section is listed by instruction in Hex form.

Inputs:
- Executable file to be listed
- Instruction Table- Instructions / instruction type
- Instruction Character- Number of bytes and displacement fields of instruction types
- Start of data segment- Determined for Linker Map

Outputs:
- Listing of header, code and data segment

Options:
- Blank displacement fields

4. COMPEX.PAS

This program, the implementation of which is illustrated in Figure 8, compares files for matching blocks. The displacement fields are blanked and the files are compared for largest matching blocks.

Inputs:
- Old executable file
- New executable file
- Instruction Table
- Instruction character
- Start of data segment for old and new program

Outputs:
- Block table of matching blocks

Options:
- Generate a log file of each compare iteration for debugging

5. BPACK.PAS

This program builds packets for the download file. The displacement fields are not blanked. The offsets are determined and the packets formed. Header and Data segments are sent as new data.

Inputs:
- Old executable file
- New executable file
- Instruction table
- Instruction character
- Output from COMPEX program

Outputs:
- Packet ready for download

6. COM1 Port Access Programs

The protocol for the IBM personal computer COM1 communication port has a number of features that make computer-to-computer communications difficult when operating under DOS. These features involve both the hardware and software of the communication port. Below are described the problem features as well as a group of assembly language subroutines that have been written to control the port directly from a higher-level language.

The following hardware and software features create problems in communicating between two computers under DOS:

1. If a character has arrived at the COM1 communication port prior to the operating system accessing the port, the system declares the receiver-full status to be a device error and will cause a run-time error.

2. When the communication port is initialized to receive data, the clear-to-send line is set high, but the data terminal ready line is set low. If the full hardware handshake lines are implemented between COM1 communication ports, the receiving port will inhibit the sending port and no data will be transmitted.

3. The software termination for a DOS input on the COM1 port is a control Z character, but the output protocol is not compatible with the input protocol.

4. The software protocol automatically sends both a carriage return and a line feed at the end of a string output, but the input only requires a carriage return to terminate the string input. This extra line feed character sent on the output usually ends up as a character left in the receiver register at the end of a transmission, which results in a run-time error as described in item 1.

The following assembly language programs were written to allow a user to access the COM1 port directly from a high-level program.

IC1LS - Reads the line status of the COM1 port

IC1MS - Reads the modem status of the COM1 port

IC1INT - Initializes the COM1 port configuration

IC1MCO - Sets the value of the COM1 port modem control lines

IC1TD - Sends one character to the COM1 port

IC1TDW - Sends one character to the COM1 port after the transmitter buffer is empty

IC1RD - Reads one character from the COM1 port with a null indicating no character is available

IC1RDW - Reads one character from the COM1 port after a character becomes available

The following FORTRAN subroutines were written to supplement the assembly language routines:

C1RSTR - Reads a string of characters into a character array from the COM1 port

C1SSTR - Sends a string of characters from a character array to the COM1 port

# SECTION 6

# FUTURE DIRECTIONS

## HEADER ALGORITHM

The header record contains information about the size of the executable module, where it is to be loaded in memory, and where the address of the stack register and relocation offsets are to be inserted into incomplete machine addresses. The largest amount of information in the header consists of the relocation table containing the relocation items. Each relocation item consists of a two-byte offset value and a two-byte segment value.

At the present the proposed algorithms do not attempt to capitalize on the similarities between an old program header and a new program header. It may be possible to develop an algorithm that can use the old header relocation table to derive the new header relocation table.

## DATA SEGMENT ALGORITHM

The proposed procedure for transmitting the changes from a host computer to a remote computer does not attempt to use the old data segments in the generation of the new data segments. At present the new data segment is transmitted in its entirety. The new data segments should be derivable from the old data segments in such a manner as to reduce the amount of information required to be transmitted to generate the new executable file data segments. An additional algorithm can be developed to handle this portion of the files.

## FILE-COMPARE ALGORITHM EFFICIENCY

There are several issues that should be addressed that have the potential to improve the file-compare efficiency. The first issue relates to large amount of memory required with the proposed scheme. For a file of size = N, the present required array size is 6N. This is hard to accomplish on a PC in PASCAL. Though there is a memory of size 640K bytes, the compiler limits its use to 64K. Perhaps a solution to this problem can be found by using a mainframe, another language, or maybe finding a way around the compiler to get access to the rest of the memory. The second issue relates to the fact that the present scheme requires a full copy of both the old and new files, and hence a large memory. It is true, however, that the operation is done only once for many downloads and that the operation can be done on a mainframe. These advantages may outweigh the disadvantage of a large memory requirement.

## Prototype Code Demonstration

A prototype code demonstration should be prepared. There are five steps to the development of a prototype code demonstration, some of which have been executed already. The code listing software, LEXEC5, and the compare algorithm software, COMPEX, are complete. The packet formation software, BPACK, has been written, but has not been debugged. The regeneration software has been flow charted and is illustrated in Figure 10, but has not been coded or debugged. A demonstration of the program has not been debugged. The last three tasks need to be completed before a demonstration can be presented.

## Analysis of Packet Size Versus Overhead Bytes

A certain number of overhead bytes are required in the preparation and transmission of each packet. This number varies with the contents of a particular packet. Clearly a packet corresponding to a large block of code warrants the overhead bytes required for its transmission; a packet corresponding to a very small block of code may not. An analysis needs to be done to determine at what point it is more economical to send a block of code in toto as opposed to sending a packet of information describing how to modify the old code to mirror the new code.

Examination of Methods for Error Correction and Encryption

When large amounts of data are transmitted over commercial phone lines, the issues of error detection and correction and data encryption are of primary concern. Methods addressing both of these issues were identified and briefly reviewed early in this effort. Information embedded in overhead bytes is used to detect and correct errors using a variety of pattern recognition techniques such as the higher-order correlation matrix associative memory method of Shiozaki. The various techniques identified in the literature need to be carefully evaluated for their appropriateness to the update scheme developed under this effort.

Through efforts by The National Bureau of Standards and others, data encryption techniques have been greatly improved over the years, especially with the adoption of the IBM-based, DES algorithm under the American National Standards Institute's title, " Data Encryption Algorithm." Work, such as Cipher Block Chaining, which establishes a chained relationship between successive blocks of ciphertext and detects unauthorized modifications, continues to improve encryption techniques. An investigation of these and other pattern recognition techniques pertinent to the data security in the proposed scheme should be investigated.

# APPENDIX A

## Table 1-22 8086/88 Instruction Encoding

**DATA TRANSFER**

**MOV = Move:**

| | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 |
|---|---|---|---|---|---|---|
| Register/memory to/from register | 1 0 0 0 1 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate to register/memory | 1 1 0 0 0 1 1 w | mod 0 0 0 r/m | (DISP-LO) | (DISP-HI) | data | data if w = 1 |
| Immediate to register | 1 0 1 1 w reg | data | data if w = 1 | | | |
| Memory to accumulator | 1 0 1 0 0 0 0 w | addr-lo | addr-hi | | | |
| Accumulator to memory | 1 0 1 0 0 0 1 w | addr-lo | addr-hi | | | |
| Register/memory to segment register | 1 0 0 0 1 1 1 0 | mod 0 SR r/m | (DISP-LO) | (DISP-HI) | | |
| Segment register to register/memory | 1 0 0 0 1 1 0 0 | mod 0 SR r/m | (DISP-LO) | (DISP-HI) | | |

**PUSH = Push:**

| | | | | |
|---|---|---|---|---|
| Register/memory | 1 1 1 1 1 1 1 1 | mod 1 1 0 r/m | (DISP-LO) | (DISP-HI) |
| Register | 0 1 0 1 0 reg | | | |
| Segment register | 0 0 0 reg 1 1 0 | | | |

**POP = Pop:**

| | | | | |
|---|---|---|---|---|
| Register/memory | 1 0 0 0 1 1 1 1 | mod 0 0 0 r/m | (DISP-LO) | (DISP-HI) |
| Register | 0 1 0 1 1 reg | | | |
| Segment register | 0 0 0 reg 1 1 1 | | | |

## Table 1-22 8086/88 Instruction Encoding (continued)

| | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 |
|---|---|---|---|---|---|---|
| **DATA TRANSFER (Cont'd.)** | | | | | | |
| **XCHG = Exchange:** | | | | | | |
| Register/memory with register | 1 0 0 0 0 1 1 w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Register with accumulator | 1 0 0 1 0 reg | | | | | |
| **IN = Input from:** | | | | | | |
| Fixed port | 1 1 1 0 0 1 0 w | DATA-8 | | | | |
| Variable port | 1 1 1 0 1 1 0 w | | | | | |
| **OUT = Output to:** | | | | | | |
| Fixed port | 1 1 1 0 0 1 1 w | DATA-8 | | | | |
| Variable port | 1 1 1 0 1 1 1 w | | | | | |
| XLAT = Translate byte to AL | 1 1 0 1 0 1 1 1 | | | | | |
| LEA = Load EA to register | 1 0 0 0 1 1 0 1 | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| LDS = Load pointer to DS | 1 1 0 0 0 1 0 1 | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| LES = Load pointer to ES | 1 1 0 0 0 1 0 0 | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| LAHF = Load AH with flags | 1 0 0 1 1 1 1 1 | | | | | |
| SAHF = Store AH into flags | 1 0 0 1 1 1 1 0 | | | | | |
| PUSHF = Push flags | 1 0 0 1 1 1 0 0 | | | | | |
| POPF = Pop flags | 1 0 0 1 1 1 0 1 | | | | | |
| **ARITHMETIC** | | | | | | |
| **ADD = Add:** | | | | | | |
| Reg/memory with register to either | 0 0 0 0 0 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate to register/memory | 1 0 0 0 0 0 s w | mod 0 0 0 r/m | (DISP-LO) | (DISP-HI) | data | data if s: w=01 |
| Immediate to accumulator | 0 0 0 0 0 1 0 w | data | data if w=1 | | | |
| **ADC = Add with carry:** | | | | | | |
| Reg/memory with register to either | 0 0 0 1 0 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate to register/memory | 1 0 0 0 0 0 s w | mod 0 1 0 r/m | (DISP-LO) | (DISP-HI) | data | data if s: w=01 |
| Immediate to accumulator | 0 0 0 1 0 1 0 w | data | data if w=1 | | | |
| **INC = Increment:** | | | | | | |
| Register/memory | 1 1 1 1 1 1 1 w | mod 0 0 0 r/m | (DISP-LO) | (DISP-HI) | | |
| Register | 0 1 0 0 0 reg | | | | | |
| AAA = ASCII adjust for add | 0 0 1 1 0 1 1 1 | | | | | |
| DAA = Decimal adjust for add | 0 0 1 0 0 1 1 1 | | | | | |

## Table 1-22 8086/88 Instruction Encoding (continued)

| ARITHMETIC (Cont'd.) | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 |
|---|---|---|---|---|---|---|
| **SUB = Subtract:** | | | | | | |
| Reg./memory and register to either | 0 0 1 0 1 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate from register/memory | 1 0 0 0 0 0 s w | mod 1 0 1 r/m | (DISP-LO) | (DISP-HI) | data | data if s: w=01 |
| Immediate from accumulator | 0 0 1 0 1 1 0 w | data | data if w=1 | | | |
| **SBB = Subtract with borrow:** | | | | | | |
| Reg./memory and register to either | 0 0 0 1 1 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate from register/memory | 1 0 0 0 0 0 s w | mod 0 1 1 r/m | (DISP-LO) | (DISP-HI) | data | data if s: w=01 |
| Immediate from accumulator | 0 0 0 1 1 1 0 w | data | data if w=1 | | | |
| **DEC Decrement:** | | | | | | |
| Register/memory | 1 1 1 1 1 1 1 w | mod 0 0 1 r/m | (DISP-LO) | (DISP-HI) | | |
| Register | 0 1 0 0 1 reg | | | | | |
| NEG Change sign | 1 1 1 1 0 1 1 w | mod 0 1 1 r/m | (DISP-LO) | (DISP-HI) | | |
| **CMP = Compare:** | | | | | | |
| Register/memory and register | 0 0 1 1 1 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate with register/memory | 1 0 0 0 0 0 s w | mod 1 1 1 r/m | (DISP-LO) | (DISP-HI) | data | data if s: w=1 |
| Immediate with accumulator | 0 0 1 1 1 1 0 w | data | | | | |
| AAS ASCII adjust for subtract | 0 0 1 1 1 1 1 1 | | | | | |
| DAS Decimal adjust for subtract | 0 0 1 0 1 1 1 1 | | | | | |
| MUL Multiply (unsigned) | 1 1 1 1 0 1 1 w | mod 1 0 0 r/m | (DISP-LO) | (DISP-HI) | | |
| IMUL Integer multiply (signed) | 1 1 1 1 0 1 1 w | mod 1 0 1 r/m | (DISP-LO) | (DISP-HI) | | |
| AAM ASCII adjust for multiply | 1 1 0 1 0 1 0 0 | 0 0 0 0 1 0 1 0 | (DISP-LO) | (DISP-HI) | | |
| DIV Divide (unsigned) | 1 1 1 1 0 1 1 w | mod 1 1 0 r/m | (DISP-LO) | (DISP-HI) | | |
| IDIV Integer divide (signed) | 1 1 1 1 0 1 1 w | mod 1 1 1 r/m | (DISP-LO) | (DISP-HI) | | |
| AAD ASCII adjust for divide | 1 1 0 1 0 1 0 1 | 0 0 0 0 1 0 1 0 | (DISP-LO) | (DISP-HI) | | |
| CBW Convert byte to word | 1 0 0 1 1 0 0 0 | | | | | |
| CWD Convert word to double word | 1 0 0 1 1 0 0 1 | | | | | |
| **LOGIC** | | | | | | |
| NOT Invert | 1 1 1 1 0 1 1 w | mod 0 1 0 r/m | (DISP-LO) | (DISP-HI) | | |
| SHL/SAL Shift logical/arithmetic left | 1 1 0 1 0 0 v w | mod 1 0 0 r/m | (DISP-LO) | (DISP-HI) | | |
| SHR Shift logical right | 1 1 0 1 0 0 v w | mod 1 0 1 r/m | (DISP-LO) | (DISP-HI) | | |
| SAR Shift arithmetic right | 1 1 0 1 0 0 v w | mod 1 1 1 r/m | (DISP-LO) | (DISP-HI) | | |
| ROL Rotate left | 1 1 0 1 0 0 v w | mod 0 0 0 r/m | (DISP-LO) | (DISP-HI) | | |

## Table 1-22 8086/88 Instruction Encoding (continued)

| LOGIC (Cont'd.) | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 |
|---|---|---|---|---|---|---|
| ROR Rotate right | 1 1 0 1 0 0 v w | mod 0 0 1 r/m | (DISP-LO) | (DISP-HI) | | |
| RCL Rotate through carry flag left | 1 1 0 1 0 0 v w | mod 0 1 0 r/m | (DISP-LO) | (DISP-HI) | | |
| RCR Rotate through carry right | 1 1 0 1 0 0 v w | mod 0 1 1 r/m | (DISP-LO) | (DISP-HI) | | |
| **AND = And:** | | | | | | |
| Reg/memory with register to either | 0 0 1 0 0 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate to register/memory | 1 0 0 0 0 0 0 w | mod 1 0 0 r/m | (DISP-LO) | (DISP-HI) | data | data if w=1 |
| Immediate to accumulator | 0 0 1 0 0 1 0 w | data | data if w=1 | | | |
| **TEST = And function to flags no result:** | | | | | | |
| Register/memory and register | 0 0 0 1 0 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate data and register/memory | 1 1 1 1 0 1 1 w | mod 0 0 0 r/m | (DISP-LO) | (DISP-HI) | data | data if w=1 |
| Immediate data and accumulator | 1 0 1 0 1 0 0 w | data | | | | |
| **OR = Or:** | | | | | | |
| Reg/memory and register to either | 0 0 0 0 1 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate to register/memory | 1 0 0 0 0 0 0 w | mod 0 0 1 r/m | (DISP-LO) | (DISP-HI) | data | data if w=1 |
| Immediate to accumulator | 0 0 0 0 1 1 0 w | data | data if w=1 | | | |
| **XOR = Exclusive or:** | | | | | | |
| Reg/memory and register to either | 0 0 1 1 0 0 d w | mod reg r/m | (DISP-LO) | (DISP-HI) | | |
| Immediate to register/memory | 0 0 1 1 0 1 0 w | data | (DISP-LO) | (DISP-HI) | data | data if w=1 |
| Immediate to accumulator | 0 0 1 1 0 1 0 w | data | data if w=1 | | | |

| STRING MANIPULATION | |
|---|---|
| REP = Repeat | 1 1 1 1 0 0 1 z |
| MOVS = Move byte/word | 1 0 1 0 0 1 0 w |
| CMPS = Compare byte/word | 1 0 1 0 0 1 1 w |
| SCAS = Scan byte/word | 1 0 1 0 1 1 1 w |
| LODS = Load byte/wd to AL/AX | 1 0 1 0 1 1 0 w |
| STOS = Stor byte/wd from AL/A | 1 0 1 0 1 0 1 w |

