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## Chosen-prefix collisions for MD5 and applications

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Marc Stevens\*

Cryptology Group, CWI,  
P.O. Box 94079, 1090 GB Amsterdam, The Netherlands  
E-mail: [marc@marc-stevens.nl](mailto:marc@marc-stevens.nl)

\*Corresponding author

Arjen K. Lenstra

Laboratory for Cryptologic Algorithms,  
École Polytechnique Fédérale de Lausanne,  
Station 14, CH-1015 Lausanne, Switzerland

Benne de Weger

EiPSI, Faculty of Mathematics and Computer Science,  
TU Eindhoven, P.O. Box 513, 5600 MB Eindhoven, The Netherlands  
E-mail: [b.m.m.d.weger@tue.nl](mailto:b.m.m.d.weger@tue.nl)

**Abstract:** We present a novel, automated way to find differential paths for MD5. Its main application is in the construction of *chosen-prefix collisions*. We have shown how, at an approximate expected cost of  $2^{39}$  calls to the MD5 compression function, for any two chosen message prefixes  $P$  and  $P'$ , suffixes  $S$  and  $S'$  can be constructed such that the concatenated values  $P\|S$  and  $P'\|S'$  collide under MD5. The practical attack potential of this construction of chosen-prefix collisions is of greater concern than the MD5-collisions that were published before. This is illustrated by a pair of MD5-based X.509 certificates one of which was signed by a commercial Certification Authority (CA) as a legitimate website certificate, while the other one is a certificate for a rogue CA that is entirely under our control (cf. <http://www.win.tue.nl/hashclash/rogue-ca/>). Other examples, such as MD5-colliding executables, are presented as well. More details can be found on <http://www.win.tue.nl/hashclash/ChosenPrefixCollisions/>.

**Keywords:** MD5; chosen-prefix collision attack; differential analysis; certification authority; playstation 3

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**Biographical notes:** Marc Stevens received his Master of Science degree from the Eindhoven University of Technology, the Netherlands, in 2007. Currently, he is a PhD student at the Mathematical Institute of Leiden University and the Cryptology group at CWI. He aims to defend his PhD thesis early 2012. His areas of interest include hash functions, cryptanalysis and efficient implementation of collision attacks.

Arjen K. Lenstra worked in the USA from 1984 until 2006: until 1989 he was a Visiting Professor at the Computer Science Department of The University of Chicago; until 1996 he was a Senior Scientist at the Mathematics and Cryptology Research Group of Bell Communications Research (Bellcore) in Morristown, NJ; until 2004 he was the Vice-president of Emerging Technologies of Citigroup in New York City, first at the corporate technology office, then from 2002 at Citigroups corporate information security office; until 2006 he was a distinguished member of technical staff at the Computing Sciences Centre of Alcatel-Lucent Bell Laboratories in Murray Hill, NJ. From 2000 to 2006, he was a Part-time Professor of Cryptology at the Technical University Eindhoven. In January 2006, he became a Full Professor at the School of Computer and Communication Sciences of EPFL, Lausanne, Switzerland, where he heads the Laboratory for Cryptologic Algorithms and works on computational and implementation aspects and design of cryptologic methods.

Benne de Weger received his PhD in computational number theory in 1988 from the University of Leiden. He worked at the universities of Twente and Rotterdam as an Assistant Professor of Mathematics; in the industry as a Cryptographic Software Engineer and Information Security Consultant, and currently he is an Assistant Professor at the Eindhoven University of Technology. His research interests include hash functions, public key cryptosystems, and computational number theory.

