

Educational Fusion: A Distributed Visual Environment for Teaching Algorithms

by

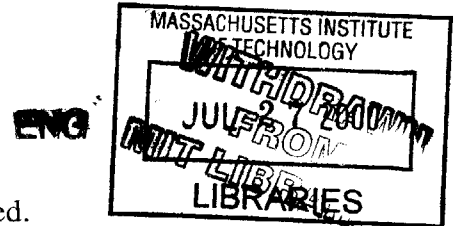
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Computer Science in Partial Fulfillment of the Requirements
for the Degrees of

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Submitted to the
Department of Electrical Engineering and Computer Science on

June 4, 1999

In partial fulfillment of the requirements for the degrees of
Bachelor of Science in Computer Science and Engineering and Master of
Engineering in Electrical Engineering and Computer Science

Abstract

Educational Fusion is a Web based learning environment for teaching algorithmic concepts. Teachers and Students access Fusion from any computer with a Java™ enable browser. Once logged in to the system, teachers and students alike are presented with a Concept Graph: a collection of modules, each representing an algorithm, that are interconnected to express a collective algorithmic concept. Students are challenged to complete the Concept Graph by implementing a chosen set of the modules. Each module provides a simulation environment that depicts the given algorithm, allowing students to visually test their implementations. Teachers use the same tools to monitor and evaluate the student's efforts. An extensive collaboration system allows for continuous communication between the educators and pupils, sharing of results, and automation of teacher feedback.

The goal of Educational Fusion is to aid teachers, students, and lesson developers in the educational process of teaching algorithms. Through Fusion's online collaborative environment, teachers and students become more accessible to each other. A server side repository frees both teacher and student from the tedious responsibility of cataloguing assignments. This accessibility and organization, combined with automated feedback tools, allows for a seamless interaction between students and teachers that helps overcome the obstacles of physical location and agenda coordination. The student's learning process is also enhanced through visualizations and automations that replace programming grunge work common to more traditional methods of teaching algorithmic concepts. Lesson developers benefit from modular lessons that lend themselves to selective reuse. Furthermore, toolkits for producing these modules expedites initial development efforts.

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Chapter 1

A New Place to Learn

Educational Fusion, hereafter referred to as eduFuse, is a Web-based online laboratory for the delivery of lessons in algorithms. eduFuse can be accessed from any computer with a Java™ enabled Web browser. Once a student or educator has accessed Educational Fusion, s/he enters an online environment where continuous collaboration is possible in the shared context of an interactive research and implementation environment.

Students are presented with a Concept Graph (CG), a high level modular depiction of the concept at hand. Each module abstracts a specific algorithm, and the interconnection of modules functions as a visual program. Instead of being faced with a large, obscure body of code and asked to fill in certain blanks, in eduFuse, students examine a large scale idea through a graphic visualization and then implement specific parts of the picture. When implementing a module, students are given a coding environment that automates compilation, as well as a simulation environment that visually describes the correct implementation and automates testing of their own implementation.

Teaching staff examine the same CGs viewed by students. To faculty, a CG is an environment that allows for convenient navigation between different students' work. A teacher can select a module on a given CG, and instantly bring up any user's code. The teacher can then use the same simulation tools to examine a student's implementation.

This streamlined evaluation coupled with automated grading forms makes it easy for faculty to produce well directed feedback.

Lesson developers use a toolkit to build modules and simulations for those modules. A complete lesson is constructed by planning, laying out, and connecting a group of modules in a CG. Reuse is supported by this modular design, and even an entire CG can be abstracted away into a “module abstraction” and then integrated into another CG.

Throughout the past year, the author’s work has been involved with nearly every aspect of the eduFuse system. As my thesis efforts progressed, I began focussing on better defining and implementing the Software Visualization, contextual collaboration, and content development facilities of eduFuse. This thesis presents an overview of the entire eduFuse platform, with special attention given to these three areas.

1.1 Motivation

The goal of Educational Fusion is to take advantage of today’s electronic infrastructure to enhance and optimize the educational process. Rapidly evolving multimedia and internet technologies that comprise the web present means of enriching course materials and the “distance learning” experience.

Users of the eduFuse environment can be categorized into three roles: student, educator, and lesson developer. We do not exclude the possibility of an individual assuming more than one of these primary roles. In developing motivational guidelines for eduFuse development, it has been helpful to consider the learning process from these perspectives: educator, student and developer.

1.1.1 Educator-Student Perspective

Comprehending algorithms is a challenging aspect of computer science education. Learning by doing is central to developing a concrete understanding of this abstract subject matter. In traditional pedagogy, educators request that students supplied with textual and perhaps pictorial resources implement specific algorithms. Students then begin an iterative process of learning, implementing, and testing until acceptable results are obtained. Completed assignments are submitted to educators for review, and eventually returned to students, hopefully with helpful comments. The eduFuse team seeks to leverage internet and multimedia technologies to enhance key elements of this learning process. Our efforts are focussed on improving three primary elements of a complete education in algorithms: administration, collaboration, and visualization.

1.1.1.1 Administration

Students' and educators' interactions are governed by administrative structure. Successful administration optimizes and conceals tasks that are incidental yet necessary to the learning process. Ideal administration is transparent: it facilitates a goal so well that the path to the goal goes unnoticed. Computer driven organization schemes and the web suggest new paradigms for administration. eduFuse seeks to optimize and conceal academic pragmatics, thereby allowing teaching staff and students to concentrate on educational content.

For students, demonstrating comprehension of algorithms usually involves several pragmatic responsibilities. To code an algorithm, students are frequently required to setup their own integrated development environment (IDE). Often, students are restricted

to using a specific unfamiliar IDE, resulting in a major time commitment. Students also must devise means for testing their algorithms. This can be especially time consuming when algorithm input and outputs are of a complex or even graphical nature, requiring yet more familiarity with the specific development platform [NT98]. Other responsibilities incumbent of a student often include managing files, preparing and handing in printouts of assignments, and filing away past homework. All of the aforementioned efforts may be well matched for Software Engineering courses, which stress the application side of computer science, but they are extraneous to learning algorithm theory.

Of course, the corollary to these student responsibilities is a myriad of clerical tasks for educators. Homework assignments must be carefully planned and clearly delivered. Coursework that includes programming requires that an appropriate IDE is made available and documentation is provided. Every implemented algorithm that is turned in must be tested, graded, and returned with relevant comments. Finally, teachers must keep a portfolio of each student's progress for later reference and evaluation.

eduFuse will provide the infrastructure for more convenient implementation and management of coursework. Why should students continue to be restricted by single platform IDEs when web based applications suggest the possibility for easily accessible, platform independent IDEs? Why should students and educators continue to exchange hard copies of assignments by hand when electronic content can be effortlessly relayed over the internet? eduFuse will deliver a simple and well-focused platform-independent IDE that is seamlessly integrated with test suites for verifying algorithms, and with utilities for coursework retrieval, submittal, and persistent archival in a web accessible

central location. Giving educators access to the same test suites that students use to examine their algorithms will provide simplified evaluation in a context familiar to the students. Finally, auto-generated feedback forms associated with each assignment expedite evaluative communication to students.

1.1.1.2 Collaboration

Collaboration between educators and students is clearly an essential element of a complete education. Unfortunately, scheduling difficulties and disparity of physical locations inhibit the opportunities for teaching staff and students to meet. Distributed computing technologies, while not able to replace the value of face to face interaction, raise the potential for teachers and students to work collectively across distances.

eduFuse seeks to provide an online environment that feels more like a unified laboratory than a multitude of disjoint work spaces. Obviously, a means for real-time question and answer sessions is essential. The value of messaging is greatly enhanced when it exists in conjunction with inherent context. When individuals communicate while immersed in the same visual¹ experience, one can use words sparingly and still be very expressive. Users connected to eduFuse should be able to communicate while sharing visual context.

1.1.1.3 Visualization

The nuances of algorithmic processes are often difficult to identify and decipher from textual explanations and pseudo code. Intuition tells us that visual aids should help us make the jump to our own mental visualization of an algorithm's operation.

¹ The same could be said for experiences relating to one or more of the other four senses. The visual experience is the most applicable to eduFuse.

To understand something is called "seeing" it. We try to make our ideas "clear," to bring them into "focus," to arrange our thoughts. The ubiquity of visual metaphors in describing cognitive processes hints at a nexus of relationships between what we see and what we think.[Car+99]

Related work suggests, and we believe, that well constructed graphical visualizations help explicate important details of algorithms. eduFuse should supply comprehensive visualization facilities that bring to life each algorithm being examined.

It seems obvious that animations should help to explain the process of algorithms. After all, algorithm animations offer a concrete representation of an otherwise abstract process. Educators have generally shared this hypothesis, leading to the creation of a number of instructional animation tools over the past decade. However, empirical research hoping to confirm the benefits of algorithm animations has returned disappointing results. In a study conducted with computer science graduates in 1993, researcher's found that students who had been supplied with algorithm animations performed nearly the same on a posttest as students who had used more typical learning resources [Sta+93]. A variety of other experiments arrived at similar conclusions [Pan+96][Keh+99].

Gradually, educators have begun to realize that a number of factors must be considered to ensure effective use of algorithm animations [Keh+99][Pan+96]. Animations present an expert's interpretation of an algorithm. Therefore, an educator can not expect a novice to examine an algorithm animation and grasp, without any additional guidance, the important details of the algorithm. In the conclusion of [Sta+93], the researchers suggest:

[An algorithm animation] is a mapping from the abstract computational algorithm domain to the animated computer graphics domain. For a student to benefit from the animation, the student must understand both this mapping and the underlying algorithm upon which the mapping is based.

Subsequent studies have shown more promising results [Keh+99][Sta+94]. In these studies, students were supplied with questions derived to guide their interactions with algorithm animation tools. The result: students who used animations performed markedly better on questions concerning the algorithm's process.

eduFuse seeks to provide a learning environment which forces students to actively interact with algorithm animations. More specifically, eduFuse lessons require students to interact with animation tools in a way that highlights the primary operations and yields insight to the mapping between those operations and the underlying algorithm.

Another challenge in learning algorithms is grasping a high level understanding of composite algorithms composed of several sub-algorithms. For example, a computer graphics course generally includes assignments that involve large-scale algorithms such as rendering pipelines. Requiring students to completely implement these pipelines is as much a lesson in the Software Engineering task of implementing large programs as it is a lesson in graphics algorithms. At the same time, implementation is considered the most efficient means of testing a student's understanding of this elaborate material. A common compromise is "fill in the blanks" assignments, where students are asked to complete the primary components of a larger body of code. Unfortunately, an understanding of how these components fit together may elude the student even upon finishing such an assignment. Comprehension of the interconnection of the underlying sub-algorithms is difficult to obtain from the lengthy body of code presented to the student. We believe that symbolic notation is not the best means of describing the "big picture."