## Table 1-22 8086/88 Instruction Encoding (continued)

CONTROL TRANSFER

| | | | | | | |
|---|---|---|---|---|---|---|
| **CALL = Call:** | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 |
| Direct within segment | 1 1 1 0 1 0 0 0 | IP-INC-LO | IP-INC-HI | | | |
| Indirect within segment | 1 1 1 1 1 1 1 1 | mod 0 1 0 r/m | (DISP-LO) | (DISP-HI) | | |
| Direct intersegment | 1 0 0 1 1 0 1 0 | IP-lo | IP-hi | | | |
| | | CS-lo | CS-hi | | | |
| Indirect intersegment | 1 1 1 1 1 1 1 1 | mod 0 1 1 r/m | (DISP-LO) | (DISP-HI) | | |
| **JMP = Unconditional Jump:** | | | | | | |
| Direct within segment | 1 1 1 0 1 0 0 1 | IP-INC-LO | IP-INC-HI | | | |
| Direct within segment-short | 1 1 1 0 1 0 1 1 | IP-INC8 | | | | |
| Indirect within segment | 1 1 1 1 1 1 1 1 | mod 1 0 0 r/m | (DISP-LO) | (DISP-HI) | | |
| Direct intersegment | 1 1 1 0 1 0 1 0 | IP-lo | IP-hi | | | |
| | | CS-lo | CS-hi | | | |
| Indirect intersegment | 1 1 1 1 1 1 1 1 | mod 1 0 1 r/m | (DISP-LO) | (DISP-HI) | | |
| **RET = Return from CALL:** | | | | | | |
| Within segment | 1 1 0 0 0 0 1 1 | | | | | |
| Within seg adding immed to SP | 1 1 0 0 0 0 1 0 | data-lo | data-hi | | | |
| Intersegment | 1 1 0 0 1 0 1 1 | | | | | |
| Intersegment adding immediate to SP | 1 1 0 0 1 0 1 0 | data-lo | data-hi | | | |
| JE/JZ = Jump on equal/zero | 0 1 1 1 0 1 0 0 | IP-INC8 | | | | |
| JL/JNGE = Jump on less/not greater or equal | 0 1 1 1 1 1 0 0 | IP-INC8 | | | | |
| JLE/JNG = Jump on less or equal/not greater | 0 1 1 1 1 1 1 0 | IP-INC8 | | | | |
| JB/JNAE = Jump on below/not above or equal | 0 1 1 1 0 0 1 0 | IP-INC8 | | | | |
| JBE/JNA = Jump on below or equal/not above | 0 1 1 1 0 1 1 0 | IP-INC8 | | | | |
| JP/JPE = Jump on parity/parity even | 0 1 1 1 1 0 1 0 | IP-INC8 | | | | |
| JO = Jump on overflow | 0 1 1 1 0 0 0 0 | IP-INC8 | | | | |
| JS = Jump on sign | 0 1 1 1 1 0 0 0 | IP-INC8 | | | | |
| JNE/JNZ = Jump on not equal/not zero | 0 1 1 1 0 1 0 1 | IP-INC8 | | | | |
| JNL/JGE = Jump on not less/greater or equal | 0 1 1 1 1 1 0 1 | IP-INC8 | | | | |
| JNLE/JG = Jump on not less or equal/greater | 0 1 1 1 1 1 1 1 | IP-INC8 | | | | |
| JNB/JAE = Jump on not below/above or equal | 0 1 1 1 0 0 1 1 | IP-INC8 | | | | |
| JNBE/JA = Jump on not below or equal/above | 0 1 1 1 0 1 1 1 | IP-INC8 | | | | |
| JNP/JPO = Jump on not par/par odd | 0 1 1 1 1 0 1 1 | IP-INC8 | | | | |
| JNO = Jump on not overflow | 0 1 1 1 0 0 0 1 | IP-INC8 | | | | |

## Table 1-22 8086/88 Instruction Encoding (continued)

**CONTROL TRANSFER (Cont'd.)**

| RET = Return from CALL: | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 | 7 6 5 4 3 2 1 0 |
|---|---|---|---|---|---|---|
| JNS = Jump on not sign | 0 1 1 1 1 0 0 1 | IP-INC8 | | | | |
| LOOP = Loop CX times | 1 1 1 0 0 0 1 0 | IP-INC8 | | | | |
| LOOPZ/LOOPE = Loop while zero/equal | 1 1 1 0 0 0 0 1 | IP-INC8 | | | | |
| LOOPNZ/LOOPNE = Loop while not zero/equal | 1 1 1 0 0 0 0 0 | IP-INC8 | | | | |
| JCXZ = Jump on CX zero | 1 1 1 0 0 0 1 1 | IP-INC8 | | | | |
| **INT = Interrupt:** | | | | | | |
| Type specified | 1 1 0 0 1 1 0 1 | DATA-8 | | | | |
| Type 3 | 1 1 0 0 1 1 0 0 | | | | | |
| INTO = Interrupt on overflow | 1 1 0 0 1 1 1 0 | | | | | |
| IRET = Interrupt return | 1 1 0 0 1 1 1 1 | | | | | |
| **PROCESSOR CONTROL** | | | | | | |
| CLC = Clear carry | 1 1 1 1 1 0 0 0 | | | | | |
| CMC = Complement carry | 1 1 1 1 0 1 0 1 | | | | | |
| STC = Set carry | 1 1 1 1 1 0 0 1 | | | | | |
| CLD = Clear direction | 1 1 1 1 1 1 0 0 | | | | | |
| STD = Set direction | 1 1 1 1 1 1 0 1 | | | | | |
| CLI = Clear interrupt | 1 1 1 1 1 0 1 0 | | | | | |
| STI = Set interrupt | 1 1 1 1 1 0 1 1 | | | | | |
| HLT = Halt | 1 1 1 1 0 1 0 0 | | | | | |
| WAIT = Wait | 1 0 0 1 1 0 1 1 | | | | | |
| ESC = Escape (to external device) | 1 1 0 1 1 x x x | m o d y y y r / m | (DISP-LO) | (DISP-HI) | | |
| LOCK = Bus lock prefix | 1 1 1 1 0 0 0 0 | | | | | |
| SEGMENT = Override prefix | 0 0 1 reg 1 1 0 | | | | | |

Table 1-23 Machine Instruction Decoding Guide

| 1ST BYTE | | 2ND BYTE | BYTES 3, 4, 5, 6 | ASM-86 INSTRUCTION FORMAT | |
|---|---|---|---|---|---|
| HEX | BINARY | | | | |
| 00 | 0000 0000 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADD | REG8/MEM8,REG8 |
| 01 | 0000 0001 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADD | REG16/MEM16,REG16 |
| 02 | 0000 0010 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADD | REG8,REG8/MEM8 |
| 03 | 0000 0011 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADD | REG16,REG16/MEM16 |
| 04 | 0000 0100 | DATA-8 | | ADD | AL,IMMED8 |
| 05 | 0000 0101 | DATA-LO | DATA-HI | ADD | AX,IMMED16 |
| 06 | 0000 0110 | | | PUSH | ES |
| 07 | 0000 0111 | | | POP | ES |
| 08 | 0000 1000 | MOD REG R/M | (DISP-LO),(DISP-HI) | OR | REG8/MEM8,REG8 |
| 09 | 0000 1001 | MOD REG R/M | (DISP-LO),(DISP-HI) | OR | REG18/MEM16,REG16 |
| 0A | 0000 1010 | MOD REG R/M | (DISP-LO),(DISP-HI) | OR | REG8,REG8/MEM8 |
| 0B | 0000 1011 | MOD REG R/M | (DISP-LO),(DISP-HI) | OR | REG16,REG16/MEM16 |
| 0C | 0000 1100 | DATA-8 | | OR | AL,IMMED8 |
| 0D | 0000 1101 | DATA-LO | DATA-HI | OR | AX,IMMED16 |
| 0E | 0000 1110 | | | PUSH | CS |
| 0F | 0000 1111 | | | (not used) | |
| 10 | 0001 0000 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADC | REG8/MEM8,REG8 |
| 11 | 0001 0001 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADC | REG16/MEM16,REG16 |
| 12 | 0001 0010 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADC | REG8,REG8/MEM8 |
| 13 | 0001 0011 | MOD REG R/M | (DISP-LO),(DISP-HI) | ADC | REG16,REG16/MEM16 |
| 14 | 0001 0100 | DATA-8 | | ADC | AL,IMMED8 |
| 15 | 0001 0101 | DATA-LO | DATA-HI | ADC | AX,IMMED16 |
| 16 | 0001 0110 | | | PUSH | SS |
| 17 | 0001 0111 | | | POP | SS |
| 18 | 0001 1000 | MOD REG R/M | (DISP-LO),(DISP-HI) | SBB | REG8/MEM8,REG8 |
| 19 | 0001 1001 | MOD REG R/M | (DISP-LO),(DISP-HI) | SBB | REG16/MEM16,REG16 |
| 1A | 0001 1010 | MOD REG R/M | (DISP-LO),(DISP-HI) | SBB | REG8,REG8/MEM8 |
| 1B | 0001 1011 | MOD REG R/M | (DISP-LO),(DISP-HI) | SBB | REG16,REG16/MEM16 |
| 1C | 0001 1100 | DATA-8 | | SBB | AL,IMMED8 |
| 1D | 0001 1101 | DATA-LO | DATA-HI | SBB | AX,IMMED16 |
| 1E | 0001 1110 | | | PUSH | DS |
| 1F | 0001 1111 | | | POP | DS |
| 20 | 0010 0000 | MOD REG R/M | (DISP-LO),(DISP-HI) | AND | REG8/MEM8,REG8 |
| 21 | 0010 0001 | MOD REG R/M | (DISP-LO),(DISP-HI) | AND | REG16/MEM16,REG16 |
| 22 | 0010 0010 | MOD REG R/M | (DISP-LO),(DISP-HI) | AND | REG8,REG8/MEM8 |
| 23 | 0010 0011 | MOD REG R/M | (DISP-LO),(DISP-HI) | AND | REG16,REG16/MEM16 |
| 24 | 0010 0100 | DATA-8 | | AND | AL,IMMED8 |
| 25 | 0010 0101 | DATA-LO | DATA-HI | AND | AX,IMMED16 |
| 26 | 0010 0110 | | | ES: | (segment override prefix) |
| 27 | 0010 0111 | | | DAA | |
| 28 | 0010 1000 | MOD REG R/M | (DISP-LO),(DISP-HI) | SUB | REG8/MEM8,REG8 |
| 29 | 0010 1001 | MOD REG R/M | (DISP-LO),(DISP-HI) | SUB | REG16/MEM16,REG16 |
| 2A | 0010 1010 | MOD REG R/M | (DISP-LO),(DISP-HI) | SUB | REG8,REG8/MEM8 |
| 2B | 0010 1011 | MOD REG R/M | (DISP-LO,(DISP-HI) | SUB | REG16,REG16/MEM16 |
| 2C | 0010 1100 | DATA-8 | | SUB | AL,IMMED8 |
| 2D | 0010 1101 | DATA-LO | DATA-HI | SUB | AX,IMMED16 |
| 2E | 0010 1110 | | | CS: | (segment override prefix) |
| 2F | 0010 1111 | | | DAS | |
| 30 | 0011 0000 | MOD REG R/M | (DISP-LO),(DISP-HI) | XOR | REG8/MEM8,REG8 |
| 31 | 0011 0001 | MOD REG R/M | (DISP-LO),(DISP-HI) | XOR | REG16/MEM16,REG16 |
| 32 | 0011 0010 | MOD REG R/M | (DISP-LO),(DISP-HI) | XOR | REG8,REG8/MEM8 |
| 33 | 0011 0011 | MOD REG R/M | (DISP-LO),(DISP-HI) | XOR | REG16,REG18/MEM16 |
| 34 | 0011 0100 | DATA-8 | | XOR | AL,IMMED8 |
| 35 | 0011 0101 | DATA-LO | DATA-HI | XOR | AX,IMMED16 |
| 36 | 0011 0110 | | | SS: | (segment override prefix) |

Table 1-23 Machine Instruction Decoding Guide (continued)

| 1ST BYTE | | 2ND BYTE | BYTES 3,4,5,6 | ASM-86 INSTRUCTION FORMAT | |
|---|---|---|---|---|---|
| HEX | BINARY | | | | |
| 37 | 0011 0110 | | | AAA | |
| 38 | 0011 1000 | MOD REG R/M | (DISP-LO),(DISP-HI) | CMP | REG8/MEM8,REG8 |
| 39 | 0011 1001 | MOD REG R/M | (DISP-LO),(DISP-HI) | CMP | REG16/MEM16,REG16 |
| 3A | 0011 1010 | MOD REG R/M | (DISP-LO),(DISP-HI) | CMP | REG8,REG8/MEM8 |
| 3B | 0011 1011 | MOD REG R/M | (DISP-LO),(DISP-HI) | CMP | REG16,REG16/MEM16 |
| 3C | 0011 1100 | DATA-8 | | CMP | AL,IMMED8 |
| 3D | 0011 1101 | DATA-LO | DATA-HI | CMP | AX,IMMED16 |
| 3E | 0011 1110 | | | DS: | (segment override prefix) |
| 3F | 0011 1111 | | | AAS | |
| 40 | 0100 0000 | | | INC | AX |
| 41 | 0100 0001 | | | INC | CX |
| 42 | 0100 0010 | | | INC | DX |
| 43 | 0100 0011 | | | INC | BX |
| 44 | 0100 0100 | | | INC | SP |
| 45 | 0100 0101 | | | INC | BP |
| 46 | 0100 0110 | | | INC | SI |
| 47 | 0100 0111 | | | INC | DI |
| 48 | 0100 1000 | | | DEC | AX |
| 49 | 0100 1001 | | | DEC | CX |
| 4A | 0100 1010 | | | DEC | DX |
| 4B | 0100 1011 | | | DEC | BX |
| 4C | 0100 1100 | | | DEC | SP |
| 4D | 0100 1101 | | | DEC | BP |
| 4E | 0100 1110 | | | DEC | SI |
| 4F | 0100 1111 | | | DEC | DI |
| 50 | 0101 0000 | | | PUSH | AX |
| 51 | 0101 0001 | | | PUSH | CX |
| 52 | 0101 0010 | | | PUSH | DX |
| 53 | 0101 0011 | | | PUSH | BX |
| 54 | 0101 0100 | | | PUSH | SP |
| 55 | 0101 0101 | | | PUSH | BP |
| 56 | 0101 0110 | | | PUSH | SI |
| 57 | 0101 0111 | | | PUSH | DI |
| 58 | 0101 1000 | | | POP | AX |
| 59 | 0101 1001 | | | POP | CX |
| 5A | 0101 1010 | | | POP | DX |
| 5B | 0101 1011 | | | POP | BX |
| 5C | 0101 1100 | | | POP | SP |
| 5D | 0101 1101 | | | POP | BP |
| 5E | 0101 1110 | | | POP | SI |
| 5F | 0101 1111 | | | POP | DI |
| 60 | 0110 0000 | | | (not used) | |
| 61 | 0110 0001 | | | (not used) | |
| 62 | 0110 0010 | | | (not used) | |
| 63 | 0110 0011 | | | (not used) | |
| 64 | 0110 0100 | | | (not used) | |
| 65 | 0110 0101 | | | (not used) | |
| 66 | 0110 0110 | | | (not used) | |
| 67 | 0110 0111 | | | (not used) | |

Table 1-23 Machine Instruction Decoding Guide (continued)

| 1ST BYTE | | 2ND BYTE | BYTES 3,4,5,6 | ASM-86 INSTRUCTION FORMAT | |
|---|---|---|---|---|---|
| HEX | BINARY | | | | |
| 68 | 0110 1000 | | | (not used) | |
| 69 | 0110 1001 | | | (not used) | |
| 6A | 0110 1010 | | | (not used) | |
| 6B | 0110 1011 | | | (not used) | |
| 6C | 0110 1100 | | | (not used) | |
| 6D | 0110 1101 | | | (not used) | |
| 6E | 0110 1110 | | | (not used) | |
| 6F | 0110 1111 | | | (not used) | |
| 70 | 0111 0000 | IP-INC8 | | JO | SHORT-LABEL |
| 71 | 0111 0001 | IP-INC8 | | JNO | SHORT-LABEL |
| 72 | 0111 0010 | IP-INC8 | | JB/JNAE/ JC | SHORT-LABEL |
| 73 | 0111 0011 | IP-INC8 | | JNB/JAE/ JNC | SHORT-LABEL |
| 74 | 0111 0100 | IP-INC8 | | JE/JZ | SHORT-LABEL |
| 75 | 0111 0101 | IP-INC8 | | JNE/JNZ | SHORT-LABEL |
| 76 | 0111 0110 | IP-INC8 | | JBE/JNA | SHORT-LABEL |
| 77 | 0111 0111 | IP-INC8 | | JNBE/JA | SHORT-LABEL |
| 78 | 0111 1000 | IP-INC8 | | JS | SHORT-LABEL |
| 79 | 0111 1001 | IP-INC8 | | JNS | SHORT-LABEL |
| 7A | 0111 1010 | IP-INC8 | | JP/JPE | SHORT-LABEL |
| 7B | 0111 1011 | IP-INC8 | | JNP/JPO | SHORT-LABEL |
| 7C | 0111 1100 | IP-INC8 | | JL/JNGE | SHORT-LABEL |
| 7D | 0111 1101 | IP-INC8 | | JNL/JGE | SHORT-LABEL |
| 7E | 0111 1110 | IP-INC8 | | JLE/JNG | SHORT-LABEL |
| 7F | 0111 1111 | IP-INC8 | | JNLE/JG | SHORT-LABEL |
| 80 | 1000 0000 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-8 | ADD | REG8/MEM8,IMMED8 |
| 80 | 1000 0000 | MOD 001 R/M | (DISP-LO),(DISP-HI), DATA-8 | OR | REG8/MEM8,IMMED8 |
| 80 | 1000 0000 | MOD 010 R/M | (DISP-LO),(DISP-HI), DATA-8 | ADC | REG8/MEM8,IMMED8 |
| 80 | 1000 0000 | MOD 011 R/M | (DISP-LO),(DISP-HI), DATA-8 | SBB | REG8/MEM8,IMMED8 |
| 80 | 1000 0000 | MOD 100 R/M | (DISP-LO),(DISP-HI), DATA-8 | AND | REG8/MEM8,IMMED8 |
| 80 | 1000 0000 | MOD 101 R/M | (DISP-LO),(DISP-HI), DATA-8 | SUB | REG8/MEM8,IMMED8 |
| 80 | 1000 0000 | MOD 110 R/M | (DISP-LO),(DISP-HI), DATA-8 | XOR | REG8/MEM8,IMMED8 |
| 80 | 1000 0000 | MOD 111 R/M | (DISP-LO),(DISP-HI), DATA-8 | CMP | REG8/MEM8,IMMED8 |
| 81 | 1000 0001 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | ADD | REG16/MEM16,IMMED16 |
| 81 | 1000 0001 | MOD 001 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | OR | REG16/MEM16,IMMED16 |
| 81 | 1000 0001 | MOD 010 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | ADC | REG16/MEM16,IMMED16 |
| 81 | 1000 0001 | MOD 011 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | SBB | REG16/MEM16,IMMED16 |