## 1 Introduction

### 1.1 Cryptographic hash functions

Modern information security methods heavily rely on cryptographic hash functions, functions that map bitstrings of arbitrary length to fixed-length bitstrings called *hash values*. Cryptographic hash functions are designed in such a way that a number of security related conditions are satisfied: *collision resistance*, *second pre-image resistance* and *pre-image resistance*. Commonly used cryptographic hash functions are MD5 (Rivest, 1992), SHA-1, and SHA-256 (NIST, 2008), mapping their inputs to fixed-lengths outputs of 128, 160, and 256 bits, respectively. We refer to Menezes et al. (1996) for a description of the iterated design principle of these hash functions and the above security properties. The focus of this article is MD5's collision resistance: it should be practically infeasible to find two different inputs that have the same MD5 hash value.

### 1.2 Previous results on collision attacks for MD5

In August 2004 at the rump session of the annual CRYPTO conference in Santa Barbara, Xiaoyun Wang (Wang et al., 2004) presented a pair of two-block messages that collide under MD5. The details of their attack construction were presented by Wang and Yu (2005). It describes a manually found differential path for MD5 and introduces the concept of *near-collision blocks*: a pair of input blocks that results in specifically targeted output-differences. It allows computation of a new collision in a few hours of CPU time. Improved versions of these attacks are commented on at the end of this section.

### 1.3 Impact of previous results

Although Wang et al.'s random looking collisions for MD5 by themselves do not pose any danger, it was shown in Kaminsky (2004) and Mikle (2004) how those original collisions can be used to mislead integrity checking software and replace benign files with malicious versions without detection. Furthermore, it was immediately clear that any value can be used for the IHV (in this paper the chaining variable will be denoted by IHV, for Intermediate Hash Value) at the beginning of the two-block collision search, not just MD5's initial value as in their example collision. This freedom to choose the IHV allowed several authors to use this attack construction for slightly more ulterior purposes, e.g. by inserting both collision blocks

in different Postscript documents that collide under MD5 (Daum and Lucks, 2005).

None of these developments in the collision attacks for MD5 spoke in favor of continued usage of MD5, but the potential for abuse of these types of collisions was limited. Initially, serious misuse was believed to be prevented by the lack of control over the contents of the collision blocks. In Lenstra and de Weger (2005), it was shown, however, that for any pair of meaningless data  $(M, M')$  a suffix  $T$  can easily be found such that both concatenations  $M||T$  and  $M'||T$  are fully meaningful. This allows the following attack construction. First, for any meaningful common prefix  $P$ , collision blocks  $(M, M')$  may be constructed using Wang and Yu's approach such that  $P||M$  and  $P||M'$  collide under MD5. Even though  $P||M$  and  $P||M'$  can be expected to be partially meaningless, an appendage  $T$  can subsequently be calculated such that both  $P||M||T$  and  $P||M'||T$  are fully meaningful. Furthermore, due to the iterative structure of MD5, they also still collide under MD5. This shows that the argument that MD5-collisions of this form are mostly harmless because of their lack of structure is in principle invalid. The above attack construction allowed the realisation of two different X.509 certificates with identical Distinguished Names and identical MD5-based signatures but different public keys (Lenstra and de Weger, 2005). Such pairs of certificates theoretically violate the security of the X.509 Public Key Infrastructure, however the limitation to identical Distinguished Names does not allow abuse in practice.

Scenarios causing more serious threats did not emerge due to a severe limitation of this collision attack, namely that both colliding messages must have identical IHVs at the beginning of the collision blocks. This requirement is most naturally fulfilled by making the documents identical up to that point. Therefore, we call such collisions *identical-prefix collisions*. In the above example,  $P$  would be the identical prefix.