EduFuse should provide graphic visualizations that effectively describe the overall structure of lengthy algorithmic processes [NB97][JN94]. Integrating such high level visualizations with "fill in the blanks" assignments will direct students attention to the primary pieces of an algorithm while providing an understanding of how the pieces fit together.

1.1.2 Developer Perspective

The goal of the lesson developer is to provide excellent content in minimal time. Lesson developers are certainly familiar with reuse to achieve this goal. Each semester's new lesson is generally a collection of the best, tried and true material from the year's past, along with any new additions that will further enhance the student experience.

The more material a developer has access too, the more refined and complete the resulting lesson will likely become. The web should drastically ramp up the range and volume of lesson aids that are available to lesson creators. Unfortunately, we cannot necessarily make this assumption for electronic teaching aids. Often, electronic lesson tools are based upon proprietary computing environments that severely limit the use of courseware at outside locations.

eduFuse seeks to foster the sharing, reuse, and improvement of lesson materials. The eduFuse environment itself is platform independent and easily portable, so it is logical that we should provide eduFuse content with the same advantages. Lessons developed with eduFuse at one location should have the potential to be easily integrated with another location's system, creating a global library of lesson data.

eduFuse will also provide a simple development kit that automates, to whatever extent possible, the creation of new content. Being an experienced software engineer should not be a prerequisite for developing eduFuse lessons.

1.2 Outline of this Document

Now that the reader has an understanding of the motivation that drives the eduFuse project, the chief technical issues that constrain its development will be introduced. The next chapter describes several other projects that are centered around technologies directly related to eduFuse.

Chapter 3 provides a tour of the system, painting a picture of the overall environment. Chapter 4 describes the client-server technology that is the foundation for this environment. The next 4 chapters expand upon four elements of the system that are considered critical to eduFuse. Chapter 5 lays out the descriptive power of the Concept Graph, a tool used to describe high-level algorithmic processes. Chapter 6 examines the algorithm visualization subsystem used to describe and verify low level algorithm implementations. Chapter 7 describes the ever present eduFuse collaboration system, and describes the technical issues that constrain its development. Chapter 8 details the system from a developer's perspective, illustrating the process that goes into creating lesson materials and describing the efforts of past third party developers.

Finally, Chapter 9 will wrap up with a reexamination of the Administration, Collaboration, and Visualization motivations, along with an assessment of the future of lesson development and eduFuse

Chapter 2

Related Work

eduFuse development is an amalgamation of work related to many areas of research. Course administration tools, software visualization, and collaborative online environments are all related to the “all-in-one” algorithms learning environment that is the goal of eduFuse. To avoid recapitulation of past thesis research [NDB97][BWP97][NJT98], I will omit a summation of related course administration tools. The focus of the thesis work presented herein has lead more towards research in the domains of Software Visualization and online collaboration.

2.1 Software Visualization

Several taxonomies have been suggested to define Software Visualization and its range of subtopics. This document adheres to the definitions proposed by [PBS98]. The work of Price, Baecker and Small defines Software Visualization as follows:

Software Visualization is the use of crafts of typography, graphics design, animation, and cinematography with modern human-computer interaction and computer graphics technology to facilitate both the human understanding and effective use of computer software.

Software Visualization is broken into two fields: Algorithm Visualization and Program Visualization. This distinction is based upon the level of abstraction of the two visualization approaches. Program Visualization is concerned with making apparent low-

level implementation details of programs, such as code structure and data types. Algorithm Visualization deals with the more abstract problem of describing how an algorithm works. Whereas Program Visualizations should explicate specific implementation details, Algorithm Visualizations can be suggestive of a variety of coding strategies. For example, an animation that illustrates a sorting algorithm might show a number of sticks of different lengths being rearranged in a manner that reflects the algorithm's process. This Algorithm Visualization will leave open to interpretation whether to code the algorithm iteratively or recursively, with linked lists or with arrays.

eduFuse contains both Program Visualization and Algorithm Visualization elements. Program Visualization is used to provide an interface for arranging modules in a data flow that indicates both program control flow and the use of important data types. Algorithm Visualization is used to delve into processes lying within the individual modules. eduFuse is quite unique in its effort to combine these two aspects of Software Visualization. Section 2.1.1 describes predominant research in Program Visualization. Algorithm Visualization systems are generally of two types: static or dynamic. The goal of eduFuse is to provide dynamic visualization, or Algorithm Animation, thus the focus of our research has been on this subset of Algorithm Visualization. Section 2.1.2 is an exploration of Algorithm Animation systems.

2.1.1 Program Visualization Systems

Development of the Application Visualization System (AVS) began in the late 1980s to facilitate rapid production of programs for scientific data visualization. In its original form, AVS provided a visual programming interface for linking a series of modules in a

data-flow [UPS+89]. AVS has since grown to encapsulate functionality more along the lines of primitive object oriented programming [AVS97][AVS98]. Modules in AVS are considered very *course-grain* [RY92] because each node or module generally encapsulates an entire program or object. AVS applications are generally built and used by experts to analyze scientific data. AVS applications are not intended to describe the algorithmic processes that produce views of the data, more important to AVS users is the data itself.

ConMan [HAE98] is an interaction intensive data flow language for manipulating graphical objects. Modules provide interactive tools for defining, transforming, and viewing graphics data. The system helps describe to users the effect of various operations on graphical data, and again, course-grain modules suppress the details of the process of each operation.

eduFuse also provides a data-flow architecture based upon course-grain modules. However, eduFuse modules are of finer grain than AVS, and perhaps even conMan, as in eduFuse each low-level module is intended to encapsulate only a single function. Generally speaking, these functions should be simple enough that their process can be described well through interactive Algorithm Animation. IBM Data Explorer uses modules of granularity about the same as those found in eduFuse [Gre+95].

The use of *fine-grain* data flows for Program Visualization has also been an active area of research. In fine-grain data flows, nodes generally represent primitive operators. Many diagramming strategies have been developed to handle expressing state, naming space, and iteration at fine-grain levels [Tri89][Nic94]. With course-grain visualizations,

complex control flow and data usage details exist only within modules and thus do not appear in the data flow [Gre+95]. The eduFuse data flow is of fine enough grain that some complex control flow details need to be handled. Presently, our data flow does not address these details and thus contains ambiguities that obscure the operation of the program being expressed. An understanding of finer grain data flow techniques may help us to resolve some of these ambiguities.

2.1.2 Algorithm Animation Systems

There are several factors by which we can measure the educative potential of Algorithm Animation systems [Pri+98]. Certainly of chief importance is the level of abstraction afforded by the system [Ken+92]. The abstraction must provide enough detail to explicate the process while abstracting pragmatic trivialities that may obscure the process. The best abstraction level provides the quickest mental path to the semantics of the algorithm. Also of importance is the level of interactivity the animation system provides. As discussed in the motivational overview, active interaction is critical if not required for unlocking the descriptive power of animations.

Connection technique, or the way in which an algorithm to be animated is connected with a graphical subsystem, is perhaps the most fundamental constraint on any algorithm visualization. After all, the connection technique is what encodes the mapping from abstract to concrete. To better understand the technical issues involved with Algorithm Animation systems, a range of these tools have been analyzed with special attention given to their connection techniques.

The Brown Algorithms Simulator and Animator [Bro+84], BALSAs, developed at Brown University, was a pioneering effort in using animations to instruct undergraduate algorithms courses. BALSAs was the first system to implement *interesting events* as its connection technique [Bro+98]. An animator working with BALSAs instruments the algorithm with a series of annotations demarcating interesting moments in the algorithm's process. These annotations are method invocations that make calls to the visualization system to animate each interesting event. For example, interesting events supported by an animation of a sorting routine might include comparison, swaps, and element in place. A major advantage of this interesting event approach is that it gives animation designers direct control over the level of abstraction of the animation – interesting events can be suggestive of an event at any level in the algorithm's process [Bro+98][Cox+92][Cox+93]. The primary drawback of this system is its invasiveness. Each algorithm to be animated must be modified with extra subroutines to drive the animation. This process alters the appearance of the code and assumes that events can be clearly identified before execution of the code.

Several systems, including BALSAs-II [Bro88], Zeus [Bro91], and Samba [Sta97] have followed Balsa's example. BALSAs-II extended BALSAs's user interaction capabilities considerably by allowing users to step forward and backwards between interesting events, thus controlling the pace of the animations. Samba a form of annotations that is at a lower level of description than "interesting events." Samba animators annotate algorithms with statements that output a primitive object/trajectory animation code interpreted by Samba. The Samba interpreter then uses the POLKA[Sta97] system to

render the animation. This system allows for the rapid building of a wide range of algorithm animations [Sta96][Sta99].

Another popular connection technique is the *declarative* method [GCR98][RC93]. Under this methodology, an animator creates a number of rules that map an algorithm's state to visual descriptions. For example, a graph algorithm may want to draw arcs whenever an edge is added, this reasoning could be handled by the rule:

$$E[i, j] \Rightarrow \text{line}(\text{position}(i), \text{position}(j))$$

Pavane [RCWP92] and LEONARDO [CDFP92] both implement a declarative approach for Algorithm Animation. Pavane affords much greater functionality than LEONARDO. Declarative rules in Pavane are based upon current state and history of past states, while LEONARDO's rules are based solely on the current state of the algorithm. Since events are generally described by successive states, Pavane is able to infer a rich set of events, while LEONARDO is only able to capture direct mappings of state. However, in comparison with the "interesting event" method, the use of rules by Pavane to capture events may present obscure reasoning.

One advantage of the declarative method is that the algorithm does not have to be altered or examined to produce an animation. Thus, the animator does not need any knowledge of the algorithm being visualized. This is especially helpful when events that should be visualized are difficult to isolate or non-deterministic, as with concurrent programs. The drawback is that compilation overhead is increased as some compile time mechanism is needed to process the rules into computations that can be executed at run time. Additionally, it is often hard to obtain a proper level of visual abstraction with the

declarative approach. Such is the case when an animator would like a single visual event to be representative of several minor state changes.

2.2 Shared Workspaces

In the past, most shared workspaces, including HP's SharedX, Sun's ShowMe SharedApp, and Microsoft's NetMeeting, revolve around a central application model [MS98][Beg+97]. The benefit of this model is that only one client need contain an application to afford real time collaboration within the application. The downside is that large amounts of visual data must be continuously updated and transmitted across the internet to give the remote clients the appearance of having a local copy of the shared application. These high bandwidth communications are suitable for LANs, but cause severe performance issues for WANs.