Table 1-23 Machine Instruction Decoding Guide (continued)

| 1ST BYTE HEX | BINARY | 2ND BYTE | BYTES 3,4,5,6 | ASM-86 INSTRUCTION FORMAT | |
|---|---|---|---|---|---|
| 81 | 1000 0001 | MOD 100 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | AND | REG16/MEM16,IMMED16 |
| 81 | 1000 0001 | MOD 101 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | SUB | REG16/MEM16,IMMED16 |
| 81 | 1000 0001 | MOD 110 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | XOR | REG16/MEM16,IMMED16 |
| 81 | 1000 0001 | MOD 111 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | CMP | REG16/MEM16,IMMED16 |
| 82 | 1000 0010 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-8 | ADD | REG8/MEM8,IMMED8 |
| 82 | 1000 0010 | MOD 001 R/M | | (not used) | |
| 82 | 1000 0010 | MOD 010 R/M | (DISP-LO),(DISP-HI), DATA-8 | ADC | REG8/MEM8,IMMED8 |
| 82 | 1000 0010 | MOD 011 R/M | (DISP-LO),(DISP-HI), DATA-8 | SBB | REG8/MEM8,IMMED8 |
| 82 | 1000 0010 | MOD 100 R/M | | (not used) | |
| 82 | 1000 0010 | MOD 101 R/M | (DISP-LO),(DISP-HI), DATA-8 | SUB | REG8/MEM8,IMMED8 |
| 82 | 1000 0010 | MOD 110 R/M | | (not used) | |
| 82 | 1000 0010 | MOD 111 R/M | (DISP-LO),(DISP-HI), DATA-8 | CMP | REG8/MEM8,IMMED8 |
| 83 | 1000 0011 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-SX | ADD | REG16/MEM16, IMMED8 |
| 83 | 1000 0011 | MOD 001 R/M | | (not used) | |
| 83 | 1000 0011 | MOD 010 R/M | (DISP-LO), (DISP-HI), DATA-SX | ADC | REG16/MEM16,IMMED8 |
| 83 | 1000 0011 | MOD 011 R/M | (DISP-LO),(DISP-HI), DATA-SX | SBB | REG16/MEM16,IMMED8 |
| 83 | 1000 0011 | MOD 100 R/M | | (not used) | |
| 83 | 1000 0011 | MOD 101 R/M | (DISP-LO),(DISP-HI), DATA-SX | SUB | REG16/MEM16,IMMED8 |
| 83 | 1000 0011 | MOD 110 R/M | | (not used) | |
| 83 | 1000 0011 | MOD 111 R/M | (DISP-LO),(DISP-HI), DATA-SX | CMP | REG16/MEM16,IMMED8 |
| 84 | 1000 0100 | MOD REG R/M | (DISP-LO),(DISP-HI) | TEST | REG8/MEM8,REG8 |
| 85 | 1000 0101 | MOD REG R/M | (DISP-LO),(DISP-HI) | TEST | REG16/MEM16,REG16 |
| 86 | 1000 0110 | MOD REG R/M | (DISP-LO),(DISP-HI) | XCHG | REG8,REG8/MEM8 |
| 87 | 1000 0111 | MOD REG R/M | (DISP-LO),(DISP-HI) | XCHG | REG16,REG16/MEM16 |
| 88 | 1000 1000 | MOD REG R/M | (DISP-LO),(DISP-HI) | MOV | REG8/MEM8,REG8 |
| 89 | 1000 1001 | MOD REG R/M | (DISP-LO),(DISP-HI) | MOV | REG16/MEM16/REG16 |
| 8A | 1000 1010 | MOD REG R/M | (DISP-LO),(DISP-HI) | MOV | REG8,REG8/MEM8 |
| 8B | 1000 1011 | MOD REG R/M | (DISP-LO),(DISP-HI) | MOV | REG16,REG16/MEM16 |
| 8C | 1000 1100 | MOD 0SR R/M | (DISP-LO),(DISP-HI) | MOV | REG16/MEM16,SEGREG |
| 8C | 1000 1100 | MOD 1-- R/M | | (not used) | |
| 8D | 1000 1101 | MOD REG R/M | (DISP-LO),(DISP-HI) | LEA | REG16,MEM16 |
| 8E | 1000 1110 | MOD 0SR R/M | (DISP-LO),(DISP-HI) | MOV | SEGREG,REG16/MEM16 |
| 8E | 1000 1110 | MOD 1-- R/M | | (not used) | |
| 8F | 1000 1111 | MOD 000 R/M | (DISP-LO),(DISP-HI) | POP | REG16/MEM16 |
| 8F | 1000 1111 | MOD 001 R/M | | (not used) | |
| 8F | 1000 1111 | MOD 010 R/M | | (not used) | |

**Table 1-23 Machine Instruction Decoding Guide (continued)**

| 1ST BYTE | | 2ND BYTE | BYTES 3,4,5,6 | ASM-86 INSTRUCTION FORMAT |
|---|---|---|---|---|
| HEX | BINARY | | | |
| 8F | 1000 1111 | MOD 011 R/M | | (not used) |
| 8F | 1000 1111 | MOD 100 R/M | | (not used) |
| 8F | 1000 1111 | MOD 101 R/M | | (not used) |
| 8F | 1000 1111 | MOD 110 R/M | | (not used) |
| 8F | 1000 1111 | MOD 111 R/M | | (not used) |
| 90 | 1001 0000 | | | NOP (exchange AX,AX) |
| 91 | 1001 0001 | | | XCHG AX,CX |
| 92 | 1001 0010 | | | XCHG AX,DX |
| 93 | 1001 0011 | | | XCHG AX,BX |
| 94 | 1001 0100 | | | XCHG AX,SP |
| 95 | 1001 0101 | | | XCHG AX,BP |
| 96 | 1001 0110 | | | XCHG AX,SI |
| 97 | 1001 0111 | | | XCHG AX,DI |
| 98 | 1001 1000 | | | CBW |
| 99 | 1001 1001 | | | CWD |
| 9A | 1001 1010 | DISP-LO | DISP-HI,SEG-LO, SEG-HI | CALL FAR_PROC |
| 9B | 1001 1011 | | | WAIT |
| 9C | 1001 1100 | | | PUSHF |
| 9D | 1001 1101 | | | POPF |
| 9E | 1001 1110 | | | SAHF |
| 9F | 1001 1111 | | | LAHF |
| A0 | 1010 0000 | ADDR-LO | ADDR-HI | MOV AL,MEM8 |
| A1 | 1010 0001 | ADDR-LO | ADDR-HI | MOV AX,MEM16 |
| A2 | 1010 0010 | ADDR-LO | ADDR-HI | MOV MEM8,AL |
| A3 | 1010 0011 | ADDR-LO | ADDR-HI | MOV MEM16,AL |
| A4 | 1010 0100 | | | MOVS DEST-STR8,SRC-STR8 |
| A5 | 1010 0101 | | | MOVS DEST-STR16,SRC-STR16 |
| A6 | 1010 0110 | | | CMPS DEST-STR8,SRC-STR8 |
| A7 | 1010 0111 | | | CMPS DEST-STR16,SRC-STR16 |
| A8 | 1010 1000 | DATA-8 | | TEST AL,IMMED8 |
| A9 | 1010 1001 | DATA-LO | DATA-HI | TEST AX,IMMED16 |
| AA | 1010 1010 | | | STOS DEST-STR8 |
| AB | 1010 1011 | | | STOS DEST-STR16 |
| AC | 1010 1100 | | | LODS SRC-STR8 |
| AD | 1010 1101 | | | LODS SRC-STR16 |
| AE | 1010 1110 | | | SCAS DEST-STR8 |
| AF | 1010 1111 | | | SCAS DEST-STR16 |
| B0 | 1011 0000 | DATA-8 | | MOV AL,IMMED8 |
| B1 | 1011 0001 | DATA-8 | | MOV CL,IMMED8 |
| B2 | 1011 0010 | DATA-8 | | MOV DL,IMMED8 |
| B3 | 1011 1011 | DATA-8 | | MOV BL,IMMED8 |
| B4 | 1011 0100 | DATA-8 | | MOV AH,IMMED8 |
| B5 | 1011 0101 | DATA-8 | | MOV CH,IMMED8 |
| B6 | 1011 0110 | DATA-8 | | MOV DH,IMMED8 |
| B7 | 1011 0111 | DATA-8 | | MOV BH,IMMED8 |
| B8 | 1011 1000 | DATA-LO | DATA-HI | MOV AX,IMMED16 |
| B9 | 1011 1001 | DATA-LO | DATA-HI | MOV CX,IMMED16 |
| BA | 1011 1010 | DATA-LO | DATA-HI | MOV DX,IMMED16 |
| BB | 1011 1011 | DATA-LO | DATA-HI | MOV BX,IMMED16 |

Table 1-23 Machine Instruction Decoding Guide (continued)

| 1ST BYTE HEX | BINARY | 2ND BYTE | BYTES 3,4,5,6 | ASM-86 INSTRUCTION FORMAT | |
|---|---|---|---|---|---|
| BC | 1011 1100 | DATA-LO | DATA-HI | MOV | SP,IMMED16 |
| BD | 1011 1101 | DATA-LO | DATA-HI | MOV | BP,IMMED16 |
| BE | 1011 1110 | DATA-LO | DATA-HI | MOV | SI,IMMED16 |
| BF | 1011 1111 | DATA-LO | DATA-HI | MOV | DI,IMMED16 |
| C0 | 1100 0000 | | | (not used) | |
| C1 | 1100 0001 | | | (not used) | |
| C2 | 1100 0010 | DATA-LO | DATA-HI | RET | IMMED16 (intraseg) |
| C3 | 1100 0011 | | | RET | (intrasegment) |
| C4 | 1100 0100 | MOD REG R/M | (DISP-LO),(DISP-HI) | LES | REG16,MEM16 |
| C5 | 1100 0101 | MOD REG R/M | (DISP-LO),(DISP-HI) | LDS | REG16,MEM16 |
| C6 | 1100 0110 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-8 | MOV | MEM8,IMMED8 |
| C6 | 1100 0110 | MOD 001 R/M | | (not used) | |
| C6 | 1100 0110 | MOD 010 R/M | | (not used) | |
| C6 | 1100 0110 | MOD 011 R/M | | (not used) | |
| C6 | 1100 0110 | MOD 100 R/M | | (not used) | |
| C6 | 1100 0110 | MOD 101 R/M | | (not used) | |
| C6 | 1100 0110 | MOD 110 R/M | | (not used) | |
| C6 | 1100 0110 | MOD 111 R/M | | (not used) | |
| C7 | 1100 0111 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | MOV | MEM16,IMMED16 |
| C7 | 1100 0111 | MOD 001 R/M | | (not used) | |
| C7 | 1100 0111 | MOD 010 R/M | | (not used) | |
| C7 | 1100 0111 | MOD 011 R/M | | (not used) | |
| C7 | 1100 0111 | MOD 100 R/M | | (not used) | |
| C7 | 1100 0111 | MOD 101 R/M | | (not used) | |
| C7 | 1100 0111 | MOD 110 R/M | | (not used) | |
| C7 | 1100 0111 | MOD 111 R/M | | (not used | |
| C8 | 1100 1000 | | | (not used) | |
| C9 | 1100 1001 | | | (not used) | |
| CA | 1100 1010 | DATA-LO | DATA-HI | RET | IMMED16 (intersegment) |
| CB | 1100 1011 | | | RET | (intersegment) |
| CC | 1100 1100 | | | INT | 3 |
| CD | 1100 1101 | DATA-8 | | INT | IMMED8 |
| CE | 1100 1110 | | | INTO | |
| CF | 1100 1111 | | | IRET | |
| D0 | 1101 0000 | MOD 000 R/M | (DISP-LO),(DISP-HI) | ROL | REG8/MEM8,1 |
| D0 | 1101 0000 | MOD 001 R/M | (DISP-LO),(DISP-HI) | ROR | REG8/MEM8,1 |
| D0 | 1101 0000 | MOD 010 R/M | (DISP-LO),(DISP-HI) | RCL | REG8/MEM8,1 |
| D0 | 1101 0000 | MOD 011 R/M | (DISP-LO),(DISP-HI) | RCR | REG8/MEM8,1 |
| D0 | 1101 0000 | MOD 100 R/M | (DISP-LO),(DISP-HI) | SAL/SHL | REG8/MEM8,1 |
| D0 | 1101 0000 | MOD 101 R/M | (DISP-LO),(DISP-HI) | SHR | REG8/MEM8,1 |
| D0 | 1101 0000 | MOD 110 R/M | | (not used) | |
| D0 | 1101 0000 | MOD 111 R/M | (DISP-LO),(DISP-HI) | SAR | REG8/MEM8,1 |
| D1 | 1101 0001 | MOD 000 R/M | (DISP-LO),(DISP-HI) | ROL | REG16/MEM16,1 |
| D1 | 1101 0001 | MOD 001 R/M | (DISP-LO),(DISP-HI) | ROR | REG16/MEM16,1 |
| D1 | 1101 0001 | MOD 010 R/M | (DISP-LO),(DISP-HI) | RCL | REG16/MEM16,1 |
| D1 | 1101 0001 | MOD 011 R/M | (DISP-LO),(DISP-HI) | RCR | REG16/MEM16,1 |
| D1 | 1101 0001 | MOD 100 R/M | (DISP-LO),(DISP-HI) | SAL/SHL | REG16/MEM16,1 |

Table 1-23 Machine Instruction Decoding Guide (continued)

| 1ST BYTE | | 2ND BYTE | BYTES 3,4,5,6 | ASM-86 INSTRUCTION FORMAT | |
|---|---|---|---|---|---|
| HEX | BINARY | | | | |
| D1 | 1101 0001 | MOD 101 R/M | (DISP-LO),(DISP-HI) | SHR | REG16/MEM16,1 |
| D1 | 1101 0001 | MOD 110 R/M | | (not used) | |
| D1 | 1101 0001 | MOD 111 R/M | (DISP-LO),(DISP-HI) | SAR | REG16/MEM16,1 |
| D2 | 1101 0010 | MOD 000 R/M | (DISP-LO),(DISP-HI) | ROL | REG8/MEM8,CL |
| D2 | 1101 0010 | MOD 001 R/M | (DISP-LO),(DISP-HI) | ROR | REG8/MEM8,CL |
| D2 | 1101 0010 | MOD 010 R/M | (DISP-LO),(DISP-HI) | RCL | REG8/MEM8,CL |
| D2 | 1101 0010 | MOD 011 R/M | (DISP-LO),(DISP-HI) | RCR | REG8/MEM8,CL |
| D2 | 1101 0010 | MOD 100 R/M | (DISP-LO),(DISP-HI) | SAL/SHL | REG8/MEM8,CL |
| D2 | 1101 0010 | MOD 101 R/M | (DISP-LO),(DISP-HI) | SHR | REG8/MEM8,CL |
| D2 | 1101 0010 | MOD 110 R/M | | (not used) | |
| D2 | 1101 0010 | MOD 111 R/M | (DISP-LO),(DISP-HI) | SAR | REG8/MEM8,CL |
| D3 | 1101 0011 | MOD 000 R/M | (DISP-LO),(DISP-HI) | ROL | REG16/MEM16,CL |
| D3 | 1101 0011 | MOD 001 R/M | (DISP-LO),(DISP-HI) | ROR | REG16/MEM16,CL |
| D3 | 1101 0011 | MOD 010 R/M | (DISP-LO),(DISP-HI) | RCL | REG16/MEM16,CL |
| D3 | 1101 0011 | MOD 011 R/M | (DISP-LO),(DISP-HI) | RCR | REG16/MEM16,CL |
| D3 | 1101 0011 | MOD 100 R/M | (DISP-LO),(DISP-HI) | SAL/SHL | REG16/MEM16,CL |
| D3 | 1101 0011 | MOD 101 R/M | (DISP-LO),(DISP-HI) | SHR | REG16/MEM16,CL |
| D3 | 1101 0011 | MOD 110 R/M | | (not used) | |
| D3 | 1101 0011 | MOD 111 R/M | (DISP-LO),(DISP-HI) | SAR | REG16/MEM16,CL |
| D4 | 1101 0100 | 00001010 | | AAM | |
| D5 | 1101 0101 | 00001010 | | AAD | |
| D6 | 1101 0110 | | | (not used) | |
| D7 | 1101 0111 | | | XLAT | SOURCE-TABLE |
| D8 | 1101 1000 | MOD 000 R/M | | | |
| | 1XXX | MOD YYY R/M | (DISP-LO), (DISP-HI) | ESC | OPCODE,SOURCE |
| DF | 1101 1111 | MOD 111 R/M | | | |
| E0 | 1110 0000 | IP-INC-8 | | LOOPNE/ LOOPNZ | SHORT-LABEL |
| E1 | 1110 0001 | IP-INC-8 | | LOOPE/ LOOPZ | SHORT-LABEL |
| E2 | 1110 0010 | IP-INC-8 | | LOOP | SHORT-LABEL |
| E3 | 1110 0011 | IP-INC-8 | | JCXZ | SHORT-LABEL |
| E4 | 1110 0100 | DATA-8 | | IN | AL,IMMED8 |
| E5 | 1110 0101 | DATA-8 | | IN | AX,IMMED8 |
| E6 | 1110 0110 | DATA-8 | | OUT | AL,IMMED8 |
| E7 | 1110 0111 | DATA-8 | | OUT | AX,IMMED8 |
| E8 | 1110 1000 | IP-INC-LO | IP-INC-HI | CALL | NEAR-PROC |
| E9 | 1110 1001 | IP-INC-LO | IP-INC-HI | JMP | NEAR-LABEL |
| EA | 1110 1010 | IP-LO | IP-HI,CS-LO,CS-HI | JMP | FAR-LABEL |
| EB | 1110 1011 | IP-INC8 | | JMP | SHORT-LABEL |
| EC | 1110 1100 | | | IN | AL,DX |
| ED | 1110 1101 | | | IN | AX,DX |
| EE | 1110 1110 | | | OUT | AL,DX |
| EF | 1110 1111 | | | OUT | AX,DX |
| F0 | 1111 0000 | | | LOCK | (prefix) |
| F1 | 1111 0001 | | | (not used) | |
| F2 | 1111 0010 | | | REPNE/REPNZ | |
| F3 | 1111 0011 | | | REP/REPE/REPZ | |
| F4 | 1111 0100 | | | HLT | |
| F5 | 1111 0101 | | | CMC | |