### 1.4 New contributions

The most important contribution of this paper is the removal of the identical prefix condition leading to *chosen-prefix collisions*, a result that we originally presented at EUROCRYPT 2007 (Stevens et al., 2007), and of which a considerably improved version was first presented at CRYPTO 2009 (Stevens et al., 2009). Here we present a full description of our improved chosen-prefix collision attack. We show how *any* pair of IHVs can be made to collide under MD5 by appending properly chosen

collision blocks. More precisely, we show how, for any two chosen message prefixes  $P$  and  $P'$ , suffixes  $S$  and  $S'$  can be constructed such that the concatenated values  $P\|S$  and  $P'\|S'$  collide under MD5. Such collisions will be called chosen-prefix collisions (though *different-prefix collisions* would have been appropriate as well). Our attack construction is based on a “birthday” search combined with a novel, automated way to find differential paths for MD5. It has an approximate expected cost of  $2^{39}$  calls to the MD5 compression function. In practical terms, this translates to about a day on a standard quad-core PC per chosen-prefix collision. This notable improvement over the 6 months on thousands of PCs for a single chosen-prefix collision that we reported earlier in the EUROCRYPT 2007 paper (Stevens et al., 2007), was triggered by the application presented in the CRYPTO 2009 paper (Stevens et al., 2009).

### 1.5 Significance and impact of the new contributions

Chosen-prefix collisions have a greater threat potential than identical-prefix ones. Using the diamond construction from Kelsey and Kohno (2006) along with chosen-prefix collisions, any number of documents of one’s choice can be made to collide after extending them with relatively short and innocuously looking appendages that can easily remain hidden to the unsuspecting reader when popular document formats (such as PDF, Postscript, or MS Word) are used. We illustrate this in Section 5.3 with a Nostradamus attack to predict the winner of the 2008 US Presidential elections. Implementing a herding attack we constructed 12 different but MD5-colliding PDF files, each predicting a different winner. Their common hash serves as commitment to our prediction of the outcome. Our prediction was correct.

Similarly, chosen-prefix collisions can be used to mislead, for instance, download integrity verification of code signing schemes, by appending collision blocks to executables. Details, and how it improves upon previous such constructions, can be found in Section 5.4.

The most convincing application of MD5-collisions, however, would target the core of the Public Key Infrastructure (PKI) and truly undermine its security by affecting authenticity of users (Section 4.1 of Stevens et al., 2007). The most obvious way to realise this would be by constructing *colliding certificates*, i.e., certificates for which the to-be-signed parts have the same cryptographic hash and therefore the same digital signature. This is undesirable, because the signature of one of the to-be-signed parts, as provided by a Certification Authority (CA), is also a valid signature for the other to-be-signed part. Thus, this gives rise to a pair of certificates, one of which is legitimate, but the other one is a rogue certificate.

Constructing colliding certificates that affect authenticity seemed to be out of reach, however. As mentioned in the EUROCRYPT 2007 paper (Stevens et al., 2007) that introduced chosen-prefix collisions, these collisions allow us to construct two X.509 certificates with different Distinguished Names and different public keys, but identical MD5-based signatures. This improves upon the

construction from Lenstra and de Weger (2005) mentioned above, but is hardly more threatening due to two problems. In the first place, we need full control over the prefixes of the certificates’ to-be-signed parts, to be able to calculate the collision blocks. When using a ‘real life’ CA, however, that CA has final control over the contents of one of the to-be-signed parts: in particular, it inserts a serial number and a validity period. Furthermore, our construction as in Stevens et al. (2007) results in 8192-bit RSA moduli, which is quite a bit longer than the 2048-bit upper bound that is enforced by some CAs.

It was pointed out to us by three of our co-authors on the CRYPTO 2009 follow-up paper (Stevens et al., 2009), that there are circumstances where, with sufficiently high probability, the first of the above two problems can be circumvented. Naively, one would expect that a somewhat more extensive search would suffice to address the remaining problem of reducing the length of the RSA moduli to a generally acceptable 2048 bits. Substantially more extensive improvements to all stages of the original chosen-prefix construction from the EUROCRYPT 2007 paper (Stevens et al., 2007) were required, though. This is a nice illustration of scientific progress being driven by practical applications. Furthermore, more computational power had to be brought to bear to deal with the timing restrictions of reliably predicting the CA’s contribution. Ultimately this led to the rogue CA certificate mentioned in the abstract, generated in about a day on a cluster of 215 PlayStation 3 game consoles. With the private key of a CA under one’s control, one can create ‘trusted’ certificates at will. This effectively allows one to perform a man-in-the-middle attack for all secure websites against users whose means of electronic communications have been subverted. We purposely crippled our rogue CA certificate to prevent such misuse. From the heartwarming industry reception of our rogue CA construction, which is further described in Section 5.2, it must be concluded that we finally managed to present a sufficiently convincing argument to discontinue usage of MD5 for digital signature applications. Furthermore, we would like to note that browser vendors such as Microsoft, Mozilla and Google and other software companies, can revoke the trust in any CA certificate in their products if deemed necessary.