The advent of Java suggests a new approach to shared workspaces [Beg+97]. When a user runs a Java applet, a complete copy of the applet is transmitted to the user's computer. Thus, the central application model immediately seems a poor fit for Java applets. Each user already has an identical copy of the applet, so sharing the related visual data is unnecessary. If each applet begins from the same starting point, and all events produced by the clients are shared among all of the applets, each client will have the appearance of a shared applet. The introduction of Remote Method Invocation, RMI, enhances the ease of constructing these shared environments [Sun98].

Collaborative Active Textbooks Using Java (JCAT) is an educational system for teaching algorithm's that makes use of the ease of collaboration made possible by Java [Bro+96][Bro+98]. JCAT presents algorithm animations in a Java applet. The JCAT

system is based upon “interesting event” methodology, where an underlying algorithm sends notification of events to the animation portion of the applet. Utilizing RMI, a central control applet can transmit these interesting events to all client applets viewing the animation. In an electronic classroom, this would allow a professor to control the steps of an animation as each student watched from his own browser.

Since eduFuse is completely written in Java, it takes advantage of the distance collaboration this web based language makes inherently possible. JCAT takes rudimentary advantage of the Java event sharing paradigm. The JCAT system is not applicable outside the realm of an electronic classroom, as all instructive context would be lost. eduFuse aims to provide complete desktop sharing along with a comprehensive package of messaging tools so that a collaborative context can be maintained in light of remote demonstration of algorithms.

Chapter 3

System Tour

This chapter presents a high level description of the system components that educators and students interact with during a standard eduFuse session. The reader is encouraged to experience eduFuse first hand while reading this overview. The eduFuse team's demonstration server can be found at our homepage, <http://edufuse.lcs.mit.edu>.

3.1 Entering eduFuse

Selecting the 'Login' link from the eduFuse homepage initiates the system's Java applet, presenting the user with a login dialog as seen in Figure 3-1. Students, educators, and system administrators use this single point of entry.

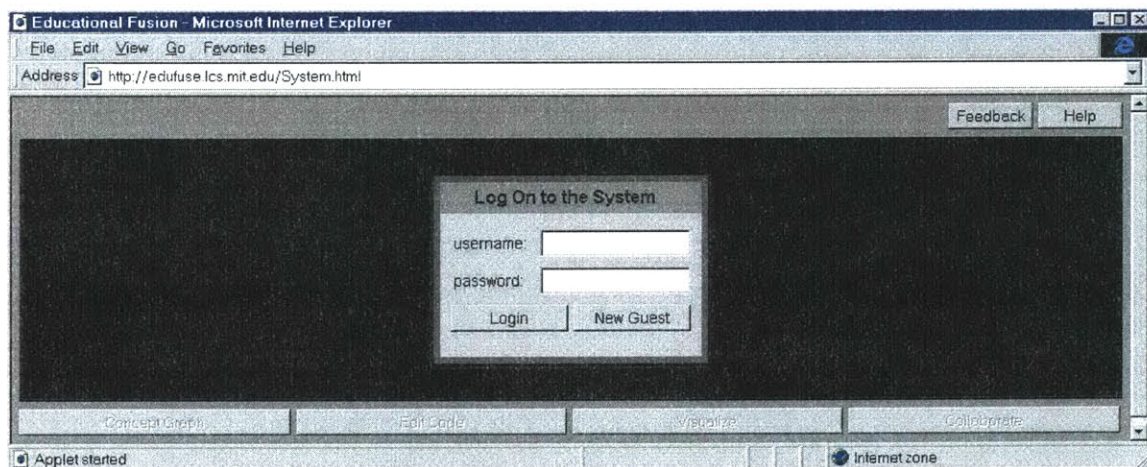


Figure 3-1: eduFuse Login

The black area occupying the majority of the client applet will be the user's window to the eduFuse laboratory. The help button at the top of the screen provides help based upon the immediate context of this window. The adjacent feedback button invokes a dialog for ready submission of bug reports. The four buttons along the bottom of the applet, hereafter referred to as navigation buttons, remain disabled until logged in.

3.2 New Guests

eduFuse visitors are encouraged to create their own account by selecting the 'New Guest' option. This presents a form for obtaining the identity of the guest, as seen in Figure 3-2. Guest accounts are presently given the same privileges as student accounts.

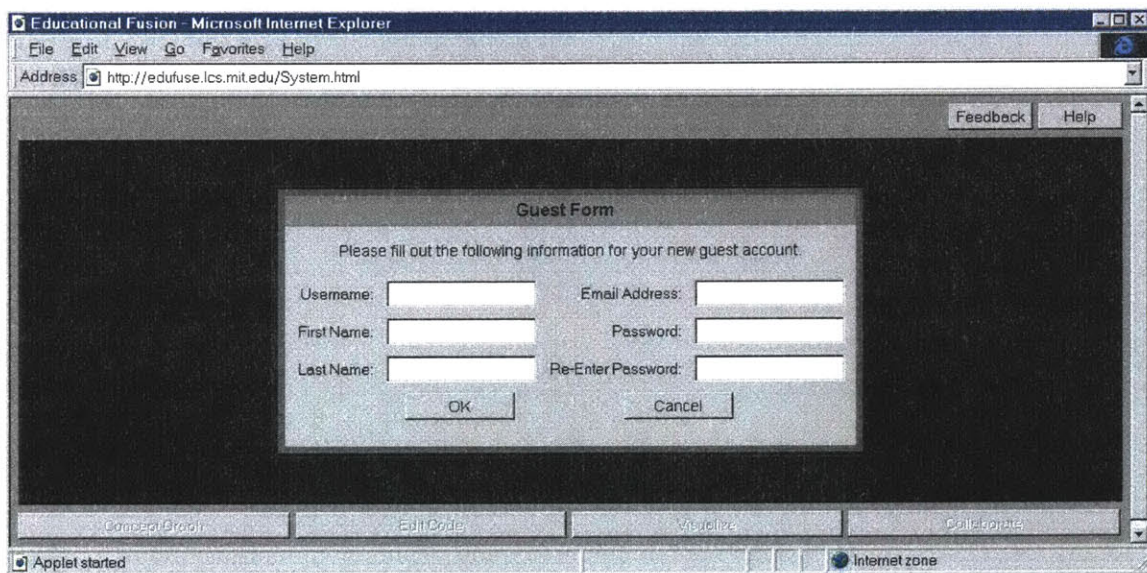


Figure 3-2: Guest Information Form

3.3 Account Administration

Each eduFuse server has an administrator account. When the administrator logs in, s/he is presented with a dialog for managing accounts on the server, as seen in Figure 3-3.

This web-based interface allows for convenient and remote management of all account properties.

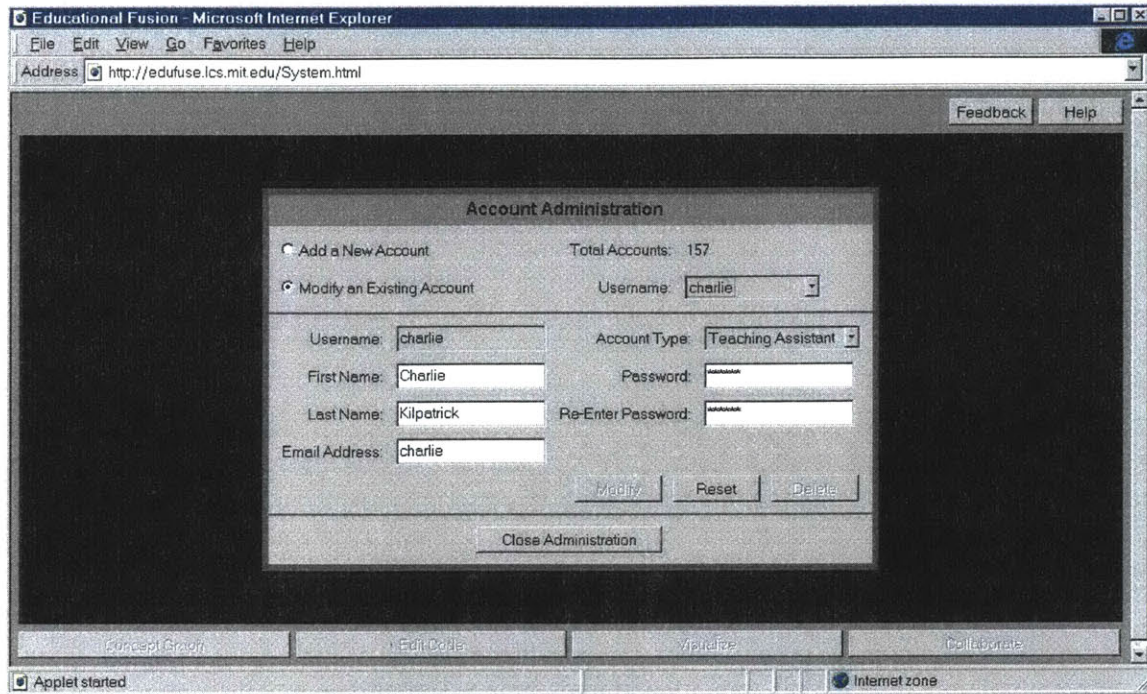


Figure 3-3: Account Administration Dialog

3.4 The Concept Graph

After a user has logged in, s/he is immediately presented with a CG, such as the one being viewed in Figure 3-4. A user can always return to the CG view via the 'Concept Graph' navigation button.

A CG is a high-level visualization of the algorithmic concept at hand. The CG in Figure 3-4 presents the process of clipping a line and displaying it on a rasterized display. The overall structure of the algorithm is shown as a data-flow of linked modules. A simple mouse drive interface allows users to alter module links, move modules, delete modules,

and insert other pre-built modules. Changes to the CG can be saved to the user's own file space on the server.

Each module is a visual abstraction of an algorithm that is part of the overall process. Color-coded triangles along the sides of the modules represent typed input and outputs. Type checking is done automatically when a user attempts to create links between modules.