Table 1-23 Machine Instruction Decoding Guide (continued)

| 1ST BYTE HEX | BINARY | 2ND BYTE | BYTES 3,4,5,6 | ASM-86 INSTRUCTION FORMAT | |
|---|---|---|---|---|---|
| F6 | 1111 0110 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-8 | TEST | REG8/MEM8,IMMED8 |
| F6 | 1111 0110 | MOD 001 R/M | | (not used) | |
| F6 | 1111 0110 | MOD 010 R/M | (DISP-LO),(DISP-HI) | NOT | REG8/MEM8 |
| F6 | 1111 0110 | MOD 011 R/M | (DISP-LO),(DISP-HI) | NEG | REG8/MEM8 |
| F6 | 1111 0110 | MOD 100 R/M | (DISP-LO),(DISP-HI) | MUL | REG8/MEM8 |
| F6 | 1111 0110 | MOD 101 R/M | (DISP-LO),(DISP-HI) | IMUL | REG8/MEM8 |
| F6 | 1111 0110 | MOD 110 R/M | (DISP-LO),(DISP-HI) | DIV | REG8/MEM8 |
| F6 | 1111 0110 | MOD 111 R/M | (DISP-LO),(DISP-HI) | IDIV | REG8/MEM8 |
| F7 | 1111 0111 | MOD 000 R/M | (DISP-LO),(DISP-HI), DATA-LO,DATA-HI | TEST | REG16/MEM16,IMMED16 |
| F7 | 1111 0111 | MOD 001 R/M | | (not used) | |
| F7 | 1111 0111 | MOD 010 R/M | (DISP-LO),(DISP-HI) | NOT | REG16/MEM16 |
| F7 | 1111 0111 | MOD 011 R/M | (DISP-LO),(DISP-HI) | NEG | REG16/MEM16 |
| F7 | 1111 0111 | MOD 100 R/M | (DISP-LO),(DISP-HI) | MUL | REG16/MEM16 |
| F7 | 1111 0111 | MOD 101 R/M | (DISP-LO),(DISP-HI) | IMUL | REG16/MEM16 |
| F7 | 1111 0111 | MOD 110 R/M | (DISP-LO),(DISP-HI) | DIV | REG16/MEM16 |
| F7 | 1111 0111 | MOD 111 R/M | (DISP-LO),(DISP-HI) | IDIV | REG16/MEM16 |
| F8 | 1111 1000 | | | CLC | |
| F9 | 1111 1001 | | | STC | |
| FA | 1111 1010 | | | CLI | |
| FB | 1111 1011 | | | STI | |
| FC | 1111 1100 | | | CLD | |
| FD | 1111 1101 | | | STD | |
| FE | 1111 1110 | MOD 000 R/M | (DISP-LO),(DISP-HI) | INC | REG8/MEM8 |
| FE | 1111 1110 | MOD 001 R/M | (DISP-LO),(DISP-HI) | DEC | REG8/MEM8 |
| FE | 1111 1110 | MOD 010 R/M | | (not used) | |
| FE | 1111 1110 | MOD 011 R/M | | (not used) | |
| FE | 1111 1110 | MOD 100 R/M | | (not used) | |
| FE | 1111 1110 | MOD 101 R/M | | (not used) | |
| FE | 1111 1110 | MOD 110 R/M | | (not used) | |
| FE | 1111 1110 | MOD 111 R/M | | (not used) | |
| FF | 1111 1111 | MOD 000 R/M | (DISP-LO),(DISP-HI) | INC | MEM16 |
| FF | 1111 1111 | MOD 001 R/M | (DISP-LO),(DISP-HI) | DEC | MEM16 |
| FF | 1111 1111 | MOD 010 R/M | (DISP-LO),(DISP-HI) | CALL | REG16/MEM16 (intra) |
| FF | 1111 1111 | MOD 011 R/M | (DISP-LO),(DISP-HI) | CALL | MEM16 (intersegment) |
| FF | 1111 1111 | MOD 100 R/M | (DISP-LO),(DISP-HI) | JMP | REG16/MEM16 (intra) |
| FF | 1111 1111 | MOD 101 R/M | (DISP-LO),(DISP-HI) | JMP | MEM16 (intersegment) |
| FF | 1111 1111 | MOD 110 R/M | (DISP-LO),(DISP-HI) | PUSH | MEM16 |
| FF | 1111 1111 | MOD 111 R/M | | (not used) | |

**Table 1-21 Key to Machine Instruction Encoding and Decoding**

| IDENTIFIER | EXPLANATION |
|---|---|
| MOD | Mode field; described in this chapter. |
| REG | Register field; described in this chapter. |
| R/M | Register/Memory field; described in this chapter. |
| SR | Segment register code: 00=ES, 01=CS, 10=SS, 11=DS. |
| W, S, D, V, Z | Single-bit instruction fields; described in this chapter. |
| DATA-8 | 8-bit immediate constant. |
| DATA-SX | 8-bit immediate value that is automatically sign-extended to 16-bits before use. |
| DATA-LO | Low-order byte of 16-bit immediate constant. |
| DATA-HI | High-order byte of 16-bit immediate constant. |
| (DISP-LO) | Low-order byte of optional 8- or 16-bit unsigned displacement; MOD indicates if present. |
| (DISP-HI) | High-order byte of optional 16-bit unsigned displacement; MOD indicates if present. |
| IP-LO | Low-order byte of new IP value. |
| IP-HI | High-order byte of new IP value |
| CS-LO | Low-order byte of new CS value. |
| CS-HI | High-order byte of new CS value. |
| IP-INC8 | 8-bit signed increment to instruction pointer. |
| IP-INC-LO | Low-order byte of signed 16-bit instruction pointer increment. |
| IP-INC-HI | High-order byte of signed 16-bit instruction pointer increment. |
| ADDR-LO | Low-order byte of direct address (offset) of memory operand; EA not calculated. |
| ADDR-HI | High-order byte of direct address (offset) of memory operand; EA not calculated. |
| —— | Bits may contain any value. |
| XXX | First 3 bits of ESC opcode. |
| YYY | Second 3 bits of ESC opcode. |
| REG8 | 8-bit general register operand. |
| REG16 | 16-bit general register operand. |
| MEM8 | 8-bit memory operand (any addressing mode). |
| MEM16 | 16-bit memory operand (any addressing mode). |
| IMMED8 | 8-bit immediate operand. |
| IMMED16 | 16-bit immediate operand. |
| SEGREG | Segment register operand. |
| DEST-STR8 | Byte string addressed by DI. |

**Table 1-21 Key to Machine Instruction Encoding and Decoding (continued)**

| IDENTIFIER | EXPLANATION |
|---|---|
| SRC-STR8 | Byte string addressed by SI. |
| DEST-STR16 | Word string addressed by DI. |
| SRC-STR16 | Word string addressed by SI. |
| SHORT-LABEL | Label within ±127 bytes of instruction. |
| NEAR-PROC | Procedure in current code segment. |
| FAR-PROC | Procedure in another code segment. |
| NEAR-LABEL | Label in current code segment but farther than −128 to +127 bytes from instruction. |
| FAR-LABEL | Label in another code segment. |
| SOURCE-TABLE | XLAT translation table addressed by BX. |
| OPCODE | ESC opcode operand. |
| SOURCE | ESC register or memory operand. |

# APPENDIX B

# Algorithms for the Longest Common Subsequence Problem

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ABSTRACT. Two algorithms are presented that solve the longest common subsequence problem. The first algorithm is applicable in the general case and requires $O(pn + n \log n)$ time where $p$ is the length of the longest common subsequence. The second algorithm requires time bounded by $O(p(m + 1 - p)\log n)$. In the common special case where $p$ is close to $m$, this algorithm takes much less time than $n^2$.

KEY WORDS AND PHRASES: subsequence, common subsequence, algorithm

CR CATEGORIES: 3.73, 3.79, 5.25, 5.39

*Introduction*

We start by defining conventions and terminology that will be used throughout this paper.

String $C = c_1c_2 \cdots c_p$ is a *subsequence* of string $A = a_1a_2 \cdots a_m$ if there is a mapping $F: \{1, 2, \ldots, p\} \rightarrow \{1, 2, \ldots, m\}$ such that $F(i) = k$ only if $c_i = a_k$ and $F$ is a monotone strictly increasing function (i.e. $F(i) = u$, $F(j) = v$, and $i < j$ imply that $u < v$). $C$ can be formed by deleting $m - p$ (not necessarily adjacent) symbols from $A$. For example, "course" is a subsequence of "computer science."

String $C$ is a *common subsequence* of strings $A$ and $B$ if $C$ is a subsequence of $A$ and also a subsequence of $B$.

String $C$ is a *longest common subsequence* (abbreviated LCS) of string $A$ and $B$ if $C$ is a common subsequence of $A$ and $B$ of maximal length, i.e. there is no common subsequence of $A$ and $B$ that has greater length.

Throughout this paper, we assume that $A$ and $B$ are strings of lengths $m$ and $n$, $m \leq n$, that have an LCS $C$ of (unknown) length $p$.

We assume that the symbols that may appear in these strings come from some alphabet of size $t$. A symbol can be stored in memory by using $\log t$ bits, which we assume will fit in one word of memory. Symbols can be compared ($a \leq b$?) in one time unit.

The number of different symbols that actually appear in string $B$ is defined to be $s$ (which must be less than $n$ and $t$).

The longest common subsequence problem has been solved by using a recursion relationship on the length of the solution [7, 12, 16, 21]. These are generally applicable algorithms that take $O(mn)$ time for any input strings of lengths $m$ and $n$ even though the lower bound on time of $O(mn)$ need not apply to all inputs [2]. We present algorithms that, depending on the nature of the input, may not require quadratic time to recover an LCS. The first algorithm is applicable in the general case and requires $O(pn + n \log n)$ time. The second algorithm requires time bounded by $O((m + 1 - p)p \log n)$. In the common special case where $p$ is close to $m$, this algorithm takes time



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much less than $n^2$. We conclude with references to other algorithms for the LCS problem that may be of interest.

## *pn Algorithm*

We present in this section algorithm *ALGD*, which will find an LCS in time $O(pn + n \log n)$ where $p$ is the length of the LCS. Thus this algorithm may be preferred for applications where the expected length of an LCS is small relative to the lengths of the input strings.

Some preliminary definitions are as follows:

We represent the concatenation of strings $X$ and $Y$ by $X\|Y$.

$A_{1i}$ represents the string $a_1a_2 \cdots a_i$ (elements 1 through $i$ of string $A$). Similarly, the prefix of length $j$ of string $B$ is represented by $B_{1j}$.

We define $L(i, j)$ to be the length of the LCS of prefixes of lengths $i$ and $j$ of strings $A$ and $B$, i.e. the length of the LCS of $A_{1i}$ and $B_{1j}$.

$\langle i, j\rangle$ represents the positions of $a_i$ and $b_j$, the $i$th element of string $A$ and the $j$th element of string $B$. We refer to $i$ ($j$) as the $i$-value ($j$-value) of $\langle i, j\rangle$.

We define $\{\langle 0, 0\rangle\}$ to be the set of *0-candidates*, and we define $\langle i, j\rangle$ to be a *k-candidate* (for $k \geq 1$) if $a_i = b_j$ and there exist $i'$ and $j'$ such that $i' < i$, $j' < j$, and $\langle i', j'\rangle$ is a $(k - 1)$-candidate. We say that $\langle i', j'\rangle$ *generates* $\langle i, j\rangle$.

Define $a_0 = b_0 = \$$ where \$ is some symbol that does not appear in strings $A$ or $B$.

LEMMA 1. *For $k \geq 1$, $\langle i, j\rangle$ is a k-candidate iff $L(i, j) \geq k$ and $a_i = b_j$. Thus there is a common subsequence of length k of $A_{1i}$ and $B_{1j}$.*

PROOF. By induction on $k$. $\langle i, j\rangle$ is a 1-candidate iff $a_i = b_j$ (by definition), in which case $L(i, j)$ necessarily is at least 1. Thus the lemma is true for $k = 1$. Assume it is true for $k - 1$. Consider $k$. If $\langle i, j\rangle$ is a $k$-candidate then there exist $i' < i$ and $j' < j$ such that $\langle i', j'\rangle$ is a $(k - 1)$-candidate. By assumption, there is a common subsequence $D' = d_1d_2 \cdots d_{k-1}$ of $A_{1i'}$ and $B_{1j'}$. Since $a_i = b_j$ ($\langle i, j\rangle$ is a $k$-candidate), $D = D'\|a_i$ is a common subsequence of length $k$ of $A_{1i}$ and $B_{1j}$. Thus $L(i, j) \geq k$.

Conversely, if $L(i, j) \geq k$ and $a_i = b_j$, then there exist $i' < i$ and $j' < j$ such that $a_{i'} = b_{j'}$ and $L(i', j') = L(i, j) - 1 \geq k - 1$. $\langle i', j'\rangle$ is a $(k - 1)$-candidate (by inductive hypothesis) and thus $\langle i, j\rangle$ is a $k$-candidate. □

The length of an LCS is $p$, the maximum value of $k$ such that there exists a $k$-candidate. As we shall see, to recover an LCS, it suffices to maintain the sequence of a 0-candidate, 1-candidate, ... , $(p - 1)$-candidate, and a $p$-candidate such that in this sequence each $i$-candidate can generate the $(i + 1)$-candidate for $0 \leq i < p$.

*Rule.* Let $x = \langle x_1, x_2\rangle$ and $y = \langle y_1, y_2\rangle$ be two $k$-candidates. If $x_1 \geq y_1$ and $x_2 \geq y_2$, then we say that $y$ *rules out* $x$ ($x$ is a superfluous $k$-candidate) since any $(k + 1)$-candidate that could be generated by $x$ can also be generated by $y$. Thus, from the set of $k$-candidates, we need consider only those that are minimal under the usual vector ordering. Note that if $x$ and $y$ are minimal elements then $x_1 < y_1$ iff $x_2 > y_2$.

LEMMA 2. *Let the set of k-candidates be $\{\langle i_r, j_r\rangle\}$ ($r = 1, 2, \ldots$). We can rule out candidates so that (after renumbering) $i_1 < i_2 < \cdots$ and $j_1 > j_2 > \cdots$.*

PROOF. Any two $k$-candidates $\langle i, j\rangle$ and $\langle i', j'\rangle$ satisfy one of the following (without loss of generality, $i \leq i'$):

(1) $i < i', j \leq j'$.
(2) $i < i', j > j'$.
(3) $i = i', j \leq j'$.
(4) $i = i', j > j'$.

In cases (1) and (3) $\langle i', j'\rangle$ can be ruled out; in case (4) $\langle i, j\rangle$ can be ruled out; and case (2) satisfies the statement of the lemma. Thus any set of $k$-candidates which cannot be reduced by further application of the rule will satisfy the condition stated in the lemma. □

The set of $k$-candidates, reduced by application of the rule so as to satisfy the statement of Lemma 2, are the minimal elements of the set of $k$-candidates (since no element can rule out a minimal element) and will be called the set of *minimal k-candidates*. By Lemma 2, there is at most one minimal $k$-candidate for each $i$-value.

We note that if $\langle i, j\rangle$ is a minimal $k$-candidate then $L(i, j) = k$ and $\langle i, j\rangle$ is the $k$-candidate with $i$-value $i$ having smallest $j$-value $j$ such that $L(i, j) = k$.

Lemma 3. *For $k \geq 1$, $\langle i, j\rangle$ is a minimal k-candidate iff j is the minimum value such that $b_j = a_i$ and low $< j <$ high, where high is the minimum j-value of all k-candidates whose i-value is less than i (no upper limit if there are no such k-candidates) and low is the minimum j-value of all $(k - 1)$-candidates whose i-value is less than i.*

Proof. Assume that $\langle i, j\rangle$ is a minimal $k$-candidate. If $j \geq high$ then there is a $k$-candidate $\langle i', j'\rangle$ such that $i' < i$ and $j' = high \leq j$. $\langle i, j\rangle$ would be ruled out by $\langle i', j'\rangle$ and thus would not be minimal.

If $j \leq low$, then there is no $(k - 1)$-candidate that can generate $\langle i, j\rangle$. $\langle i, j\rangle$ would not be a $k$-candidate.

$b_j = a_i$ is required by the definition of $k$-candidate and $low < j < high$ has just been shown. If $j$ and $j'$ both satisfy these constraints, $j < j'$, then $\langle i, j'\rangle$ is ruled out by $\langle i, j\rangle$. Thus, for a particular $i$, $j$ must be the minimum $j$-value of all $k$-candidates satisfying these constraints.

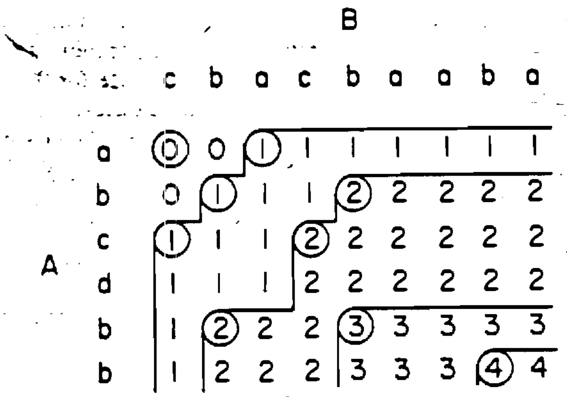
The *if* of the lemma has thus been shown.

The converse is easily shown: If $\langle i, j\rangle$ is not a $k$-candidate, then either $a_i \neq b_j$ or there is no $(k - 1)$-candidate that can generate $\langle i, j\rangle$. That is, the $j$-value of all $(k - 1)$-candidates with $i$-value less than $i$ is greater than or equal to $j$. This is equivalent to $j \leq low$.

If $\langle i, j\rangle$ is a $k$-candidate but is not minimal, say $\langle i', j'\rangle$ rules out $\langle i, j\rangle$, then $i' \leq i$ and $j' \leq j$. If $i' < i$, then clearly $j < high$ is violated. Otherwise, $i' = i$. In this case $j' > low$ since $\langle i', j'\rangle$ must be generated from a $(k - 1)$-candidate and $b_{j'} = a_i$ since $\langle i', j\rangle$ is a $k$-candidate. Also $j' < j < high$. Thus $j'$ satisfies all the constraints and $j$ is not the minimum value that does so, a contradiction. □

We present algorithm $ALGD$, which, using the results of Lemma 3, obtains an LCS $C$ of length $p$ of input strings $A$ and $B$ in time $O(pn + n \log n)$.

The algorithm is based on an efficient representation of the $L$ matrix. Since $L$ is nondecreasing in both arguments, we may draw contours in its matrix as shown in the following example:




The entire matrix is specified by its contours. The contours are described by sets of minimal $k$-candidates. The contour between $L$-values of $k - 1$ and $k$ is defined by the set of minimal $k$-candidates whose elements are positioned at the convex corners of the contour.

To keep track of the minimal $k$-candidates, we use the matrix $D$. $D[k, i]$ is the $j$-value of the unique minimal $k$-candidate having $i$-value of $i$ or 0 if there is no such minimal $k$-candidate. Thus $D[k, i]$ describes the contours by giving the number of the first column of row $i$ that is in region $k$ (if that number is different from $D[k, i - 1]$).

*lowcheck* is the smallest $i$-value of a $(k-1)$-candidate. *FLAG* has value 1 iff there are any $k$-candidates.

$NB[\theta]$ is the number of times symbol $\theta$ occurs in string $B$. $PB[\theta, 1], \ldots, PB[\theta, NB[\theta]]$ is the ordered list, smallest first, of positions in $B$ in which symbol $\theta$ occurs.