### 1.6 Very brief summary of new techniques

The possibility of chosen-prefix collisions was mentioned already in Gauravaram et al. (2006, Section 4.2 case 1) and, in the context of SHA-1, in de Cannière and Rechberger (2006) and on <http://www.iaik.tugraz.at/content/research/krypto/sha1/>.

This paper is an updated version of the EUROCRYPT 2007 paper (Stevens et al., 2007), incorporating the improvements mentioned above and as described in Stevens (2007) and in the CRYPTO 2009 paper (Stevens et al., 2009). The new applications mentioned above have been realised using the following main improvements. In the first place we introduce an extended family of differential

paths compared to Stevens et al. (2007). Secondly, we use a more powerful birthday search procedure which reduces the overall complexity from  $2^{50}$  to  $2^{39}$  MD5 compression function calls. This procedure also introduces a time-memory trade-off and more flexibility in the birthday search complexity to allow for variability in the expected number of near-collision blocks. Finally, we have a much improved implementation exploiting the wide variety of features of a cluster of PlayStation 3 game consoles.

### 1.7 Outline of article

MD5 and the Merkle-Damgård construction on which it is based are described in detail in Section 2. Section 3 gives a high level overview of our method to construct chosen-prefix collisions. Section 4 presents the method in full detail. The three proof of concept applications are presented in Section 5.

### 1.8 Other improvements of Wang et al.'s original collision finding method

Another application of our automated differential path finding method is a speedup of the identical-prefix collision attack by Wang et al. In combination with the idea of tunnels from Klima (2006) collisions can be found in  $2^{25}$  MD5 compression function calls, see Stevens (2007). Source and binary code for this improvement is available on <http://www.win.tue.nl/hashclash/>. Note that Xie et al. (2008) used a different method for identical-prefix collisions, reaching a complexity of  $2^{21}$  MD5 compression function calls, and that in the meantime identical-prefix collisions for MD5 can be found in  $2^{16}$  MD5 compression function calls (Stevens et al., 2009).

This new identical-prefix collision attack is used in Section 4.8 to construct very short chosen-prefix collisions with complexity of about  $2^{53.2}$  MD5 compressions, where the collision-causing suffixes are only 596 bits long instead of several thousands of bits.

### 1.9 Summary of old and new results

In Table 1 we present a historical overview of the decline in complexity of MD5 and SHA-1 collision finding. For historical interest we include claims that were presented but that have never been published (indicated by “u: ...” in Table 1) and a claim that has been withdrawn (indicated by “w: ...” in Table 1). It clearly illustrates that attacks against MD5 keep getting better, and that the situation around SHA-1 is unclear. Not reflected in the table is the fact that already in 1993 it was known that there was serious trouble with MD5, based on collisions in its compression function (den Boer and Bosselaers, 1994; Dobbertin, 1996). We leave any speculation about the future of SHA-1 cryptanalysis to the knowledgeable reader.

## 2 Merkle-Damgård and MD5

In this section we describe the Merkle-Damgård construction in Section 2.1, then we fix some notation in Section 2.2 and give a description of MD5 in Section 2.3.