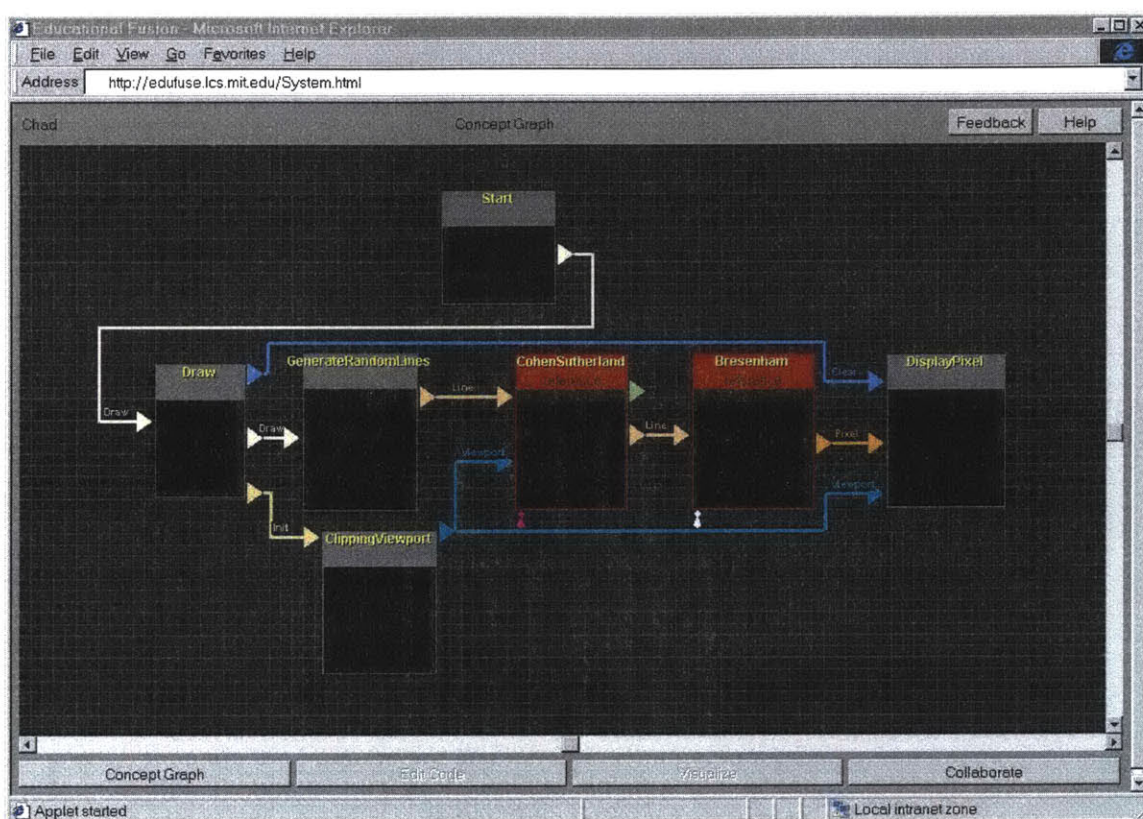


Figure 3-4: A Concept Graph

A CG can be executed by clicking on its root module. Data then propagates through the CG and each module displays a visual representation of its operation upon execution. Figure 3-5 shows our CG after it has been executed.

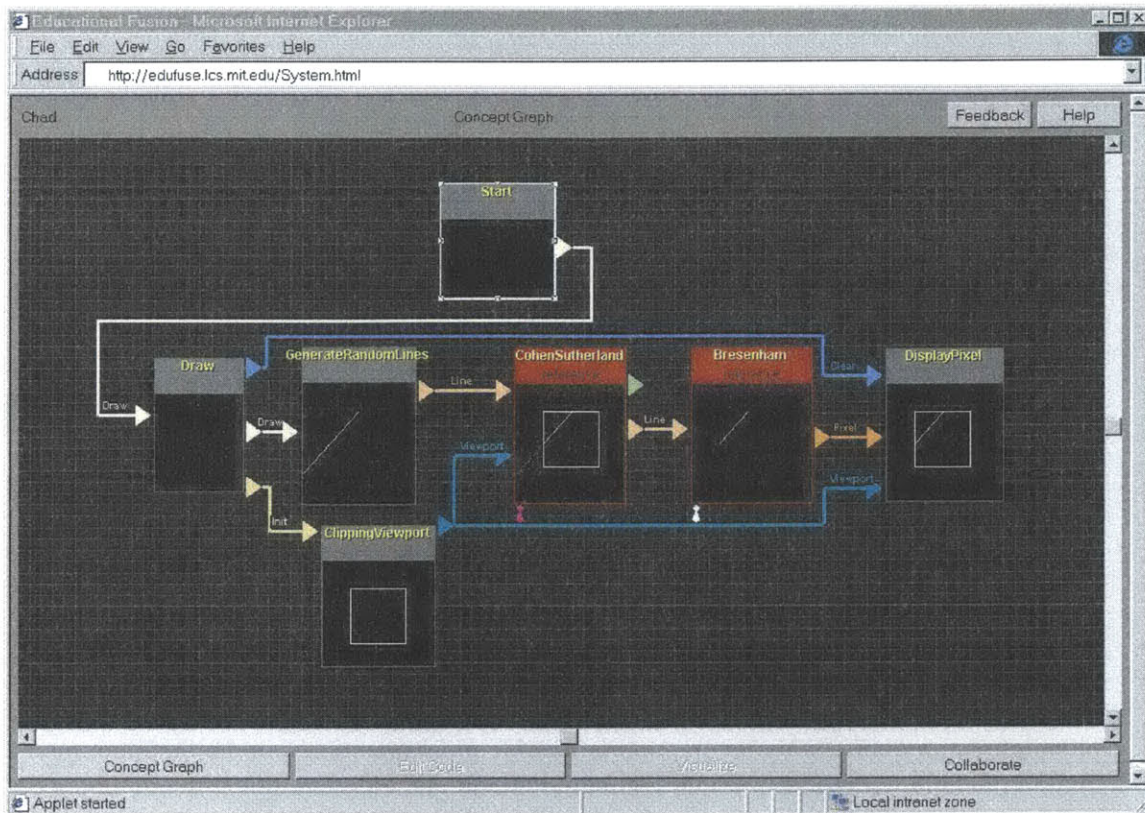


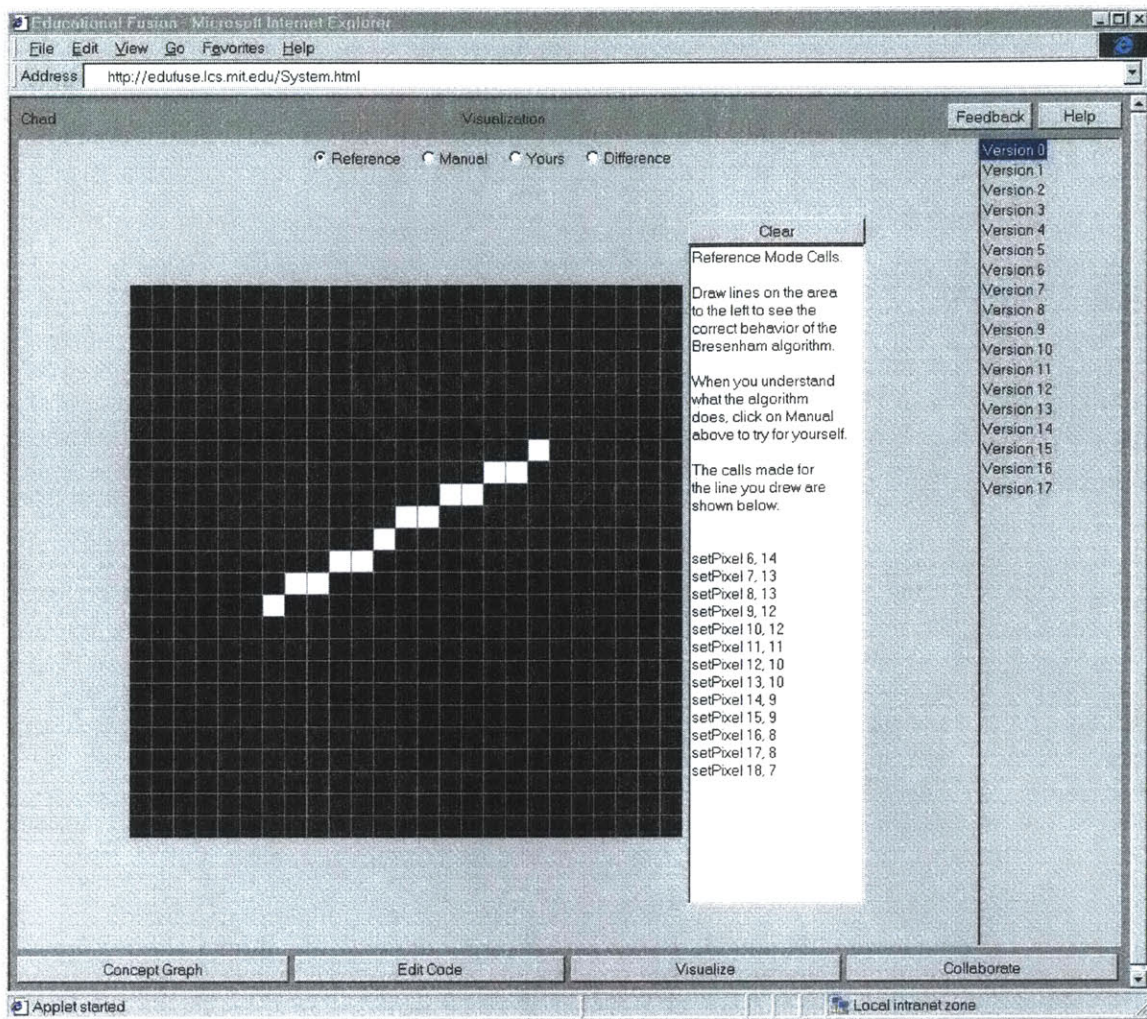
Figure 3-5: The Same CG After Execution

Students are challenged to implement specific modules. All modules contain a reference algorithm. Modules considered central to the lesson also contain a user implementation of the algorithm. In Figure 3-5 there are two such modules. The CohenSutherland and Bresenham modules currently have their reference algorithms loaded. Simply clicking on the word 'reference' or 'yours' toggles between the reference and user implementation of the algorithm. Module displays reflect the actual operation of the currently selected implementations. The effects of broken implementations are readily seen in the displays of the corresponding and downstream modules. Color provides pronounced indication of the module's mode, where red indicates 'reference' and green indicates 'yours.' Simply put, students are challenged to turn all red modules to green and still have a working CG.

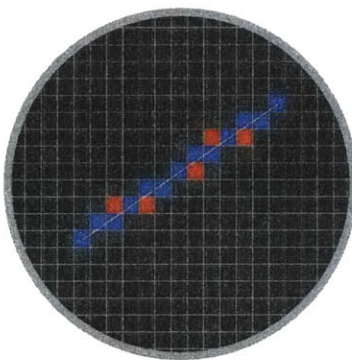
3.5 Visualization Panels

Each module that allows for student implementation also has an associated Visualization Panel (VP). While the CG presents a high level understanding of the overall algorithmic process, the goal of each VP is to provide an understanding of an important sub-algorithm. To access a VP the user selects a module and presses the ‘Visualize’ navigation button.