If $t$, the size of the symbol alphabet, is not large compared to $n$, then we may index an array by the bit representation of a symbol. Otherwise, if $t \gg n$, then we construct a balanced binary search tree which provides a mapping from symbols that appear in string $B$ to the integers 1 through $s$ (there are $s$ different symbols that appear in $B$). Whenever string element $a_i$ appears as an array subscript (as in $N[a_i]$), it should be understood that we are indexing $N$ by the integer $s_i$ which has been obtained (during initialization for *ALGD*) from traversing the search tree just described. If $a_i$ does not appear in $B$, then the integer $s_i$ is zero. An equivalent assumption is followed for subscript $b_j$ in step 1.

```
ALGD(m, n, A, B, C, p)
 1. NB[θ] ← 0 for θ = 1, ... , s
    PB[θ, 0] ← 0 for θ = 1, ... , s
    PB[0, 0] ← 0; PB[0, 1] ← 0
    for j ← 1 step 1 until n do
    begin
      NB[b_j] ← NB[b_j] + 1
      PB[b_j, NB[b_j]] ← j
    end
 2. D[0, i] ← 0 for i = 0, ... , m
    lowcheck ← 0
 3. for k ← 1 step 1 do
    begin
 4.   N[θ] ← NB[θ] for θ = 1, ... , s
      N[0] ← 1
      FLAG ← 0
      low ← D[k - 1, lowcheck]
      high ← n + 1
 5.   for i ← lowcheck + 1 step 1 until m do
      begin
 6.     while PB[a_i, N[a_i] - 1] > low do N[a_i] ← N[a_i] - 1
 7.     if high > PB[a_i, N[a_i]] > low
          then begin
            high ← PB[a_i, N[a_i]]
            D[k, i] ← high
            if FLAG = 0 then {lowcheck ← i; FLAG ← 1}
          end
          else D[k, i] ← 0
 8.     if D[k - 1, i] > 0 then low ← D[k - 1, i]
      end loop of step 5
 9. if FLAG = 0 then go to step 10
    end loop of step 3
10. p ← k - 1
    k ← p
    for i ← m + 1 step - 1 until 0 do
    if D[k, i] > 0 then
    begin
      c_k ← a_i
      k ← k - 1
    end
```

The loop of step 3 evaluates the set of minimal $k$-candidates for $k = 1, 2, \ldots$. The loop of step 5 evaluates the set of minimal $k$-candidates, smallest $i$-value first, and fills in the $D$ array accordingly (in the example given previously this is left-to-right) while scanning the chains of occurrences of a given character in $B$ with largest $j$-value first (right-to-left). For each $i$, $i$ can be the $i$-value of a minimal $k$-candidate if there is a $j$ satisfying the constraints of Lemma 3. This is tested by determining the minimum $j$-value of symbol $a_i$ that is greater than *low*. If that value is less than *high*, then $(i, j)$ is a minimal $k$-candidate. [illegible]

Steps 7 and 8 are done in constant time. Total time is $O(pm)$. Step 9 is done in constant time. Total time is $O(p)$. Step 10 is done in time $O(m)$. Total execution time is thus as stated above. □

Note that for $p \geq O(\log s)$, *ALGD* requires time $O(pn)$.

### *pe log n Algorithm*

We now consider a special case that often occurs in applications such as determining the discrepancies between two files, one of which was obtained by making minor alterations to the other (and we wish to recover those alterations). We assume that there is an LCS of length at least $m - \epsilon$ (for some given $\epsilon$).

If $C$ is an LCS of $A$ and $B$, there will be at most $\epsilon$ elements of $A$ that do not appear in $C$. The position of each such element will be called a *skipped position*. Thus there are at most $\epsilon$ skipped positions. We define $e$ to be $\epsilon + 1$.

If $\langle i, j\rangle$ is a minimal $k$-candidate that can be an element in an LCS (that is, $a_i = b_j$ is the $k$th element of an LCS), then $k \leq i \leq k + \epsilon$ (otherwise more than $\epsilon$ positions in $A$ would be skipped). We shall call such candidates *feasible k-candidates*. Let $h = i - k$. Then $0 \leq h \leq \epsilon$ and $h$ is the number of positions in $A$ that have been skipped thus far (through $a_{k+h}$). By Lemma 2, there is at most one feasible $k$-candidate with $i$-value of $i$.

Let the feasible $k$-candidate pairs ($i$-value and $j$-value) be held in arrays $F$ and $G$, e.g. $\langle h + k, j\rangle$ would be described by $F[h] = h + k$, $G[h] = j$. If there is no feasible $k$-candidate with $i$-value $h + k$, let $F[h] = F[h - 1]$, $G[h] = G[h - 1]$, and define $F[-1] = 0$, $G[-1] = n + 1$ By this construction and by Lemma 2, $F$ is a nondecreasing sequence and $G$ is a nonincreasing sequence.

Define $NEXTB(\theta, j)$ to be the minimum $r > j$ such that $b_r = \theta$. If there is no such $r$, then $NEXTB(\theta, j)$ is defined to be $n + 1$.

LEMMA 6. *If $\langle i, j\rangle$ is a feasible k-candidate, then $j = NEXTB(a_i, G[h])$, where $h = i - k$ and where $G[h]$ is the value associated with the set of feasible $(k - 1)$-candidates.*

PROOF. Let $\langle i, j\rangle$ be a feasible $k$-candidate. By definition of $k$-candidate, there must exist $i' < i$ and $j' < j$ such that $\langle i', j'\rangle$ is a feasible $(k - 1)$-candidate. By Lemma 3, $j$ is the minimum (over possible $j'$) of $NEXTB(a_i, j')$. But $j'' < j'$ implies that $NEXTB(\theta, j'') \leq NEXTB(\theta, j')$. Therefore $j = NEXTB(a_i$, min possible $j')$. Since $j$-values of minimal $k$-candidates decrease as their $i$-values increase, the minimum possible $j'$ is the $j$-value of the feasible $(k - 1)$-candidate whose $i$-value is as large as possible but less than $i = h + k$, i.e. not more than $h + (k - 1)$. $G[h]$ is precisely that $j$-value. So we conclude that $j = NEXTB(a_i, G[h])$. □

In order to be able to recover an LCS, we shall keep track (for each feasible $k$-candidate) of which $h$ positions in $A$ have been skipped. A straightforward method, keeping values of $F[h]$ for all $h$ and $k$, requires space of $O(pc)$. We shall use a data structure that requires only $O(e^2 + n)$ space without changing the order of magnitude of time requirements.

Let there be an array *KEEP* whose elements are triples such that

$$KEEP[x] = \langle aa[x], nskip[x], pt[x]\rangle.$$

$P$ is an array of size $e$ such that, after the set of feasible $k$-candidates has been determined, $x = P[h]$ will be the index of the element of *KEEP* that has information enabling recovery of a common subsequence that has $a_{F[h]} = b_{G[h]}$ as its $k$th element. $F[h] = h + k$, and thus precisely $h$ of the elements $a_1, \ldots, a_{F[h]}$ will not appear in the common subsequence. To recover the common subsequence, it is sufficient to recover these $h$ skipped positions. If $x = 0$, then no positions were skipped, and if $x < 0$, then there is no common subsequence to be recovered.

The method of recovery is as follows:

If $x$ is zero, there are no more skipped positions to be recovered.

**Otherwise, $aa[x]$ is the largest index of a skipped position in string $A$. $nskip[x]$ is the number of consecutive positions ending in $aa[x]$, all of which are skipped positions.**

If all of the skipped $A$-positions have been recovered, then $pt[x]$ is zero.

Otherwise, $pt[x]$ is the index of $KEEP$ that has information enabling recovery of the skipped $A$-positions having indices smaller than $aa[x] - nskip[x] + 1$.

*Example.* If positions 2, 5, 6, 7, 9, 10 in string $A$ correspond to a common subsequence of length 6 (of $A_{1,10}$), then $h = 4$ and $KEEP[P[4]]$ will enable recovery of positions 1, 3, 4, 8: $aa[P[4]] = 8$, $nskip[P[4]] = 1$, $pt[P[4]] = y$ (another index of $KEEP$). $aa[y] = 4$, $nskip[y] = 2$ (positions 3 and 4 have been skipped), $pt[y] = z$. $aa[z] = 1$, $nskip[z] = 1$, $pt[z] = 0$ (all skipped positions have been recovered).

Reference counts are kept for each element of $KEEP$. Spaces in the $KEEP$ array are maintained by garbage collection functions $GETSPACE$ which provides an available space and $PUTSPACE$ which places a newly available space (i.e. one whose reference count drops to zero) on the garbage linked list. See [10] for implementation techniques.

We now present $ALGE$, which uses Lemma 6 in order to solve the LCS problem in time $O(pe \log n)$:

```
ALGE (m, n, A, B, C, p, ε)
 1. F[h], G[h] ← 0 for h = 0, ... , ε
    P[0] ← 0; P[h] ← −1 for h = 1, ... , ε
 2. for k ← 1 step 1 while there were candidates found in the last pass do
    begin
 3.   imax ← 0
      jmin ← n + 1
 4.   for h ← 0 step 1 until ε do
      begin
 5.     i ← h + k
        j ← NEXTB(a_i, G[h])
        if j ≥ jmin
 6.     then begin
          F[h] ← imax
          G[h] ← jmin
          NEWP[h] ← −1
        end
 7.     else begin
          nskip ← (i − 1) − F[h]
          if nskip = 0
          then NEWP[h] ← P[h]
          else begin
            NEWP[h] ← GETSPACE
            KEEP[NEWP[h]] ← (i − 1, nskip, P[h − nskip])
          end
 8.       imax ← i
          jmin ← j
          F[h] ← i
          G[h] ← j
        end
 9.   end loop of step 4
10.   if no k-candidates were found then goto step 13
      for i ← 0 step 1 until ε do
      begin
11.     REMOVE(P[i])
        P[i] ← NEWP[i]
      end loop of step 10
12. end loop of step 2
13. x ← min h such that P[h] ≥ 0, −1 if none such
    p ← k − 1
    if x < 0 OR p < m − ε then {print "NO"; goto step 15}
14. RECOVER
15. END of ALGE
```

```
SUBROUTINE RECOVER
 1. SKIP[x + 1] ← 0
    lastmatch ← F[x]
    y ← P[x]
```

```
2. while y ≠ do
   begin
     count ← nskip[y]
     position ← aa[y]
3.   while count > 0 do
     begin
       SKIP[x] ← position
       x ← x − 1
       position ← position − 1
       count ← count − 1
     end loop of step 3
     y ← pt[y]
   end loop of step 2
4. x ← 1
   k ← 1
   for i ← 1 step 1 until lastmatch do
   if i = SKIP[x] then x ← x + 1
   else begin
     c_k ← a_i
     k ← k + 1
   end
5. END OF RECOVER
```

The loop of step 2 evaluates sets of feasible $k$-candidates for $k = 1, 2, \ldots$ . The loop of step 4 evaluates whether there is a feasible $k$-candidate having precisely $h$ skipped positions, for $h = 0, 1, \ldots, \epsilon$, by using Lemma 6 to determine the $j$-value for a particular $i$-value and then checking, by using Lemma 2, whether $\langle i, j \rangle$ is minimal. *imax* is the maximum $i$-value of feasible $k$-candidates generated thus far (i.e. with $i$-values less than the current value of $i$); *jmin* is the corresponding $j$-value (which is the minimum $j$-value of feasible $k$-candidates generated thus far). If $\langle i, j \rangle$ is a feasible $k$-candidate, then it is stored in the $F$ and $G$ arrays and information *will be* stored in $P[h]$, enabling recovery of any additional skipped positions that occur between $i$ and $F[h]$ as well as the skipped positions occurring before $F[h]$ ($\langle F[h], G[h] \rangle$ is a $(k-1)$-candidate that can generate $\langle i, j \rangle$). The $h$ skipped positions corresponding to $\langle F[h], G[h] \rangle$ are recoverable by accessing $KEEP[P[h]]$. In general there may be more than one feasible $k$-candidate that will be generated by $\langle F[h], G[h] \rangle$. Thus we must not destroy $P[h]$ until all required references to $KEEP[P[h]]$ are made. For this reason, new values for the $P$ array are stored in the *NEWP* array. When we no longer need the old values of $P$ (after the inner loop of steps 4–9), we can then replace them with the new values, being careful to decrement reference counts of *KEEP* elements that were pointed to by the old $P$ array.

Function *REMOVE*($x$) decrements the reference count of *KEEP*[$x$] (unless $x \le 0$, in which case nothing is done), and, if *KEEP*[$x$] now has reference count zero, then a call will be made to *REMOVE*(*pt*[$x$]) after *KEEP*[$x$] has been put on the garbage linked list by using *PUTSPACE*.

### *Implementation of NEXTB*

The following should be done before using *ALGE*:

```
1. Sort the symbols in A and then construct a balanced binary search tree of symbols that appear in string A.
   Let there be ss such symbols (ss ≤ m).
2. for k ← 1 step 1 until ss do LAST[k] ← 0
3. for i ← 1 step 1 until n do
   begin
     find out that b_i = θ_k
     j ← LAST[k]
     LAST[k] ← i
     if j ≠ 0 then NEXT[j] ← i
     else FIRST[k] ← i
   end loop of step 3
```

4. **start** ← 1
   **for** $k$ ← 1 **step** 1 **until** $ss$ **do**
   **begin**
   Place the positions $j$ of $B$ such that $b_j = \theta_k$ into $N[start]$ through $N[start + nn - 1]$ where $\theta_k$ occurs $nn$ times in string $B$. The first position in $B$ at which $\theta_k$ occurs is at $FIRST[k]$. If $\theta_k$ occurs at position $j$, then the next occurrence of $\theta_k$ in $B$ will be at position $NEXT[j]$ unless $LAST[k] = j$, in which case there are no more occurrences of $\theta_k$ in $B$.
   $S[k] \leftarrow start$
   $start \leftarrow start + nn$
   **end**

We can find out that $a_i = \theta_k$ in time $O(\log s)$. $N[S[1]:S[k + 1] - 1]$ holds the block of positions $j$ with $b_j = \theta_k$. This block of cells can be searched by using binary search of a linearly ordered array [11, Sec. 6.2.1]. $NEXT(a_i, j)$ can thus be executed in time $O(\log n)$.

If $s$ is very small, then the following alternate way of computing $NEXTB(\theta, j)$ may be preferred: Instead of constructing a compressed array in step 4, construct a $NEXTB$ matrix while in step 3. For each $i$, set $NEXTB[k, t] = i$ for $j \le t < i$. This will result in time and space complexity (of the setup) of $O(sn)$. The function $NEXTB(\theta, j)$ can be evaluated by determining that $\theta = \theta_k$ in time $O(\log S)$ and by doing a simple table look-up.

*ALGE* retains $k$-candidates, as did *ALGD*, except for those candidates that cannot lead to a sufficiently long common subsequence because too many $A$-positions have already been skipped. The $(k + 1)$-candidates that can be generated by the dropped $k$-candidates also skip too many $A$-positions.

LEMMA 7. *ALGE retains all feasible k-candidates.*

PROOF. By induction on $k$. It is trivially true for $k = 0$ (the $F$ and $G$ arrays are initialized to zero in step 1). Assume that the set of feasible $(k - 1)$-candidates has been evaluated and stored in arrays $F$ and $G$. *ALGE* generates the set of feasible $k$-candidates in order of increasing $i$-value. $F[h]$ is to hold $i = h + k$ if $i$ is an $i$-value of a feasible $k$-candidate; otherwise $F[h]$ is to hold the maximum $i' < i$ such that $i'$ is a feasible $k$-candidate. $G[h]$ is to hold the corresponding $j$-value. *imax* and *jmin* hold the last-generated feasible $k$-candidate, which, by Lemma 2, has the maximum $i$-value and minimum $j$-value generated thus far. Step 3 initializes them to correctly indicate that no $k$-candidates have yet been generated. Step 5 evaluates the $j$-value for a given potential $k$-candidate by using Lemma 6. If $j \ge jmin$ then, even though the necessary condition for feasibility has been met, $\langle i, j \rangle$ is not minimal since it would be ruled out by $\langle imax, jmin \rangle$. In this case step 6 sets $F[h]$ and $G[h]$ to *imax* and *jmin*. If $j < jmin$, then $\langle i, j \rangle$ is minimal since it cannot be ruled out by any previously generated $k$-candidate $(j < jmin)$ and it cannot be ruled out by any future generated $k$-candidate (all future $i' > i$). In this case step 8 sets $F[h]$ and $G[h]$ and also updates *imax* and *jmin*. □

THEOREM 3. *ALGE correctly computes the LCS of strings A and B if the LCS is of length at least $m - \epsilon$.*

PROOF. By Lemma 7, *ALGE* correctly keeps minimal $k$-candidates. Thus, if there is a common subsequence of length $p \ge m - \epsilon$, then there is a minimal $p$-candidate which will be feasible. The data structure of *ALGE* keeps track, for each feasible $k$-candidate $\langle i, j \rangle$, of the $h = i - k$ positions in string $A$ that have been skipped in the common subsequence of length $k$ of $A_{1i}$ and $B_{1j}$. $P[h]$ points to the element of *KEEP* that contains the necessary information. $P$ is updated in step 7 when a feasible $k$-candidate is generated. If any additional positions are skipped (between the $k$-candidate $\langle i, j \rangle$ and the $(k - 1)$-candidate $\langle i', j' \rangle$ that generated $\langle i, j \rangle$), then that information is recorded in an element of *KEEP* as well as a pointer, enabling recovery of the $h - nskip$ previously skipped $A$-positions (of $\langle i', j' \rangle$). Subroutine *RECOVER* recovers the skipped positions of a feasible $p$-candidate by reversing the process in which they were stored and then computes the LCS by deleting the skipped positions from string $A$. □

THEOREM 4. *For $\epsilon \le O(n^{1/2})$, ALGE requires space linear in n.*

PROOF. The *KEEP* array requires $O(\epsilon^2)$ space: The common subsequence implied by $k$-candidate $\langle h + k, j \rangle$ has $h$ skipped $A$-positions, $h \leq \epsilon$, and thus can use at most $h$ spaces in the *KEEP* array. The total number of spaces referred to by all feasible $k$-candidates is thus at most $\epsilon(\epsilon + 1)/2$. Adding to that the (exactly) $\epsilon$ references to get the set of feasible $(k + 1)$-candidates gives a total of no more than $(e^2 + e)/2$. Each element of array *KEEP* requires four words (*aa*, *nskip*, *pt*, and a reference counter).