### 2.1 Merkle-Damgård

The well known Merkle-Damgård construction describes exactly how to construct a hash function based on a compression function with fixed-size inputs in an iterative

**Table 1** Collision complexities – historical overview

Year	MD5			
	Identical-prefix		Chosen-prefix	
pre-2004	$2^{64}$	(Trivial)	$2^{64}$	(Trivial)
2004	$2^{40}$	(Wang et al., 2004), (Wang and Yu, 2005)		
2005	$2^{37}$	(Klima, 2005)		
2006	$2^{32}$	(Klima, 2006), (Stevens, 2006)	$2^{49}$	(Stevens et al., 2007)
2007	$2^{25}$	(Stevens, 2007)	$2^{42}$	
2008	$2^{21}$	(Xie et al., 2008)		
2009	$2^{16}$	(Stevens et al., 2009)	$2^{39}$	(Stevens et al., 2009)
Year	SHA-1			
	Identical-prefix		Chosen-prefix	
pre-2004	$2^{80}$	(Trivial)	$2^{80}$	(Trivial)
2005	$2^{69}$	(Wang et al., 2005b)		
	(u: $2^{63}$ )	(Wang et al., 2005a)		
2006			(u: $2^{80-\epsilon}$ )	(Rechberger, 2006)
2007	(u: $2^{61}$ )	(Mendel et al., 2007)		
2008				
2009	(w: $2^{52}$ )	(McDonald et al., 2009)		
2012	$2^{65}$	(Stevens, 2012)	$2^{77}$	(Stevens, 2012)

Notes: Claims preceded by ‘u:’ remain unpublished and ‘w:’ indicates that the paper was withdrawn. Complexity is given as the number of calls to the relevant compression function (cf. Section 2). The figures are optimised for speed, i.e., for collisions using any number of near-collision blocks. For other collision lengths the complexities may differ.

structure as is depicted in Figure 1. Since it has been proven that the hash function is collision resistant if the underlying compression function is collision resistant, the majority of all the currently used hash functions are based on this Merkle-Damgård construction. The construction builds a hash function based on a compression function that takes two fixed-size inputs, namely a chaining value denoted by IHV and a message block, and outputs a new IHV. For instance, MD5's compression function operates on an IHV of bit length 128 and a message block consisting of 512 bits. An input message is first padded with a single 1 bit followed by a number  $X$  of 0 bits and lastly the original message length encoded in 64 bits. The number  $X$  of 0 bits to be added is defined as the lowest possible number so that the entire padded message bit length is an integer multiple of 512. The padded message is now split into  $N$  blocks of size exactly 512 bits. The hash function starts with a fixed public value for  $\text{IHV}_0$  called the IV (Initial Value). For each subsequent message block  $M_i$  it calls the compression function with the current  $\text{IHV}_i$  and the message block  $M_i$  and stores the output as the new  $\text{IHV}_{i+1}$ . After all blocks are processed it outputs the last  $\text{IHV}_N$  after an optional finalisation transform.

## 2.2 Preliminaries

MD5 operates on 32-bit words  $(v_{31}v_{30} \dots v_0)$  with  $v_i \in \{0, 1\}$ , that are identified with elements  $v = \sum_{i=0}^{31} v_i 2^i$  of  $\mathbb{Z}/2^{32}\mathbb{Z}$  (the ring of integers modulo  $2^{32}$ , represented by the set of least non-negative residues  $\{0, 1, \dots, 2^{32} - 1\}$ ) and referred to as 32-bit integers. In this paper we switch freely between these representations.