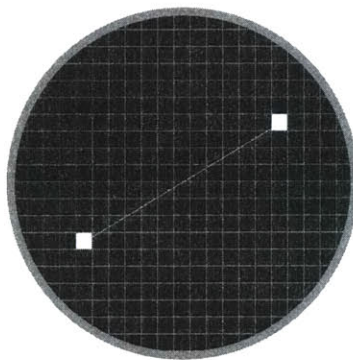
Figure 3-6 presents a user’s view of the VP for Bresenham’s line clipping algorithm. The educational value of this and all VPs hinges on the implementation of four different pedagogical modes: ‘reference’ mode, ‘manual’ mode, ‘yours’ mode, and ‘difference’ mode.



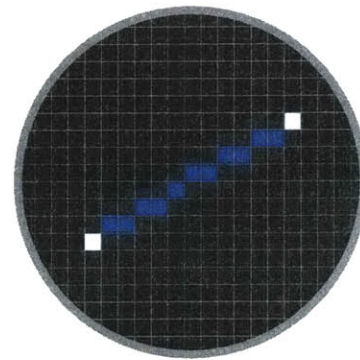
(a)



(b)



(c)



(d)

Figure 3-6: A visualization panel for Bresenham's algorithm with a caption for each of the four pedagogical modes: a) reference; b) manual; c) yours; d) difference.

Reference mode presents the user with a correct implementation of the algorithm. Users provide input by sweeping out a line segment, the underlying reference algorithm is

called, and a rasterization of the line is computed and shown. The text window to the right of the display gives the viewer a trace of calls to the method `setPixel` that were directly responsible for the rasterization, thus providing symbolic notation along with the visual expression. Repeating this experiment and examining the graphical and trace results allows students to understand what output will result from a given input.

Manual mode allows the user to further test this understanding. Again, the user suggests input to the algorithm by sweeping out a line. The user then conjectures the output by selecting appropriate pixels on the rasterized view. Evaluation of each trial pixel is performed by comparison with the underlying reference algorithm's output. With each mouse click, a pixel is lit either blue or red, indicating correct and incorrect respectively.

Yours mode should be used after the user has gained a general understanding of the algorithm through experimentation with the first two modes. This mode provides a visualization of the output of the user's implementation. The user sweeps out a line, the line definition is sent to the user's implementation, and the algorithm's output is displayed. The version list bordering the right side of the VP allows a user to select from any of his compiled implementation attempts. In *yours* mode, a user can easily examine the output produced by his algorithm on a variety of input tests.

Difference mode allows a user to verify the correctness of his implementation. After the user has swept out a line, both the user's implementation and the reference implementation of the algorithm are called, and the results are visually compared. White indicates correct pixels, blue indicates pixels that should have been output, and red indicates pixels that were output but should not have been. This visual comparison

allows a user to quickly identify where his implementation has erred. Repeated tests on different input cases may yield similar errors that suggest the nature of the problem to the user.

3.6 Integrated Development Environment

By now, the reader is probably wondering *how* the students supply their implementations to the eduFuse environment. Programming in eduFuse does not require a student to setup his own coding environment and submit compiled files. Instead, an IDE is seamlessly integrated with the eduFuse environment. When a student is ready to edit an implementation of an algorithm, s/he simply clicks the 'Edit Code' navigation button, and the IDE is brought to the screen, as shown in Figure 3-7.

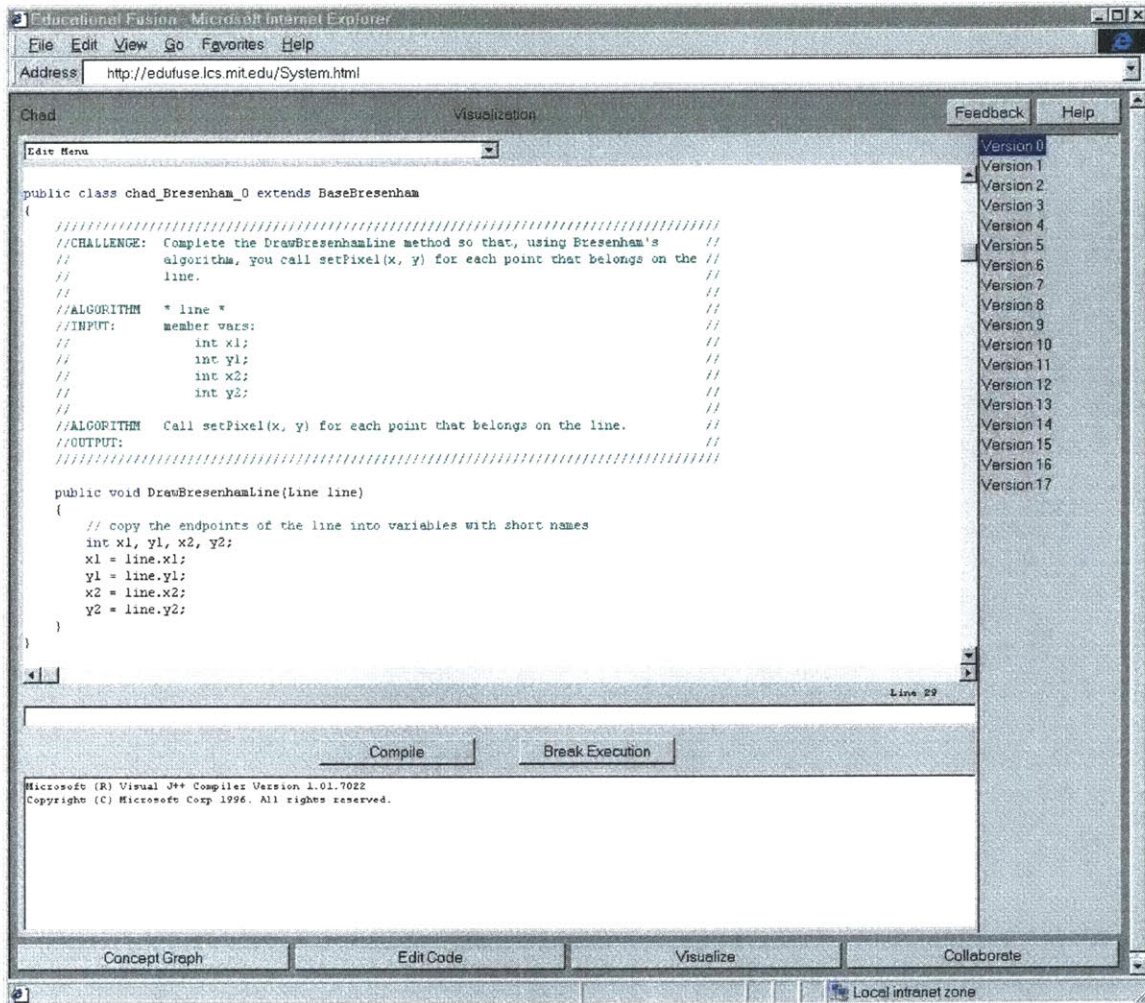


Figure 3-7: The eduFuse IDE

The main window of the IDE presents the code for the user's implementation of the algorithm. Presently, eduFuse only supports Java, but interpreters such as JScheme make inclusion of other languages plausible in the near future. Figure 3-7 shows the body of code that a student is initially challenged to fill in with an implementation of Bresenham's line drawing algorithm. Notice that the function takes an input of type `Line`, and output is sent by making calls to the `setPixel` method. The reader may confirm that these are the same input and output types expressed visually by the CG and VP. This consistency between the graphical and symbolic notations makes it easy for students to jump between code, visualization, and CG.

When a user is ready to compile his code, s/he simply presses the compile button located beneath the editor window. The code is sent to the server and compiled. If the compilation is not successful, compilation errors appear in the window at the bottom of the screen. If the compilation is successful, the class file is made available to the eduFuse client.

As when examining a VP, a version list is presented along the right of the IDE. Each compile attempt adds a version to the list, and all versions are persistently stored on the server for convenient review or modification at any time.

3.7 Collaboration Facilities

When a user enters eduFuse, s/he is immediately presented with visual indication of all users currently in the same lesson environment. Each user is portrayed by an avatar that sits beneath the module that the user is currently working with. Avatars are color coded to indicate the type of account each user has. For example, in Figure 3-4, the user can observe that a professor, indicated by purple, is currently working with the CohenSutherland module. The user's own avatar is always white.

eduFuse provides a complete set of messaging utilities. Included are quick messages, private and group chat sessions, and a TA help queue to be used when educators do not have time to instantly respond. All discussions can be logged to a history file for later review.

Messages can be sent or discussion windows launched by right clicking on the appropriate avatar. The more advanced features, such as TA queues and discussion

histories, can be accessed from the collaboration panel, which is entered by clicking the 'Collaborate' navigation button [Ken99].

The true strength of collaboration in eduFuse is due to the shared visual contexts which discussions can be centered around. If a student is having trouble with a module, the student sends a message to a TA, who can subsequently load the student's implementation of the module for review.

When an educator clicks on a module's mode indicator, a popup menu presents 'reference' and 'yours' options along with a list of all users who have implemented the module. Selecting a user's name loads the module with that user's implementation, and colors the module blue to indicate the foreign implementation. Figure 3-8 depicts this interaction. A teacher can review a student's implementation as it appears on the CG, or through use of the IDE and associated VP. Meanwhile the student and educator can be engaged in active conversation through a discussion window.

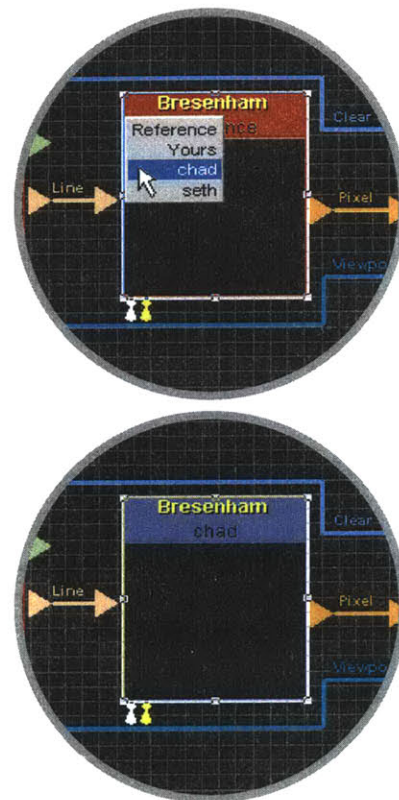


Figure 3-8: A teaching assistant loads a student's implementation for review.