The arrays and space that they use are as follows: $F[e]$, $G[e]$, $C[p]$, $P[e]$, $NEWP[e]$, $KEEP[2e^2 + 2e]$, $FIRST[ss]$, $NEXT[n]$, $LAST[ss]$, $SKIP[e]$, $S[ss]$, $N[n]$.

The *NEXTB* function requires at most $2n$ locations to store the various balanced binary search trees.

Thus a total of at most $2e^2 + 7e + 4n + p + 3ss$ locations is used. For $e \leq O(n^{1/2})$, space requirements are linear in $n$. □

THEOREM 5. *ALGE requires time $O(pe \log n)$.*

PROOF. Preprocessing for the *NEXTB* function requires time $O(n \log m)$. Step 1 takes time $O(e)$. Step 2 executes steps 3–12 $p$ times. Step 3 takes constant time for a total time of $O(p)$. Step 4 executes steps 5–9 at most $e$ times. Step 5 takes time $O(\log n)$ for a total time of $O(pe \log n)$. Steps 6–9 take constant time for a total time of $O(pe)$. Steps 10–12, excluding time spent in function *REMOVE*, take time $O(e)$ for a total time of $O(pe)$.

Subroutine *RECOVER* recovers at most $\epsilon$ skipped positions (taking time $O(e)$) and then deletes them from string $A$ (taking time $O(m)$) for a total time of $O(m)$.

The number of references (to array *KEEP*) removed is at most the number of references inserted. There are at most $pe$ references inserted (one per execution of step 7), and the amount of time (per reference removal) spent in function *REMOVE* is constant. Therefore the total time spent in function *REMOVE* is $O(pe)$.

Therefore the total time of execution of *ALGE* is $O(pe \log n)$. □

It is noted that step 5, requiring $O(\log n)$ time, is the bottleneck, causing total time requirements of $O(pe \log n)$. P. van Emde Boas's recent algorithm for priority queues [19] appears capable of solving the position-finding problem in time $O(\log \log n)$. If so, this would reduce the time bound of this problem to $O(pe \log \log n)$.

*ALGE* assumes that $\epsilon$ is known. If $\epsilon$ is not known, then set $\epsilon \leftarrow 2$ and proceed through the algorithm. If that value of $\epsilon$ is insufficient (i.e. there is no common subsequence of length $m - \epsilon$), then double the guess for $\epsilon$ and continue iteratively until a common subsequence is found.

Total time spent will be (letting $k$ be the multiplicative coefficient of the time requirement)

$$2pk \log n + 4pk \log n + \cdots + epk \log n,$$

which is less than $2pek \log n$. Since $e < 2(m + 1 - p)$, we can recover an LCS in time $O(p(m + 1 - p)\log n)$.

*Other Algorithms*

The only known algorithm for the LCS problem with worst-case behavior less than quadratic is due to Paterson [14]. The algorithm has complexity $O(n^2 \log \log n / \log n)$. It uses a "Four Russians" approach (see [3] or [1, pp. 244–247]). Essentially, instead of matrix $L$ (where $L[i, j]$ is the length of an LCS of $A_{1i}$ and $B_{1j}$) being calculated one element at a time (see [7]), the matrix is broken up into boxes of some appropriate size $k$. The *high* sides of a box (the $2k - 1$ elements of $L$ on the edges of the box with largest indices) are computed from $L$-values known for boxes adjacent to it on the *low* side and from the relevant symbols of $A$ and $B$ by using a look-up table which was precomputed.

The algorithm assumes a fixed alphabet size although modifications to the algorithm may be able to get around that condition.

There are $2k + 1$ elements of $L$ adjacent to a box on the *low* side. Two adjacent $L$-elements can differ by either zero or one. There are thus $2^{2k}$ possibilities in this respect. The $A$- and $B$-values range over an alphabet of size $s$ for each of $2k$ elements, yielding a multiplicative factor of $s^{2k}$, and the total number of boxes to be precomputed is therefore $2^{2k(1+\log s)}$. Each such box can be precomputed in time $O(k^2)$ for a total precomputing time of $O(k^2 2^{2k(1+\log s)})$.

There are $(n/k)^2$ boxes to be looked up, each of which will require $O(k \log k)$ time to be read, for a total time of $O(n^2 \log k/k)$.

The total execution time will therefore be $O(k^2 2^{2k(1+\log s)} + n^2 \log k/k)$. If we let $k = \log n/2(1 + \log s)$, we see that the total execution time will be $O(n^2 \log \log n/\log n)$.

*Restrictions on the LCS Problem*

Szymanski [17] shows that if we consider the LCS problem with the restriction that no symbol appears more than once within either input string, then this problem can be solved in time $O(n \log n)$.

In addition if one of the input strings is the string of integers $1 - n$, this problem is equivalent to finding the longest ascending subsequence in a string of distinct integers. If we assume that a comparison between integers can be done in unit time, this problem can be solved in time $O(n \log \log n)$ by using the techniques of van Emde Boas [18].

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Programming Techniques

G. Manacher, S.L. Graham Editors

# A Fast Algorithm for Computing Longest Common Subsequences

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**Previously published algorithms for finding the longest common subsequence of two sequences of length n have had a best-case running time of $O(n^2)$. An algorithm for this problem is presented which has a running time of $O((r + n) \log n)$, where r is the total number of ordered pairs of positions at which the two sequences match. Thus in the worst case the algorithm has a running time of $O(n^2 \log n)$. However, for those applications where most positions of one sequence match relatively few positions in the other sequence, a running time of $O(n \log n)$ can be expected.**

**Key Words and Phrases: Longest common subsequence, efficient algorithms**

**CR Categories: 3.73, 3.63, 5.25**



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## troduction

Many algorithms [1, 4, 6] for finding the longest ommon subsequence of two sequences of length $n$ ave appeared in the literature. These algorithms all ave a worst-case (as well as a best-case) running time f $O(n^2)$.[1]

A more relevant parameter for this problem is $r$, the otal number of matching pairs of positions within the quences in question. We shall present an $O((r+n)$ g $n)$ algorithm for the longest common subsequence roblem. In the worst case this is of course $O(n^2 \log n)$. owever, for a large number of applications, we can pect $r$ to be close to $n$. In these situations our al- orithm will exhibit an $O(n \log n)$ behavior. Typical of ch applications are the following:

1) Finding the longest ascending subsequence of a permutation of the integers from 1 to $n$ [3].
2) Finding a maximum cardinality linearly ordered subset of some finite collection of vectors in 2-space [7].
3) Finding the edit distance between two files in which the individual lines of the files are considered to be atomic. The longest common subsequence of these files, considered as sequences, represents that common "core" which does *not* have to be changed if we desire to edit one file into the other.

hus in the general case our algorithm will not take ch longer than the algorithms of [1, 4, 6], whereas in ny common applications, our algorithm will per- rm substantially better.

Let $A$ be a finite sequence of elements chosen from me alphabet. We denote the length of $A$ by $|A|$. $i]$ is the $i$th element of $A$ and $A[i:j]$ denotes the se- ence $A[i], A[i+1], \cdots, A[j]$.

If $U$ and $V$ are finite sequences, then $U$ is said to be a *bsequence* of $V$ if there exists a monotonically in- easing sequence of integers $r_1, r_2, \cdots, r_{|U|}$ such that $U[i] = V[r_i]$ for $1 \leq i \leq |U|$. $U$ is a *common subse- ence* of $A$ and $B$ if $U$ is a subsequence of both $A$ and . A *longest common subsequence* is a common subse- ence of greatest possible length.

Throughout this paper $A$ and $B$ will be used to note the sequences in question. For ease of presenta- n, we shall assume both sequences have the same gth which will be denoted by $n$. The number of ments in the set $\{(i, j)$ such that $A[i] = B[j]\}$ will denoted by $r$.

## minary Results

The key data structure needed by our algorithm is array of "threshhold values" $T_{i,k}$ defined by $T_{i,k} =$ smallest $j$ such that $A[1:i]$ and $B[1:j]$ contain a mmon subsequence of length $k$. For example, given uences $A = abcbdda$, $B = badbabd$ we have $T_{5,1} = 1$, $T_{5,2} = 3$, $T_{5,3} = 6$, $T_{5,4} = 7$, $T_{5,5} =$ undefined.

Each $T_{i,k}$ may thus be considered as a pointer which tells us how much of the $B$ sequence is needed to produce a common subsequence of length $k$ with the first $i$ elements of $A$.

Note that each row of the $T$ array is strictly increasing; that is,

LEMMA 1. *If* $T_{i,1}, T_{i,2}, \cdots, T_{i,p}$ *are defined, then* $T_{i,1} < T_{i,2} < \cdots < T_{i,p}$.

PROOF. Consider the common subsequence of length $k$ contained in $A[1:i]$ and $B[1:T_{i,k}]$. Clearly $B[T_{i,k}]$ is the last member of this common subsequence or else $T_{i,k}$ would not be minimal. Therefore $A[1:i]$ and $B[1:T_{i,k} - 1]$ contain a common subsequence of length $k - 1$, that is, $T_{i,k-1} \leq T_{i,k} - 1$. □

This linear ordering is of paramount importance in the efficient implementation of our algorithm.

Suppose that we have computed $T_{i,k}$ for all values of $k$ and wish to compute $T_{i+1,k}$ for all values of $k$. We first show $T_{i+1,k}$ must lie in a specific range of values.

LEMMA 2. $T_{i,k-1} < T_{i+1,k} \leq T_{i,k}$.

PROOF. If $A[1:i]$ and $B[1:T_{i,k}]$ have a common subsequence of length $k$, then certainly $A[1:i+1]$ and $B[1:T_{i,k}]$ do also. Thus $T_{i+1,k} \leq T_{i,k}$.

By definition, $A[1:i+1]$ and $B[1:T_{i+1,k}]$ have a common subsequence of length $k$. Deleting the last element from each of these sequences can remove at most one element from this common subsequence. thus $A[1:i]$ and $B[1:T_{i+1,k} - 1]$ have a common subsequence of length $k - 1$. Accordingly $T_{i,k-1} \leq T_{i+1,k} - 1$ and $T_{i,k-1} < T_{i+1,k}$. □

The following rule suffices to compute $T_{i+1,k}$ from $T_{i,k-1}$ and $T_{i,k}$.

LEMMA 3.

$$T_{i+1,k} = \begin{cases} \textit{smallest } j \textit{ such that } A[i+1] = B[i] \\ \qquad \textit{and } T_{i,k-1} < j \leq T_{i,k} \\ T_{i,k} \textit{ if no such } j \textit{ exists.} \end{cases}$$

PROOF.

*Case* 1. No such $j$ exists. By the minimality of $T_{i+1,k}$, any common subsequence of the sequences $A[1:i+1]$ and $B[1:T_{i+1,k}]$ must have $B[T_{i+1,k}]$ as its last element. Moreover, by Lemma 2 and the premise of this case, $B[T_{i+1,k}]$ does not match $A[i+1]$. Therefor the same common subsequence of length $k$ is also contained in $A[1:i]$ and $B[1:T_{i+1,k}]$. Thus $T_{i,k} \leq T_{i+1,k}$ and by Lemma 2, $T_{i,k}$ must equal $T_{i+1,k}$.

*Case* 2. There exists a minimal $j$ for which $A[i+1] = B[j]$ and $T_{i,k-1} < j \leq T_{i,k}$. Certainly $A[1:i+1]$ and $B[1:j]$ contain a common subsequence of length $k$, namely the length $k-1$ common subsequence of

[1] An unpublished result of Michael Paterson shows how to construct an $O(n^2/\log n)$ algorithm for the longest common subsequence problem for sequences over a finite alphabet, and an $O((n^2 \log \log n)/\log n)$ algorithm for sequences over an infinite ordered alphabet. All results of this paper apply to the case of the infinite ordered alphabet.

$A[1:i]$ and $B[T_{i,k-1}]$ with the pair $A[i+1]$, $B[j]$ "tacked" onto the end. Thus $T_{i+1,k} \le j$.

Assume temporarily that $T_{i+1,k} < j$. Since Lemma 2 guarantees that $T_{i,k-1} < T_{i+1,k}$ we can conclude that the last element of the length $k$ common subsequence of $A[1:i+1]$ and $B[1:T_{i+1,k}]$ does *not* match $A[i+1]$. Thus $A[1:i]$ and $B[1:T_{i+1,k}]$ also contain a common subsequence of length $k$ which implies that $T_{i,k} \le T_{i+1,k}$. By Lemma 2 then, $T_{i,k} = T_{i+1,k}$. However, by the above assumption and the premise of this case, $T_{i+1,k} < j \le T_{i,k}$, implying that $T_{i,k} \ne T_{i+1,k}$. This contradiction leads us to conclude that the original assumption of $T_{i+1,k} < j$ is incorrect and hence we must have $T_{i+1,k} = j$. □

We can now present an $O(n^2 \log n)$ algorithm for determining the length of the longest common subsequence. Subsequent refinements will enable us to not only improve the running time to $O((r + n) \log n)$ but also recover the actual longest common subsequence.

**Algorithm 1**

```
element array A[1:n], B[1:n];
integer array THRESH[0:n];
integer i, j, k;
THRESH[0] := 0;
for i := 1 step 1 until n do
  THRESH[i] := n + 1;
for i := 1 step 1 until n do
  for j := n step − 1 until 1 do
    if A[i] = B[j] then
      begin
        find k such that THRESH[k−1] < j ≤ THRESH[k];
        THRESH[k] := j;
      end;
print largest k such that THRESH[k] ≠ n + 1;
```

The correctness of the algorithm follows from consideration of the invariant relation "$THRESH[k] = T_{i-1,k}$ for all $k$" which holds at the start of each iteration on $i$, and the invariant relation "$THRESH[k] = T_{i,k}$ for all $k$" which holds at the end of each iteration on $i$.

Since the *THRESH* array is monotonically increasing (Lemma 1) we can utilize a binary search to implement the "find" operation in time $O(\log n)$. Thus Algorithm 1 may be implemented to run in $O(n^2 \log n)$ time.

Finally, notice that the direction of the loop on $j$ is crucial. Suppose that for some value of $i$, $A[i]$ matches several different $B$ elements in a given "threshold" interval, say $B[j_1], \cdots, B[j_m]$ with $THRESH[k-1] = T_{i-1,k-1} < j_1 < \cdots < j_m \le T_{i-1,k} = THRESH[k]$. From Lemma 3, we see that $T_{i,k} = j_1$ and that $THRESH[k]$ should be updated to this value. Since the inner loop of Algorithm 1 considers values of $j$ in decreasing order, each of the values $j_m, j_{m-1}, \cdots, j_1$ will cause $THRESH[k]$ to take on successively smaller values until it is set equal to the desired value of $j_1$. If instead the loop on $j$ ran upwards from 1 to $n$, then not only would $THRESH[k]$ be set to $j_1$, but $THRESH[k+1]$ would be set to $j_2$, $THRESH[k+2]$ would be set to $j_3$ and so forth. Since these latter assignments are unwarranted, we see that the loop on $j$ *must* run downwards.

**The Algorithm**

A small amount of preprocessing will vastly improve the performance of Algorithm 1. The main source of inefficiency in this algorithm is the inner loop on $j$ in which we repeatedly search for elements of the $B$ sequence which match $A[i]$. Linked list techniques obviate the need for this search.

For each position $i$ we need a list of corresponding $j$ positions such that $A[i] = B[j]$. These lists must be kept in decreasing order in $j$. All positions of the $A$ sequence which contain the same element may be set up to use the same physical list of matching $j$'s; for the sequences $A = abcbdda$, $B = badbabd$ the desired lists are

$$MATCHLIST[1] = \langle 5, 2 \rangle$$
$$MATCHLIST[2] = \langle 6, 4, 1 \rangle$$
$$MATCHLIST[3] = \langle\ \rangle$$
$$MATCHLIST[4] = MATCHLIST[2]$$
$$MATCHLIST[5] = \langle 7, 3 \rangle$$
$$MATCHLIST[6] = MATCHLIST[5]$$
$$MATCHLIST[7] = MATCHLIST[1].$$

We can now display our final algorithm.

**Algorithm 2**

```
element array A[1:n], B[1:n];
integer array THRESH[0:n];
list array MATCHLIST[1:n];
pointer array LINK[1:n];
pointer PTR;
comment Step 1: build linked lists;
for i := 1 step 1 until n do
  set MATCHLIST[i] := ⟨j1, j2, ···, jp⟩ such that
    j1 > j2 > ··· > jp and A[i] = B[jq] for 1 ≤ q ≤ p;
comment Step 2: initialize the THRESH array;
THRESH[0] := 0;
for i := 1 step 1 until n do
  THRESH[i] := n + 1;
LINK[0] := null;
comment Step 3: compute successive THRESH values;
for i := 1 step 1 until n do
  for j on MATCHLIST[i] do
    begin
      find k such that THRESH[k−1] < j ≤ THRESH[k];
      if j < THRESH[k] then
        begin
          THRESH[k] := j;
          LINK[k] := newnode (i, j, LINK[k−1]);
        end;
    end;
comment Step 4: recover longest common subsequence in reverse
  order;
k := largest k such that THRESH[k] ≠ n + 1;
PTR := LINK[k];
while PTR ≠ null do
  begin
    print (i, j) pair pointed to by PTR;
    advance PTR;
  end;
```

The subroutine *newnode* invoked in step 3 is a subroutine which creates a list node whose fields contain the values of the arguments to *newnode*. These arguments are, respectively, an index of a position in the $A$ sequence, an index of a position in the $B$ sequence, and a pointer to some other list node. The value returned by *newnode* is a pointer to the list node just created.

THEOREM 1. *Algorithm 2 finds and prints a longest common subsequence of the sequences A and B in time* $O((r+n)\log n)$ *and space* $O(r+n)$.

PROOF. Step 1 can be implemented by sorting each sequence while keeping track of each element's original position. We may then merge the sorted sequences creating the *MATCHLIST*s as we go. This step takes a total of $O(n \log n)$ time and $O(n)$ space.

Step 2 clearly takes $O(n)$ time.

The two outer loops of step 3 should be considered as a single loop over all pairs $(i, j)$ such that $A[i] = B[j]$ taken in order of decreasing $j$ within increasing $i$. In other words, the outer loops of step 3 induce exactly $r$ executions of the innermost statements of step 3. Since these innermost statements involve one binary search plus a few operations which require constant time, we conclude that the time requirement for step 3 is $O(n + r \log n)$.

In this step we also implement a simple backtracking device that will allow us to recover the longest common subsequence. We record each $(i, j)$ pair which causes an element of the *THRESH* array to change value. Thus whenever *THRESH*$[k]$ is defined, *LINK*$[k]$ points to the head of a list of $(i, j)$ pairs describing a common subsequence of length $k$. Since at most one list node is created per search, Step 3 will require the allocation of at most $O(r)$ list nodes.