A *binary signed digit representation* (BSDR) for a 32-bit word  $X$  is defined as  $(k_i)_{i=0}^{31}$ , where

$$X = \sum_{i=0}^{31} 2^i k_i, \quad k_i \in \{-1, 0, +1\}.$$

Many different BSDRs exist for any non-zero  $X$ . The *weight* of a BSDR is the number of non-zero  $k_i$ 's. A particularly useful BSDR is the Non-Adjacent Form (NAF), where no two non-zero  $k_i$ 's are adjacent. The NAF is not unique since we work modulo  $2^{32}$  (making  $k_{31} = +1$

equivalent to  $k_{31} = -1$ ), but uniqueness of the NAF can be enforced by choosing  $k_{31} \in \{0, +1\}$ . Among the BSDRs of an integer, the NAF has minimal weight (Clark and Liang, 1973). It can easily be computed as  $\text{NAF}(n) = (a_i - b_i)_{i=0}^{31}$  where  $a_i, b_i \in \{0, 1\}$  such that  $\sum_{i=0}^{31} a_i 2^i = n + \lfloor \frac{n}{2} \rfloor \bmod 2^{32}$  and  $\sum_{i=0}^{31} b_i 2^i = \lfloor \frac{n}{2} \rfloor$ .

Integers are denoted in hexadecimal as, for instance,  $1\text{E}_{16}$  and in binary as  $00011110_2$ . For bitstrings  $X$  and  $Y$  we use the following notation:

- $X \wedge Y$  is the bitwise AND of  $X$  and  $Y$ ;
- $X \vee Y$  is the bitwise OR of  $X$  and  $Y$ ;
- $X \oplus Y$  is the bitwise XOR of  $X$  and  $Y$ ;
- $\bar{X}$  is the bitwise complement of  $X$ ;
- for  $X, Y \in \mathbb{Z}/2^{32}\mathbb{Z}$ :
- $X[i]$  is the  $i$ -th bit of the regular binary representation of  $X$ ;
- $X + Y$  resp.  $X - Y$  is the addition resp. subtraction modulo  $2^{32}$ ;
- $RL(X, n)$  (resp.  $RR(X, n)$ ) is the cyclic left (resp. right) rotation of  $X$  by  $n$  bit positions:

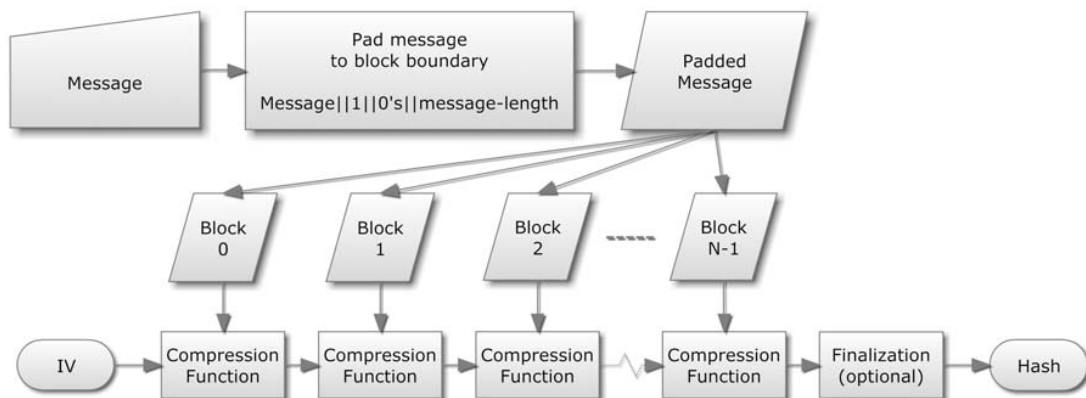
$$\begin{aligned} &RL(10100100 \dots 00000001_2, 5) \\ &= 100 \dots 0000000110100_2; \end{aligned}$$

and for a 32-digit BSDR  $X$ :

- $X[i]$  is the  $i$ -th signed bit of  $X$ ;
- $RL(X, n)$  (resp.  $RR(X, n)$ ) is the cyclic left (resp. right) rotation of  $X$  by  $n$  positions.
- $w(X)$  is the weight of  $X$ .