3.8 Administrative Facilities

eduFuse offers vast simplification of the myriad of administrative tasks that would normally surround a course in algorithms. Most of these enhancements are not provided by independent features, rather, they are inherent to the design of the eduFuse environment.

The Concept Graph is not only a visual program, it is a visually navigable library of coursework. All assignments are persistently stored and conveniently organized to the advantage of both student and educator. Parties on both sides of the lesson table are detached from the task of archiving course content. Moreover, there still exists, but in different form, a *process* of turning in and handing back assignments, since student work is always persistently viewable by both student and teacher.

One feature that has been added to facilitate traditional grading of homework is Feedback Forms. Each module has a Feedback Form associated with it. After reviewing a student's work on a module, an educator can summon the Feedback Form by pressing the 'Grade' button that appears in his IDE window. Feedback Forms are standard HTML documents, with fields that direct an educator's comments to topics appropriate for the algorithm under consideration. When the educator is finished with the form, s/he presses a submit button, and the form is emailed to the student via the address in the student's account information.

Chapter 4

Client-Server Foundation

The eduFuse laboratory is constructed on top of a client-server architecture intended to readily facilitate collaboration and persistent storage of coursework. Both the client and server are platform independent as they are both written purely in Java.

4.1 Communications

Before users enter the eduFuse environment, a session connection must be established with the eduFuse server. The HTML that presents the client-side applet provides a port number through which the client applet communicates with the eduFuse server. The client sends a connection request to the server via the supplied port, and a dedicated socket is established for stream based communications. All communications between the server and client will be facilitated by this socket.

An alternative to streaming is CGI posting. CGI posting requires a new TCP/IP connection to be established for each request, while streaming keeps a socket continuously open between the client and server. For this reason, a series of stream based requests can be fulfilled much faster than a series of CGI requests. eduFuse uses stream based communications because of this performance benefit.

The major draw back of streams is that they cannot be established across firewalls. Thus, eduFuse currently cannot be accessed from the other side of a firewall.

Plans are in place for replacing our custom stream handling routines with Java Remote Method Invocation (RMI). Currently, a common interface lying on top of the client-server stream is used for all messages placed on the stream. This interface was developed to make it easy to produce new client-server queries. Since the interface is now used for all client-server queries, simply sliding RMI beneath this interface will direct all communications through RMI. RMI automatically determines if a firewall is present, and chooses accordingly between CGI posting and stream-based communications.

4.2 Routing

Each user is assigned a unique user ID (UID) when his account is created. When a user logs in to eduFuse, the UID is paired with the user's socket number and placed in a server side hash table. Conflict resolution exists to handle when the same user logs in multiple times. All clients are notified of a new user's arrival, and the entering user receives notification of each resident client.

Each client maintains a hash table of username and UID pairs. When a client wants to send a message to a specific user, the client applet looks up the recipient's UID and attaches it to the message sent to the server. The server then uses the UID to look up the recipient's socket, and the message is forwarded.

4.3 Persistent File Storage

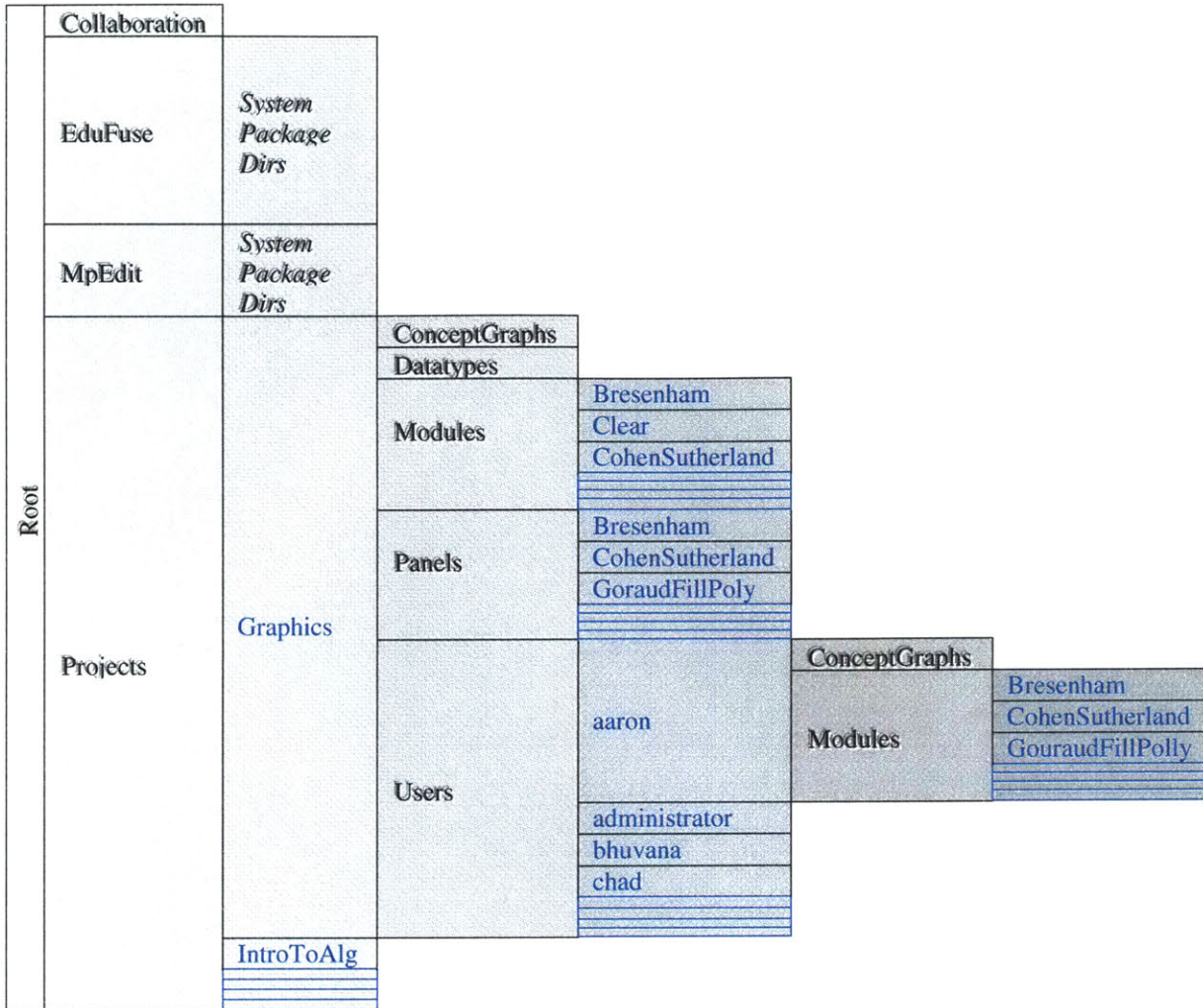


Figure 4-1: A diagram of the eduFuse file hierarchy. Each cell in the diagram represents a folder. Cells to the right are nested in adjacent cells to the left. Black cell names indicate system folders, while blue cell names indicate data folders particular to this demonstration installation of the eduFuse system.

The eduFuse server contains a wealth of persistent course data, as detailed by Figure 3-2.

For each course, the eduFuse server provides a repository for lesson materials, student coursework, and account information.

Serialization is used to persistently store CGs on the server [Boy97]. Each visual element of a CG has a textual description that is read and written by the client upon loading and

storing the CG. Serialization makes it possible to transmit the description of the CG between server and client. The first time a CG is opened, a reference version is retrieved from the server. Subsequent changes to the CG are saved to the user's file area.

Chapter 5

Program Visualization in Edufuse: An Extended Data Flow Model

The goal of the Concept Graph Data Flow model is twofold [Abr+95][Kod+91]. First, it should clearly describe the control flow of a program. Second, the data used by each component of the flow should be clearly indicated. If both of these factors are achieved, the high level operation of a CG program is clearly explained.

Data flows apply well to programs based upon a linear execution. Control flow and data usage can easily be described statically when execution proceeds sequentially from beginning to end. Unfortunately, only simple programs, or *very* coarse-grain views of programs, can be observed as a linear sequence of events.

When iteration or recursion is part of a program's process, more complex diagramming techniques, or even dynamic visualizations, are needed to help trace control flow and the use of data. In this section we analyze how well the CG data flow model applies to complex control structures, namely iterations and recursions, and suggest extensions where appropriate.

5.1 Modeling Iteration

There are two iterative process in Figure 5-1¹. Can you spot the loop within a loop? Unless you are very familiar with data flow processes, chances are you cannot identify the iterations from this static capture of a Concept Graph. The outer loop starts at the ‘BreakMeshIntoFaces’ module and completes at the ‘Display’ module. The inner loop starts at the ‘GouraudFillPoly’ module, and again ends at the ‘Display’ module.