In step 4 we recover the actual longest common subsequence. Clearly this takes at most $O(n)$ time. □

We note that certain input sequences such as $A$ = "*aabaabaab*..." and $B$ = "*ababab*..." cause Algorithm 2 to use $O(r)$ space even if list nodes are reclaimed whenever they become inaccessible. See [4] for an algorithm which never uses more than $O(n)$ space nor less than $O(n^2)$ time.

## A Final Note

The key operations in the implementation of our algorithm are the operations of inserting, deleting, and testing membership of elements in a set where all elements are restricted to the first $n$ integers. Peter van Emde Boas has shown that each such operation can be performed in $O(\log \log n)$ time [2]. His data stucture requires $O(n \log \log n)$ time for initialization. Although the necessary algorithms are quite complex, we can use them to present the following theoretical result.

THEOREM 2. (a) *Algorithm 2 can be implemented to have a running time of* $O(r \log \log n + n \log n)$ *over an infinite alphabet.* (b) *Algorithm 2 can be implemented to have a running time of* $O((n + r) \log \log n)$ *over a fixed finite alphabet.* (c) *The longest ascending subsequence of a permutation of the first n integers may be found in* $O(n \log \log n)$ *time.*

PROOF. The problem of part (c) is, of course, equivalent to finding the longest common subsequence of the given permutation and the sequence $1, 2, \cdots, n$. All three parts of the theorem use basically the same algorithm although the implementation of some of the steps varies slightly. We shall present a common analysis.

In all three cases we require $O(n \log \log n)$ time to initialize van Emde Boas's data structures. Step 1 entails a sorting procedure to set up the *MATCHLIST*s. For the infinite alphabet case, this sort can be done in $O(n \log n)$ time. In the other two cases, we can use a distribution sort to create the *MATCHLIST*s in $O(n)$ time. Step 2 takes $O(n)$ time, step 3 takes $O(n + r \log \log n)$ time and step 4 takes $O(n)$ time. Finally, for the permutation case note that each integer appears exactly once in each sequence and thus we have $r = n$. □

*Acknowledgments*. The authors are indebted to M. Douglas McIlroy who first suggested this problem to us. Harold Stone suggested a variant of the problem (described and solved in [5]) which led to the development of the present algorithm. Alfred V. Aho and Jeffrey D. Ullman provided us with several enlightening conversations including the particular example given following Theorem 1 which shows that our algorithm can require as much as $O(r)$ space. Peter van Emde Boas made several helpful comments on an early draft of this paper.

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# File Comparison Algorithms

by Tom Steppe

***Determining which files are more equal than others***

Several popular algorithms exist for comparing two files. All of these actually look first for matches rather than differences. After the matching process has been completed, the remainders of the files that are not included in the matches are then reported as differences. (See Figure 1, page 29.)

The algorithms differ greatly in their conceptualization of the problem, however. In this article, I examine several algorithms for comparing text files—specifically, source code files—using a line as the basic unit of comparison. The ideas and algorithms I present here, however, can be extended to other types of files and other units of comparison as well. I also present a new algorithm with some interesting properties.

### *Evaluating The Algorithms*

Any file comparison algorithm should be evaluated according to several criteria:

- Is it efficient? Time efficiency (speed) and space efficiency (memory usage) are both practical considerations. Usually they are related to the lengths of the files being compared.
- Is it robust? No algorithm is flawless. For any given file comparison algorithm, it is always possible to concoct devious situations in which its performance appears less than perfect. The algorithm should, however, be able to produce reasonable difference reports for a variety of test cases.
- Can it let differences go undetected? No algorithm should allow a file difference to go undetected.
- Can it let matches go undetected? If an algorithm can overlook matching lines, it will report these lines as differences when they are not. If the file comparison is being performed to produce a delta file, this usually is not a major problem, even though each undetected match does increase the size of the delta file unnecessarily. If the differences are to be inspected visually, however, a report of false differences can be a serious drawback.

Say, for example, that you do not have a file comparison utility and so you have to compare two files by eye. This process is certainly tedious and prone to error, especially if some of the differences are subtle. If you now use a file comparison utility that is known to report false differences, you have to inspect the output by eye and decide which reported differences are true differences. The utility has not really done the job for you, it has only made your "by eye" inspection a smaller job that is still prone to error.

- Can it detect blocks of text that have been moved? Typically, if a block of text has been moved, it simply shows up in the report of differences as a large deletion of text at one location and a large insertion of text at another. Unfortunately, no differences within the moved block are highlighted.

When a file comparison is used to create a delta file, the ability to detect moved blocks of text is probably desirable because it can lead to smaller delta files. But, when a file comparison is performed so that the differences can be inspected visually, the ability to detect moved blocks is not always as handy as it might seem to be. Trying to report the moved blocks is often difficult and can lead to complicated reports of the differences, especially when a large block of text is moved, a piece of that block is moved to another location, a piece of that piece is moved to still another location, and so on. Also, the difference report can sometimes be overburdened by uninteresting reports of small blocks (one-line and two-line blocks of text) being moved all over the place.

Only one algorithm discussed here can inherently detect moved blocks of text. The other algorithms, however, can be extended to do so, as follows. After applying the algorithm, replace each matching line in each file with a line that is guaranteed never to match. This leaves only the differences, which could contain moved blocks of text. Next, reapply the algorithm to the transformed files. Any match that is found in this pass will represent a moved block of text (see Figure 2, page 29). Continue this process iteratively until no new matches can be found. Of course, the cost of this iterative behavior is longer execution time.

These criteria help to provide a useful basis for surveying popular file comparison algorithms.

### *Popular Algorithms for Finding Matches*

#### Scan Until Next Match

The "scan until next matching se-

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quence" algorithm is probably the oldest method of file comparison. This algorithm starts at the tops of both files and matches as many lines as possible. When a difference is detected, the next M lines are scanned until at least N consecutive matching lines are found. If a sequence of N or more consecutive matching lines is found, the process begins again after the matching sequence. If such a sequence is not found, the process begins again M lines further down in the files. This process is repeated until the ends of the files are reached.

The values of M and N can be adjusted to affect the algorithm's performance. The value of M is used to control efficiency by restricting the number of lines that will be examined while searching for a sequence of matching lines. When an improper sequence of matching lines is discovered, the algorithm can be reapplied using a new value for N that is larger than the length of the improper sequence. In this way, the algorithm will overlook the undesirable sequence because it contains fewer than N matching lines, but as is always the case, the algorithm will also overlook any legitimate matching sequences that contain fewer than N lines (see Figure 3, page 30). Unfortunately, these matching lines are then reported as differences. All too often, this algorithm produces bad reports in common situations.

Although this algorithm is often highly time efficient, requires minimal memory, and frequently produces good difference reports, it does not take long to become frustrated with its shortcomings and inherent problems and begin looking for a better solution.

**Longest Common Subsequence**
Think of a file as representing a sequence of lines. A subsequence of those lines is defined simply as any sequence of lines that results from removing zero or more lines from the original sequence— for example, the longest subsequence of any sequence of lines is the sequence itself, with zero lines removed. Also, a sequence of zero lines would be a subsequence of any sequence because it could be created by removing all the lines from any sequence.

The "longest common subsequence" approach to file comparison takes the two files to be compared and finds the longest sequence of lines that is a subsequence of each of the files' lines—the longest common subsequence (see Figure 4, page 30). The details of the algorithm are not discussed here, but sources of such discussions are included in the bibliography. The Unix diff command is based on this algorithm.

This algorithm provides a simple, compact formalization of the file comparison problem and produces reasonable difference reports in a variety of test cases. The reports are quite acceptable whether the comparison is being used for visual inspection of the differences or for creating a delta file. In fact, among all the algorithms discussed here, it is probably safe to say that this one con-

```
file1   file2
  A       A
  B       BB
  C       C
  D       E
  E       F

Difference report:
  #####00001######################file1
  #     2  B
  #  ----------------------------changed to
  #     2  BB
  #####00001######################file2

  #####00001######################file1
  #     4  D
  #  ------------------------------------
  #  deleted
  #####00001######################file2

  #####00001######################file1
  #  inserted
  #  ------------------------------------
  #     5  F
  #####00001######################file2
```

*Figure 1: File comparison algorithms actually look first for line matches and then report lines that are not included in the matches as differences. The differences are usually expressed as the changes, insertions, and deletions that can be applied to one file to make it identical to the other.*

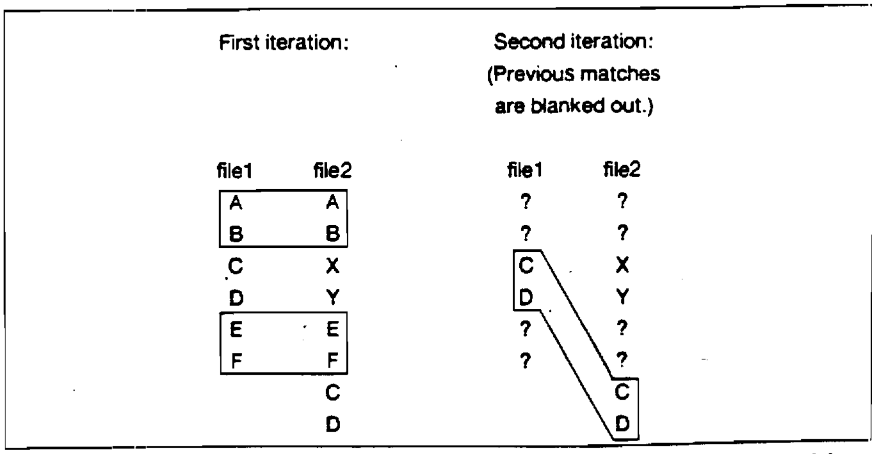


*Figure 2: Moved blocks of text can be found by applying a standard line-matching algorithm to the files and then reapplying the algorithm iteratively to the remainders of both files.*

*(continued from page 29)*

sistently produces the best reports when comparing files that do not involve blocks of text that have been moved.

Sometimes the quality of the reports can be overshadowed by issues of time and space efficiency. This is not always true, but situations that include a poor combination of large files and limited computer resources can lead to less than desirable performance by this algorithm. A basic implementation of the algorithm requires linear space and quadratic time. In some cases, the quadratic time can prove to be unacceptable. In summary, the "longest common subsequence" algorithm produces excellent reports, but it can be slow.

**Extended Unique Line Matching**

The "extended unique line matching" algorithm is based on the idea that a line that occurs once and only once in each file must be the same line. These pairs of "unique" lines determine the initial set of matched lines. (Imaginary lines at the tops and the bottoms of the files are also added to the set of matched lines.) Then, in each file, the lines adjacent to each match are examined and, if identical, are added to the set of matched lines. This process is repeated until no new matches can be found.

This algorithm has strong intuitive appeal. It is efficient, being linear in both time and space. Also, it is the only popular algorithm that inherently detects blocks of text that have been moved (even if some differences exist within the blocks). Moved blocks can be detected because the search for pairs of unique lines is in no way sequential and, therefore, can result in matches that indicate that a block of text has been moved. Note that the algorithm can find a moved block of text only if it contains a unique line match within it.

A significant problem with this algorithm is that it is prone to allowing some matches to go undetected. This occurs when matching lines are not neatly flanked by either unique line matches or the adjacent matches that have grown outward from unique line matches (see Figure 5, below).

This algorithm is fast and can frequently detect moved blocks of text, but a sacrifice is often made in the quality of the difference report. Probably its best application is in the generation of delta files when speed is the primary concern.

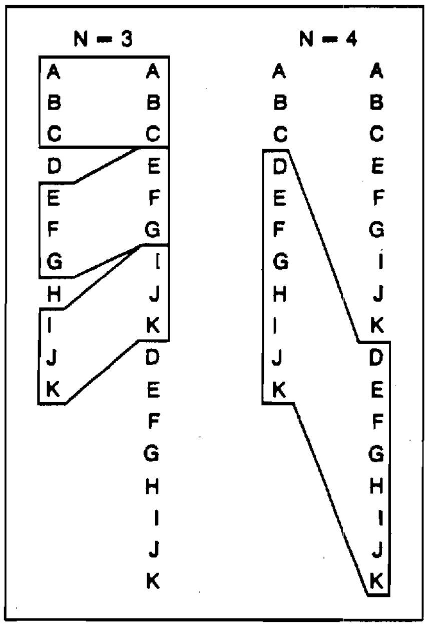


***Figure 3:*** *The "scan until next matching sequence" algorithm often produces bad reports in common situations. When N=3, the algorithm settles for matches of three lines, never realizing that a match of eight lines is possible. When N=4, it discovers the match of eight lines but does not detect the remaining match of three lines (A, B, C).*

***A New Algorithm***

The "recursive longest matching sequence" algorithm uses a simple yet effective approach to the problem. This method first scans both files from beginning to end, looking for the longest sequence of consecutive matching lines. That sequence is then thought of as dividing each of the two files into an upper section and a lower section. Then, the algorithm proceeds by scanning both upper sections looking for the longest sequence of consecutive matching lines and, similarly, both lower sections for the same. These matching sequences then divide their respective sections, and the process continues recursively until no more matches can be found.

This method of file comparison is easy to understand and produces acceptable difference reports across a spectrum of test cases. It uses linear space but quadratic time. Because time efficiency can be a problem in some situations, a simple modification of the algorithm is needed. An explanation of the modification requires an understanding of the method used to locate the longest sequence of matching lines between sections of two files.

First of all, once the longest sequence is known, it can be identified by a pair of starting lines—one line from each file that specifies where the sequence begins in that file. So, when searching for the longest sequence, candidate pairs of starting lines are examined successively (in some intelligent order that starts at the beginnings of both file sections), and information is continually maintained about the length and location of the longest sequence of matching lines that has been discovered so far.

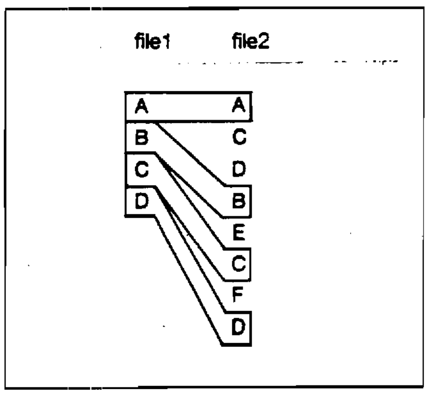


***Figure 4:*** *The "longest common sequence" algorithm finds the longest (not necessarily consecutive) sequence of lines that is contained in both files.*

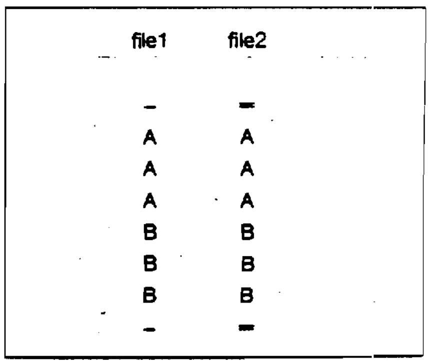


***Figure 5:*** *The "extended unique line matching" algorithm is prone to detecting false differences. In this case, no matches are found (because there are no unique line matches) and all lines are reported as differences.*

*(continued from page 30)*

When the ends of the file sections are reached, the longest sequence is known and information about the sequence is reported.

The modification to this algorithm allows the searching to stop if a sequence of N matching lines is found, realizing that it might not be the longest sequence that would be discovered if the searching were allowed to continue to the ends of the sections. This allows the searching to end prematurely (before the longest sequence has been assured) and can save considerable time. N is called the "long-enough" value. The effects of the long-enough value can be examined by choosing some test pairs of files and comparing the behavior of the algorithm when a long-enough value is used and when one is not used. Quite often, the use of a reasonable long-enough value will find exactly the same sequences of matching lines (although the discoveries may occur in a different order), thus producing an identical report of the differences but with a significant improvement in speed (see Figure 6, page 32). In fact, the use of a reasonable long-enough value allows this algorithm to perform in essentially linear time for typical cases, overcoming the previous worry of time efficiency.

The long-enough value is a parameter that you can specify. To determine a good value for your purposes, first guess at the length of the longest

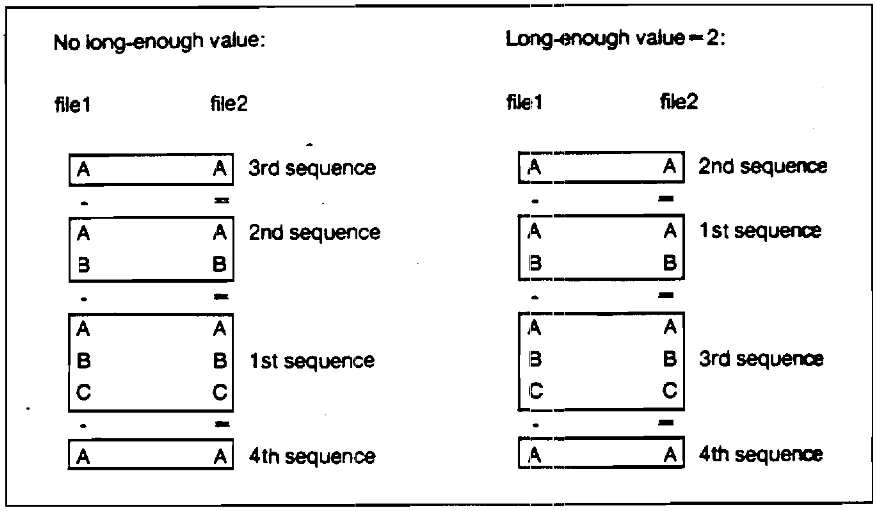


***Figure 6:** With the "recursive longest matching sequence" algorithm, the use of a long-enough value often finds exactly the same sequences of matching lines although the discoveries may occur in a different order.*

# Delta Files and User Reports

A file comparison utility is a versatile tool for a range of situations. It is useful to partition these situations into two distinct cases.

In the most common case, a file comparison is performed so that the differences between two versions of a text file can be inspected visually. The differences are usually expressed as the changes, insertions, and deletions that can be applied to one file to make it identical to the other file. In this case, the primary job of the comparison is to produce a concise and readable report of the differences.

In the course of editing, a file comparison can be used in this way to highlight the differences between a previous version of a file and the current version. Valid modifications can be verified, and spurious edits can be detected. As another example, if a new version of a program is produced, a partial test of its integrity could include a file comparison of its output with the output from a previous version of the program that is known to be correct. If the two outputs compare favorably, the new program passes this integrity test. If they do not compare favorably, another file comparison can be used in the debugging process to highlight the changes between a version of a source code file that is known to work and the version that does not work.