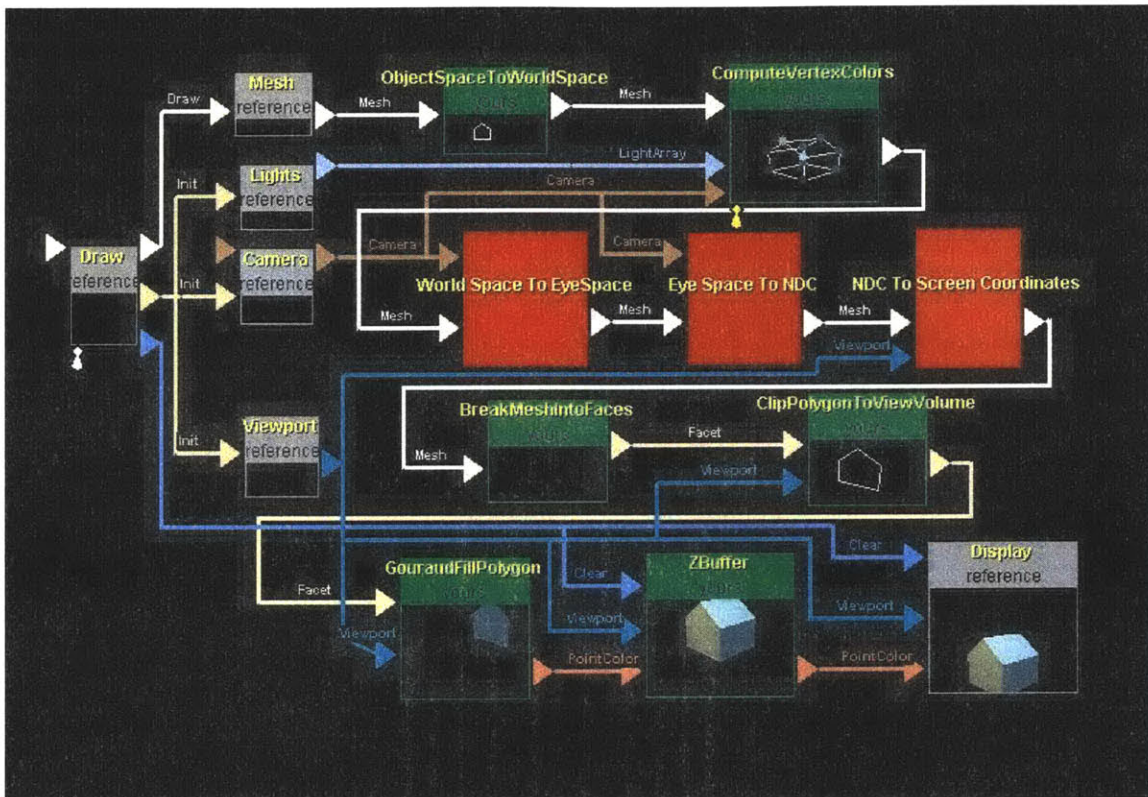


Figure 5-1: A Concept Graph with Iterations

In viewing the CG’s dynamic execution, these loops are much more obvious, as the viewer sees the displays of the modules update with corresponding frequency. The *static* clues are the data types passed at the beginning of these loops. In the CG data flow, control flow is *data driven*[AVS91][Gre+95][Kod+91]. Thus, an iterative process begins when a module emits multiple sets of output data for one set of input data. Modules

¹ This Concept Graph was produced by Charlie Kilpatrick, Wesleyan University ’00.

down stream up to a *collection module* are then executed multiple times. The *collection module* receives multiple input sets for single or no output sets. In this case, ‘Display’ is the collection module.

Loops tend to break an important property of data flows. In order to prevent ambiguity, each module should be a pure function [Gre+95]. That is to say, the output of each module is fully defined by its input. However, iterative computations are stateful as they rely on values computed in past executions of the loop. The ‘Zbuffer’ and ‘Display’ module both contain state in the form of a buffer.

Outside of the CG’s loops, all state is seen transmitted through the Concept Graph. In order to capture this same clear logic within the loops, modules need to pass data upstream. For example, if the ‘ZBuffer’ module contained an output of type ‘Buffer’ connected to its own input of type ‘Buffer,’ then the module would not hide state.

Control flow could be made clearer by dynamically highlighting links when fired. This would make iterative processes inherently animated by the eduFuse system, instead of having to rely upon module displays produced by third party module designers.

5.2 Modeling Recursion

Data flow systems do not generally attempt to model recursion [AVS89][AVS97][AVS98][Gre+95][Kod+91]. The reason for this seems to be based upon the fact that recursion does not have an obvious static graphical representation. Self reference seems to require symbolic notation – one can not draw an object within itself. Indeed, many conjecture that recursion is not a visual concept, it is a symbolic one [Nic94].

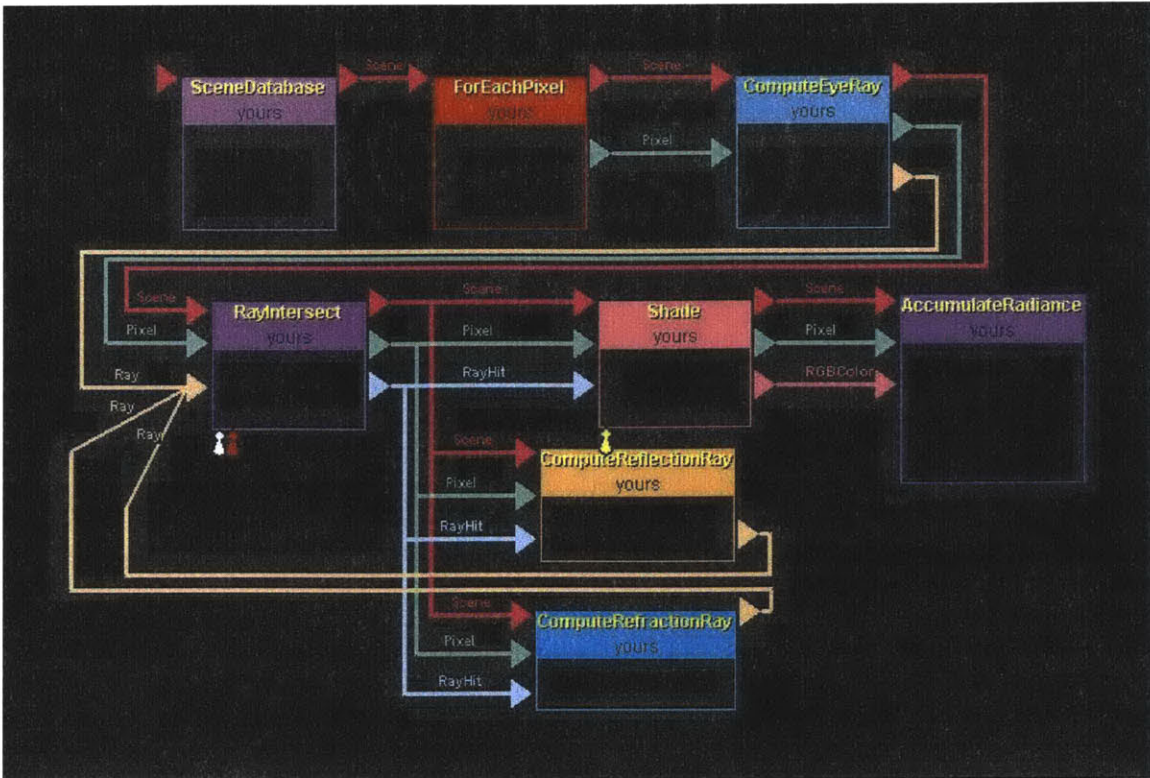


Figure 5-2: A Concept Graph with Recursion

However, the author believes that *dynamic* visualization is capable of capturing the notion of self reference. Figure 4-2¹ is a concept graph of a recursive ray tracer. The recursive step is shown using notation that the author has suggested should be used for iterative manipulation, not recursion. eduFuse offers an abstraction technique that allows a module to define itself in terms of abstracted modules. Solid colored modules without a display, as seen in Figure4-1, are examples of such modules. Clicking on one of these modules reveals another CG contained inside. Recursion can be elegantly expressed by using this abstraction technique and placing a module within itself. During execution, dynamically expanding abstraction modules would reveal this recursion in action.

5.3 Visual Ambiguities of a Module

eduFuse modules have very flexible execution scheduling. Each module defines its own routine for collecting inputs and deciding when to fire its underlying algorithm. While this affords useful flexibility that makes the CG data flow capable of handling a wide range of algorithms, it also makes control flow visually ambiguous. Figure 5-3 depicts this problem.

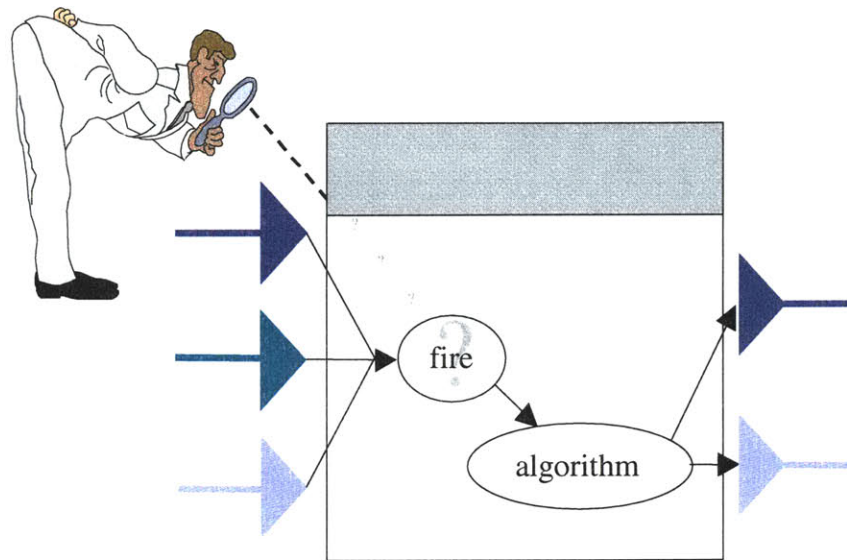


Figure 5-3: The CG observer can not directly infer when a module’s algorithm will fire.

Overly constraining the firing policy will result in less CG flexibility, making it more difficult to efficiently express complex control flows. The author believes that some flexibility should be maintained, and could be visualized by offering a variety of input or module types. Certainly, this is an area for further exploration.

¹ This Concept Graph was also produced by Charlie Kilpatrick, Wesleyan University '00.

Chapter 6

Algorithm Visualization in eduFuse: The Visualization Panel

The goal of the Visualization Panel is twofold. First, by presenting students with a simple means of verifying their algorithms, we hope to make better use of students' time by removing the "grunge" work usually associated with the testing cycle. Second, the four pedagogical modes should guide the user to a better understanding of the algorithm's process. We have succeeded in the former goal, but the latter more challenging goal has not yet been realized. We are confident that the four pedagogical modes inherent to each visualization panel do focus our efforts in the right direction. The problem, then, lies in the implementation of those modes.

In light of the motivation and research presented in the beginning of this document, it is clear that the visualization panels must contain animation if they are to yield insight into an algorithm's process. Simply viewing an algorithm's inputs and outputs presents the novice only with an understanding of the algorithm's purpose. An expert can make inferences from flawed output, but the ignorant student has no understanding from which to draw conclusions about the underlying operations.

6.1 Algorithm Connection Technique

VPs are components of the eduFuse system that communicate with modules to produce a visualization of the underlying algorithm's animation. VPs are coupled with modules through the module's inputs and outputs. Thus, a VP links with a module in the same way that other modules in the CG do. The VP associated with a module can be changed at any time, so multiple VPs can be produced for the same algorithm. The functionality of the module and VP are elegantly separated to allow for nearly independent development of algorithm code and algorithm visualization.

6.2 Incorporating Interesting Events

To produce animations with VPs, a clear connection technique for animation, not just static visualization of inputs and outputs, must be implemented. An approach based on "interesting events" would provide appropriately abstract events for animation. The module architecture should be extended to allow for modules to announce interesting events. More specifically, ports could be easily added to a module for each interesting event in the same way that ports are added for each data output, the only difference being that interesting event ports would not be visualized on the CG. In the same way that a VP has been made to map itself to an algorithm's output data, VPs could also be mapped to the interesting events produced by modules. To insure that a VP is appropriate for a module, the interesting events received by the VP should be a subset of the interesting events produced by the module.

Once the base classes for algorithms and modules are extended with this infrastructure, lesson developers can instrument reference code with appropriate event annotations. This

would greatly enhance the expressiveness of both the Reference and Manual pedagogical modes.

6.3 Manual Mode Issues

A Manual mode based on interesting events would present the student with the challenge of correctly guiding the process of an algorithm. The VP designer is challenged with providing an effective interface for capturing interesting events from the user. Manual mode demonstrations now should be able to provide students with a mental picture of the all important mapping from underlying operations to animation since the student himself suggests the operations. Under this new scenario, Manual mode would perhaps be the first pedagogical mode offered to the user, requiring that it be “solved” before unlocking the other three pedagogical modes..

Direct Manipulation is the study of graphically defining algorithms [Sta+98]. Instead of a mapping from algorithm to animation, Direct Manipulation investigates the potential of mapping an interactively input animation description to an algorithm. This work provides insight into how to effectively design Manual modes that map user interactions to interesting events.

6.4 User Mode Issues

Allowing users to instrument their own code with interesting events would allow user’s to animate their own implementations. However, several issues challenge the effectiveness of using interesting events for debugging. First, erred interesting events could drive an animation in unsuspected ways. What happens if the animation is asked to

swap an array element with another array element that does not exist? Additionally, interesting events may hide programming errors that are of a finer granularity than the events[Baz+98].

In light of these serious challenges, allowing users to animate their own implementations should not be an initial goal for the use of interesting events in eduFuse. Concentration should be focused on using interesting events to make reference mode and manual mode powerful tools for expressing the process of an algorithm. Students should continue to use *verification* of their code at an input/output as a final test to see if they can implement the algorithm.

Chapter 7

Contextual Collaboration

Since the inception of eduFuse, one of the most compelling visions that has driven its development is the desire to provide an online laboratory that is truly a shared workplace. The first thesis written on eduFuse presented the idea of NetEvents [Boy97], later termed Network Transparent Events [Tor98]. The concept behind this event model is the same as Event Broadcasting: desktops are synchronized and then all events received by one desktop are received by all desktops, thus maintaining synchronized views.

7.1 Issues with Shared Events

Nick Tornow developed a prototype system for desktop sharing in his thesis work [Nic98]. Several synchronization issues have prevented the full realization of this work.

The Concept Graph was one of the few pieces of the eduFuse environment where synchronization was not a problem. There are two underlying reasons. First, synchronizing eduFuse lesson data is straightforward. CGs were already made serializable to facilitate storage on the eduFuse server. This same serialization can be used to package up a CG and transmit it to another client, effectively performing synchronization. Thus, successful desktop sharing was achieved in the CG context.

Unfortunately, the CG was the only area of the eduFuse environment where event sharing was feasible. During the 1998 Fall Semester, eduFuse was used in an electronic classroom environment. Each student's client ran on an SGI O2 workstation. The eduFuse team was surprised to see several *variations* of the eduFuse interface appear on students' screens. Different window managers gave the eduFuse several different look-and-feels.

It was apparent that it would not be possible to ensure synchronization on any part of the eduFuse environment that relied on a system's window manager. The Java AWT had been the foundation for the eduFuse user interface, and thus nearly every view within eduFuse would not adequately support desktop sharing.

The Java AWT uses system calls to create GUIs from the system's own library of components – the root of the problem. Not only can the appearance of the components not be constrained, even worse, these AWT components do not pass the occurrence of *all* system events to the underlying Java program. For example, buttons only pass notification of being clicked, they do not pass the occurrence of mouse-over events. Thus, events that would be important for context sharing are lost.

7.2 Using Swing

Fortunately, the advent of SWING has completely alleviated the AWT problem. SWING provides pure Java GUI components. Kevin Kennedy, another eduFuse developer, outlines this solution in [Ken99].

Chapter 8

Lesson Development

eduFuse lessons are built from modular, interchangeable components. An elegant separation of Concept Graph, Module, and Visualization Panel makes it possible for eduFuse developers to share and reuse material for appropriate customization of their own lessons. Figure 8-1 depicts the current architecture and relationship of these three primary elements of eduFuse lesson content.

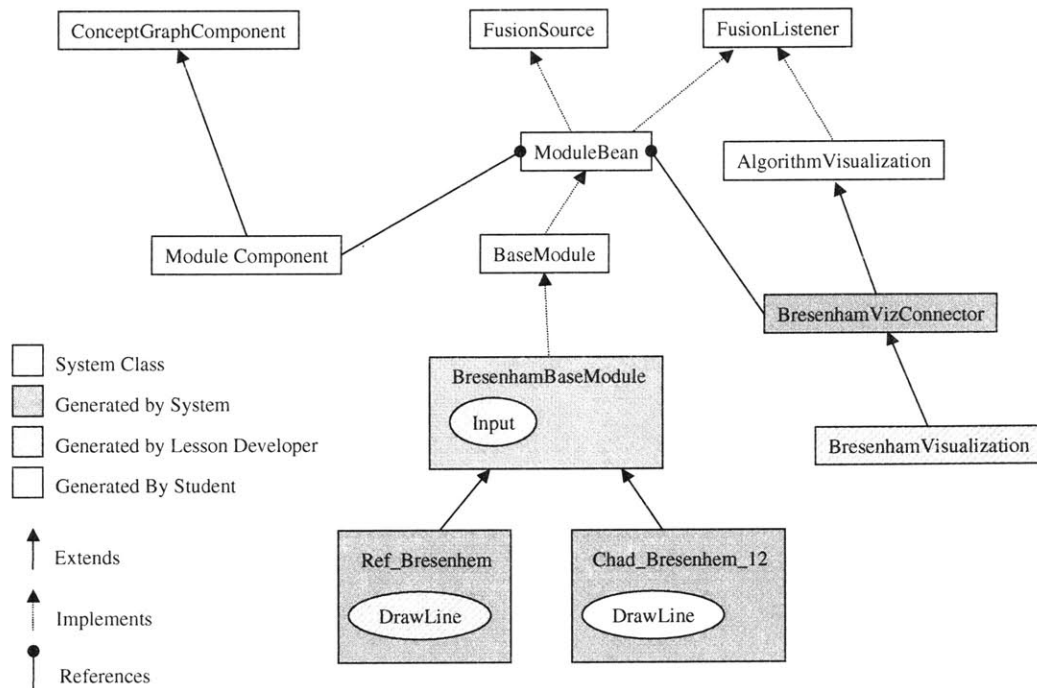


Figure 8-1: Classes Representing Elements of Lesson Content

8.1 Building Modules

As well as fostering reuse, eduFuse also supports tools for the rapid development of new content. Developers can create new modules by filling in a ‘Module Constructor’ dialog with input and output type information along with the name of the new module. The Constructor then produces the reference code base for editing by the developer, as well as a student class template that is used to create the code base for each student’s first version of the module implementation. The production of these files is nearly automated, but some work is still incumbent of the lesson developer. Figure 7-1 presents the framework that we would like to see auto generated.

Each algorithm’s unique base module class contains an `input` method that must be implemented by the lesson developer. This method is used to collect inputs and decide when to fire the module’s algorithm. As long as the firing of a module’s algorithm is not constrained by specific rules (see Section 5), this step will be necessary.

8.2 Building Visualization Panels

Visualization Panels are developed primarily outside of the eduFuse environment. To hook a VP into the system, it must extend the `AlgorithmVisualization` class. Figure 7-1 suggests that a class that handles the connections between a specific visualization and a module is supplied to the developer. This is not yet the case, but this model is currently used as a guideline for connecting a new VP with the system. Eventually, a user should

be able to select a module, and have a connection class auto-generated based upon the module's description.

8.3 Lesson Development in Practice

During the Fall 1999 semester, an eduFuse server was deployed for use by a small computer science class at Washington State University instructed by Professor Ulrike Axen. The goal of the class was to produce a series of module lessons for the eduFuse system. Professor Axen and each of the students from the class created a VP for an algorithm likely to be found in an introductory algorithms course. The group developed a noteworthy addition to eduFuse's algorithm animation framework: a "VCR" API. This allows an Algorithm Animation to be played and rewound at single steps or various speeds. Some of the students actually managed to create VPs that produced pseudo animations (a series of static frames) which took advantage of the VCR interface. These VPs produced significant insight into the process of their topic algorithms.

The animations produced by the WSU group are based upon "interesting events." The reference algorithms were annotated with a series of calls that acknowledged the occurrence of the events. Trace files were created by the module, and delivered through an output to the VP. The VP equipped with the VCR control panel produced animation by stepping forward and backwards the animation at a rate controlled by the user.

Although the method by which trace files were presented to the VP is a bit of a hack on the eduFuse architecture, this work did serve as a "proof of concept" for the value of animations in eduFuse. The WSU developers made vast improvements to the educational power of the VP's manual mode. Instead of simply guessing outputs, students would

start from the beginning of the algorithms operation and interactively suggest interesting events to drive the algorithm.

Chapter 9

Conclusions and Future Direction

Perhaps the most unique aspect of the eduFuse platform is not any singular facility that it offers, but rather the breadth of technology that it attempts to integrate into a unified learning environment. What besides eduFuse offers a single place for examining coursework, collaborating, learning through interactive visualizations, verifying through interactive visualization, and submitting and receiving feedback?

9.1 Administration

Administration is so convenient in eduFuse that it practically happens without educators or pupils being away. This is primarily because administrative organizations are visibly abstracted, and administrative tasks, such as grading assignments, are available at the click of a button. Administration can be greatly enhanced by associating more administrative data within the context of the Concept Graph modules. For example, Feedback Forms should not only be sent to students by email, they should be appended to graded modules for convenient retrieval by students. Modules could also contain hyperlinks to relevant educational materials.

9.2 Collaboration

Collaboration will truly take off when visualization panels written in SWING allow for desktop sharing. With manual modes that actually drive the *process* of algorithms,

educators or simply peers will be able to watch and interactively help students explore a visual mapping of the algorithms process.

9.3 Visualization

Interactive visualization can be a cornerstone to education in theoretical material. Better defined CGs will more clearly establish high level programming ideas, and the use of interactive algorithm *animation* can make Visualization Panels true teachers as well as verifiers.

9.4 Lesson Development

Modular lesson content lends itself reuse and augmentation. The ability for client side developers to submit content via the web will foster circulation, and in turn, creation of course material.

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