In the second case, a file comparison is performed to generate a delta file—a file that contains a report of the differences between the two files. If the file comparison is thought of as comparing an old file with a new file, a backward delta file is designed so that it contains all the information necessary to recreate the old file, given the new file. A forward delta file is designed to be able to recreate the new file, given the old file. In either case, one of the original files can be eliminated without loss of information. If the delta file is smaller than the file it allows to be eliminated, this will result in a savings of disk space. The primary job of a file comparison in this case is to produce a compact delta file.

This use of a file comparison utility is particularly common in version control systems that maintain multiple historical versions of source code files. Only the current version of a source code file is saved, whereas a backward delta file is saved for each historical version. Any historical version can be recreated by applying the appropriate delta files to the current version of the file. The savings in disk space can be tremendous. (Alternatively, some version control systems save the first version of the file and the subsequent forward delta files.)

This usage is also common in telecommunications applications where a file at one or more remote sites has to be updated from a host. A forward delta file is created on the host by comparing the new file with the old file (a copy of the file that exists at the remote site). If the delta file is small, it is often more efficient to transmit the forward delta file and apply it to the old file than it is to transmit the new file in its entirety.

(continued from page 32)

sequence of lines you can imagine appearing more than once in a typical file. The long-enough value should be at least one larger than your guess. This will help the algorithm to avoid matching the wrong instance when a sequence of lines appears multiple times in a file. If a particular choice of long-enough value produces unsatisfactory difference reports, the algorithm can always be applied again with a larger value. When comparing C source code, I typically choose a generous value of 25, and I rarely have to rerun the comparison.

The "recursive longest matching sequence" algorithm is particularly well suited to take advantage of some common hash code technology as a means of improving time performance even more. In applications that involve repetitive string comparisons, it is often useful to calculate hash codes initially for all the strings. Then, the hash codes are compared instead of the strings themselves. The comparison of two hash code values is much quicker than is the comparison of two strings. If the hash codes are not equal, the strings cannot possibly be the same and need not be compared. If the hash codes are equal, only then must the strings be compared to prove or disprove their equality.

The performance benefits are even more dramatic when hash codes are used with the "recursive longest matching sequence" algorithm. When searching for the longest sequence of matching lines, strings do not have to be compared every time a pair of matching hash codes is found. Instead, strings only have to be compared once a sequence of matching hash codes is found that is longer than the longest sequence yet found.

The time efficiency can be improved even further if a hash code table is maintained for each file. The table should consist of an array that contains as many elements as there are possible hash code values. Each element of the array should consist of a linked list of line numbers for lines whose hash code values are equal to the array index. This table can easily be created by processing each line in the file, calculating its hash code value, and adding its line number to the proper linked list. Now, while searching for the longest sequence of matching lines by examining pairs of starting line numbers, the number of candidate pairs can be greatly reduced. For any given line in one file, only those lines in the other file that have the same hash code value (as can be easily determined from the file's hash code table) need to be considered.

A basic C implementation of the "recursive longest matching sequence" algorithm is shown in Listing One, page 54. Its simplicity, combined with a long-enough value modification and some clever use of hash codes, makes it a viable solution to the file comparison problem. It is suitable for both delta creation and visual inspection purposes.

### *Availability*

All the source code for articles in this issue is available on a single disk. To order, send $14.95 to *Dr. Dobb's Journal*, 501 Galveston Dr., Redwood City, CA 94063, or call (415) 366-3600, ext. 216. Please specify issue number and format (MS-DOS, Macintosh, Kaypro).

You can also purchase a full-featured executable version of this algorithm from Stepping Stone Software, P.O. Box 2887, Ann Arbor, MI 48106 for $30. The available format is MS-DOS 5¼-inch DSDD.

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DDJ

**(Listing begins on page 54.)**

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**Listing One** *(Text begins on page 28.)*

```
/*
** Copyright (c) 1987,  Tom Steppe.  All rights reserved.
**
** This module compares two arrays of lines (representing
** files) and reports the sequences of consecutive matching
** lines between them using the "recursive longest matching
** sequence" algorithm.  This is useful for implementing a
** file comparison utility.
**
** Compiler:  Microsoft (R) C Compiler  Version 4.00
*/

#include <stdio.h>
#include <ctype.h>
#include <string.h>
#include <malloc.h>

/* Boolean type and values. */
typedef int     BOOLEAN;
#define TRUE    1
#define FALSE   0

/* Minimum macro. */
#define min(x, y)    (((x) <= (y)) ? (x) : (y))

/* Value to indicate identical strings with strcmp. */
#define ALIKE   0

/* Result of hashing function for a line of text. */
typedef unsigned int   HASH;

/* Mask for number of bits in hash code.  (12 bits). */
#define MASK    (unsigned int) 0x0FFF

/* Number of possible hash codes. */
#define HASHSIZ    (MASK + 1)

/* Information about an entry in a hash table. */
typedef struct tblentry
{
    int    frst;    /* First line # with this hash code. */
    int    last;    /* Last line # with this hash code. */
} TBLENTRY;

/* Information about a line of text. */
typedef struct lineinf
{
    HASH   hash;     /* Hash code value. */
    int    nxtln;    /* Next line with same hash (or 0). */
} LINEINF;

/* Information about a file. */
typedef struct fileinf
{
    char       **txt;      /* Array of lines of text. */
    LINEINF    *line;      /* Array of line info structs. */
    TBLENTRY   *hashtbl;   /* Hash table. */
} FILEINF;

/* Function declarations. */
BOOLEAN filcmp      (char **, int, char **, int, int);
BOOLEAN get_inf     (char **, int, FILEINF *);
HASH    calc_hash   (char *);
void    fnd_seq     (FILEINF *, int, int,
                         FILEINF *, int, int, int);
BOOLEAN chk_hashes  (LINEINF *, LINEINF *, int);
int     cnt_matches (char **, char **, int);
void    rpt_seq     (int, int, int);

/************************************************************
** compare compares two arrays of lines and reports the
** sequences of consecutive matching lines.  The zeroth
```

```
** element of each array is unused so that the index into
** the array is identical to the associated line number.
**
** RETURNS:  TRUE if comparison succeeded.
**           FALSE if not enough memory.
***********************************************************/

BOOLEAN compare (a1, n1, a2, n2, lngval)

char   **a1;      /* (I) Array of lines of text in #1. */
int    n1;        /* (I) Number of lines in a1.
                         (Does not count 0th element.) */
char   **a2;      /* (I) Array of lines of text in #2. */
int    n2;        /* (I) Number of lines in a2.
                         (Does not count 0th element.) */
int    lngval;    /* (I) "Long enough" value. */
{
    FILEINF   f1;    /* File information for #1. */
    FILEINF   f2;    /* File information for #2. */
    BOOLEAN   rtn;   /* Return value. */

    /* Gather information for each file, then compare. */
    if (rtn =
        (get_inf (a1, n1, &f1) && get_inf (a2, n2, &f2)))
    {
        fnd_seq (&f1, 1, n1, &f2, 1, n2, lngval);
    }

    return (rtn);
}

/************************************************************
** get_inf calculates hash codes and builds a hash table.
**
** RETURNS:  TRUE if get_inf succeeded.
**           FALSE if not enough memory.
***********************************************************/

static BOOLEAN get_inf (a, n, f)

char      **a;    /* (I) Array of lines of text. */
int       n;      /* (I) Number of lines in a. */
FILEINF   *f;     /* (O) File information. */
{
    unsigned int   size;     /* Size of hash table. */
    register int   i;        /* Counter. */
    TBLENTRY       *entry;   /* Entry in hash table. */

    /* Assign the array of text. */
    f->txt = a;

    /* Allocate and initialize a hash table. */
    size = HASHSIZ * sizeof (TBLENTRY);
    if (f->hashtbl = (TBLENTRY *) malloc (size))
    {
        memset ((char *) f->hashtbl, '\0', size);
    }
    else
    {
        return (FALSE);
    }

    /* If there are any lines: */
    if (n > 0)
    {
        /* Allocate an array of line structures. */
        if (f->line = (LINEINF *)
                malloc ((n + 1) * sizeof (LINEINF *)))
        {
            /* Loop through the lines. */
            for (i = 1; i <= n; i++)
            {
```

*(continued on next page)*

**Listing One** *(Listing continued, text begins on page 28.)*

```
                /* Calculate the hash code value. */
                f->line[i].hash = calc_hash (f->txt[i]);

                /* Locate the entry in the hash table. */
                entry = f->hashtbl + f->line[i].hash;

                /* Update the linked list of lines with */
                /* the same hash code.                  */
                f->line[entry->last].nxtln = i;
                f->line[i].nxtln = 0;

                /* Update the first and last line */
                /* information in the hash table. */
                if (entry->frst == 0)
                {
                    entry->frst = i;
                }
                entry->last = i;
            }
        }
        else
        {
            return (FALSE);
        }
    }
    else
    {
       f->line = NULL;
    }

    return (TRUE);
}

/*************************************************************
** calc_hash calculates a hash code for a line of text.
**
** RETURNS:  a hash code value.
*************************************************************/

static HASH calc_hash (buf)

char    *buf;    /* (I) Line of text. */
{
    register unsigned int   chksum;    /* Checksum. */
    char                    *s;        /* Pointer. */
    HASH                    hash;      /* Hash code value. */

    /* Build up a checksum of the characters in the text. */
    for (chksum = 0, s = buf; *s; chksum ^= *s++)
    {
        ;
    }

    /* Combine the 7-bit checksum and as much of the */
    /* length as is possible.                        */
    hash = ((chksum & 0x7F) | ((s - buf) << 7)) & MASK;

    return (hash);
}
/*************************************************************
** Given starting and ending line numbers, fnd_seq finds a
** "good sequence" of lines within those ranges.  fnd_seq
** then recursively finds "good sequences" in the sections
** of lines above the "good sequence" and below it.
*************************************************************/

static void fnd_seq (f1, beg1, end1, f2, beg2, end2, lngval)

FILEINF   *f1;      /* (I) File information for #1. */
int       beg1;     /* (I) First line # to compare in #1. */
int       end1;     /* (I) Last line # to compare in #1. */
```

```
FILEINF   *f2;       /* (I) File information for #2. */
int       beg2;      /* (I) First line # to compare in #2. */
int       end2;      /* (I) Last line # to compare in #2. */
int       lngval;    /* (I) "Long enough" value. */
{
    LINEINF       *line1;    /* Line information ptr in #1. */
    LINEINF       *line2;    /* Line information ptr in #2. */
    register int limit;     /* Looping limit. */
    int           ln1;       /* Line number in #1. */
    int           ln2;       /* Line number in #2. */
    register int ln;        /* Working line number. */
    BOOLEAN       go;        /* Continue to loop? */
    int           most;      /* Longest possible seq. */
    int           most1;     /* Longest possible due to #1. */
    int           most2;     /* Longest possible due to #2. */
    int           cnt;       /* Length of longest seq. */
    int           oldcnt;    /* Length of prev longest seq. */
    int           n;         /* Length of cur longest seq. */
    int           m1;        /* Line of longest seq. in #1. */
    int           m2;        /* Line of longest seq. in #2. */

    /* Initialize. */
    go    = TRUE;
    line1 = f1->line;
    line2 = f2->line;

    /* Initialize longest sequence information. */
    cnt    = 0;          /* Length of longest seq. */
    m1     = beg1 - 1;   /* Line # of longest seq. in #1. */
    m2     = beg2 - 1;   /* Line # of longest seq. in #2. */
    oldcnt = 0;          /* Length of prev longest seq. */

    /* Calculate maximum possible number of consecutive */
    /* lines that can match (based on line # ranges).   */
    most1 = end1 - beg1 + 1;
    most2 = end2 - beg2 + 1;

    /* Scan lines looking for a "good sequence".
    ** Compare lines in the following order of line numbers:
    **
    **                (1, 1)
    **         (1, 2), (2, 1), (2, 2)
    ** (1, 3), (2, 3), (3, 1), (3, 2), (3, 3)
    ** etc.
    */
    for (ln1 = beg1, ln2 = beg2; TRUE; ln1++, ln2++)
    {
        if (ln2 <= end2 - cnt)
        /* There are enough lines left in #2 such that it */
        /* is possible to find a longer sequence.         */
        {
            /* Determine the limit in #1 that both       */
            /* enforces the order scheme and still makes */
            /* it possible to find a longer sequence.    */
            limit = min (ln1 - 1, end1 --cnt);

            /* Calculate first potential match in #1. */
            for (ln = f1->hashtbl[line2[ln2].hash].frst;
                    ln && ln < beg1; ln = line1[ln].nxtln)
            {
                ;
            }

            /* Loop through the lines in #1. */
            for (; ln && ln <= limit; ln = line1[ln].nxtln)
            {
                if (line1[ln].hash == line2[ln2].hash &&
                        line1[ln + cnt].hash ==
                            line2[ln2 + cnt].hash &&
                        !(ln - m1 == ln2 - m2 &&
                        ln < m1 + cnt && m1 != beg1 - 1))
                /* A candidate for a longer sequence has */
```

*(continued on next page)*

**Listing One** *(Listing continued, text begins on page 28.)*

```
        /* been located.  The current lines      */
        /* match, the current lines + cnt match, */
        /* and this sequence is not a subset of  */
        /* the longest sequence so far.          */
        {
            /* Calculate most possible matches. */
            most = min (end1 - ln + 1, most2);

            /* First compare hash codes.  If the  */
            /* number of matches exceeds the      */
            /* longest sequence so far, then      */
            /* compare the actual text.           */
            if (chk_hashes (line1 + ln,
                        line2 + ln2, cnt) &&
                    (n = cnt_matches (f1->txt + ln,
                        f2->txt + ln2, most)) > cnt)
            /* This is the longest seq. so far. */
            {
                /* Update longest sequence info. */
                oldcnt = cnt;
                cnt    = n;
                m1     = ln;
                m2     = ln2;

                /* If it's long enough, end the */
                /* search.                      */
                if (cnt >= lngval)
                {
                    break;
                }

                /* Update limit, using new count. */
                limit = min (ln1 - 1, end1 - cnt);
            }
        }
    }

    /* If it's long enough, end the search. */
    if (cnt >= lngval)
    {
        break;
    }
    most2--;
}
else
{
    go = FALSE;   /* This file is exhausted. */
}

/* Repeat the process for the other file. */
if (ln1 <= end1 - cnt)
{
    limit = min (ln2, end2 - cnt);

    for (ln = f2->hashtbl[line1[ln1].hash].frst;
            ln && ln < beg2; ln = line2[ln].nxtln)
    {
       ;
    }

    for (; ln && ln <= limit; ln = line2[ln].nxtln)
    {
        if (line1[ln1].hash == line2[ln].hash &&
                line1[ln1 + cnt].hash ==
                    line2[ln+ cnt].hash &&
                !(ln1 - m1 == ln - m2 &&
                ln1 < m1 + cnt && m2 != beg2 - 1))
        {
            most = min (end2 - ln + 1, most1);

            if (chk_hashes (line1 + ln1,
                        line2 + ln, cnt) &&
```

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```
                        (n = cnt_matches (f1->txt + ln1,
                           f2->txt + ln, most)) > cnt)
                    {
                        oldcnt = cnt;
                        cnt    = n;
                        m1     = ln1;
                        m2     = ln;

                        if (cnt >= lngval)
                        {
                            break;
                        }

                        limit = min (ln2, end2 - cnt);
                    }
                }
            }

            if (cnt >= lngval)
            {
                break;
            }
            most1--;
        }
        else if (!go)
        {
            break;   /* This file is exhausted, also. */
        }
    }

    /* If the longest sequence is shorter than the "long */
    /* enough" value, the "long enough" value can be     */
    /* adjusted for the rest of the comparison process.  */
    if (cnt < lngval)
    {
        lngval = cnt;
    }

    if (cnt >= 1)
    /* Longest sequence exceeds minimum necessary size. */
    {
        if (m1 != beg1 && m2 != beg2 && oldcnt > 0)
        /* There is still something worth comparing */
        /* previous to the sequence.                */
        {
            /* Use knowledge of the previous longest seq. */
            fnd_seq (f1, beg1, m1 - 1,
                     f2, beg2, m2 - 1, oldcnt);
        }

        /* Report the sequence. */
        rpt_seq (m1, m2, cnt);

        if (m1 + cnt - 1 != end1 && m2 + cnt - 1 != end2)
        /* There is still something worth comparing */
        /* subsequent to the sequence.              */
        {
            fnd_seq (f1, m1 + cnt, end1,
                     f2, m2 + cnt, end2, lngval);
        }
    }
}

/*************************************************************
** chk_hashes determines whether this sequence of matching
** hash codes is longer than cnt.  It knows that the first
** pair of hash codes is guaranteed to match.
**
** RETURNS:  TRUE if this sequence is longer than cnt.
**           FALSE if this sequence is not longer than cnt.
*************************************************************/
```

*(continued on next page)*

**Listing One** *(Listing continued, text begins on page 28.)*

```
static BOOLEAN chk_hashes (line1, line2, cnt)

LINEINF        *line1;   /* (I) Line information for #1. */
LINEINF        *line2;   /* (I) Line information for #2. */
register int   cnt;      /* (I) Count to try to exceed. */
{
    register int    n;   /* Count of consecutive matches. */

    for (n = 1; n <= cnt &&
        ((++line1)->hash == (++line2)->hash); n++)
    {
        ;
    }

    return (n > cnt);
}

/*************************************************************
** cnt_matches counts the number of consecutive matching
** lines of text.
**
** RETURNS:  number of consecutive matching lines.
*************************************************************/

static int cnt_matches (s1, s2, most)

char          **s1;   /* (I) Starting line in file #1. */
char          **s2;   /* (I) Starting line in file #2. */
register int most;    /* (I) Most matching lines possible. */
{
    register int    n;   /* Count of consecutive matches. */

    /* Count the consecutive matches. */
    for (n = 0; n < most && strcmp (*s1++, *s2++) == ALIKE;
            n++)
    {
        ;
    }

    return (n);
}

/*************************************************************
** rpt_seq reports a matching sequence of lines.
*************************************************************/

static void rpt_seq (m1, m2, cnt)

int   m1;    /* (I) Location of matching sequence in #1. */
int   m2;    /* (I) Location of matching sequence in #2. */
int   cnt;   /* (I) Number of lines in matching sequence. */
{
    fprintf (stdout,
        "Matched %5d lines:  (%5d - %5d) and (%5d - %5d)\n",
         cnt, m1, m1 + cnt - 1, m2, m2 + cnt - 1);
}
```

**End Listing**