For chosen message prefixes  $P$  and  $P'$  we seek suffixes  $S$  and  $S'$  such that the messages  $P\|S$  and  $P'\|S'$  collide under MD5. In this paper any variable  $X$  related to the message  $P\|S$  or its MD5 calculation, may have a corresponding variable  $X'$  related to the message  $P'\|S'$  or its MD5 calculation. Furthermore, for such a 'matched' variable  $X \in \mathbb{Z}/2^{32}\mathbb{Z}$  we define  $\delta X = X' - X$  and  $\Delta X = (X'[i] - X[i])_{i=0}^{31}$ , which is a BSDR of  $\delta X$ . For a matched

**Figure 1** Merkle-Damgård construction



variable  $Z$  that consist of tuples of 32-bit integers, say  $Z = (z_1, z_2, \dots)$ , we define  $\delta Z$  as  $(\delta z_1, \delta z_2, \dots)$ .

### 2.3 Description of MD5

#### 2.3.1 MD5 overview

MD5 follows the Merkle-Damgård construction and works as follows, (Rivest, 1992):

- 1 *Padding*. Pad the message: first a ‘1’-bit, next the least number of ‘0’ bits to make the bitlength equal to  $448 \bmod 512$ , and finally the bitlength of the original unpadded message as a 64-bit little-endian integer. As a result the total bitlength of the padded message is  $512N$  for a positive integer  $N$ .
- 2 *Partitioning*. Partition the padded message into  $N$  consecutive 512-bit blocks  $M_1, M_2, \dots, M_N$ .
- 3 *Processing*. To hash a message consisting of  $N$  blocks, MD5 goes through  $N + 1$  states  $\text{IHV}_i$ , for  $0 \leq i \leq N$ , called the *intermediate hash values*. Each intermediate hash value  $\text{IHV}_i$  consists of four 32-bit words  $a_i, b_i, c_i, d_i$ . For  $i = 0$  these are fixed public values:

$$(a_0, b_0, c_0, d_0) = (67452301_{16}, \text{EFCDB89}_{16}, \\ 98BADCFE_{16}, 10325476_{16}).$$

For  $i = 1, 2, \dots, N$  intermediate hash value  $\text{IHV}_i$  is computed using the MD5 compression function described in detail below:

$$\text{IHV}_i = \text{MD5Compress}(\text{IHV}_{i-1}, M_i).$$

- 4 *Output*. The resulting hash value is the last intermediate hash value  $\text{IHV}_N$ , expressed as the concatenation of the hexadecimal byte strings of the four words  $a_N, b_N, c_N, d_N$ , converted back from their little-endian representation.

#### 2.3.2 MD5 compression function

The input for the compression function  $\text{MD5Compress}(\text{IHV}, B)$  consists of an intermediate hash value  $\text{IHV} = (a, b, c, d)$  and a 512-bit message block  $B$ . The compression function consists of 64 *steps* (numbered 0 to 63), split into four consecutive *rounds* of 16 steps each. Each step  $t$  uses modular additions, a left rotation, and a non-linear function  $f_t$ , and involves an *Addition Constant*  $AC_t$  and a *Rotation Constant*  $RC_t$ . These are defined as follows (see also Appendix A):

$$AC_t = \lfloor 2^{32} |\sin(t+1)| \rfloor, \quad 0 \leq t < 64,$$

$$(RC_t, RC_{t+1}, RC_{t+2}, RC_{t+3}) = \begin{cases} (7, 12, 17, 22) & \text{for } t = 0, 4, 8, 12, \\ (5, 9, 14, 20) & \text{for } t = 16, 20, 24, 28, \\ (4, 11, 16, 23) & \text{for } t = 32, 36, 40, 44, \\ (6, 10, 15, 21) & \text{for } t = 48, 52, 56, 60. \end{cases}$$

The non-linear function  $f_t$  depends on the round:

$$f_t(x, y, z) = \begin{cases} F(x, y, z) = (x \wedge y) \oplus (\bar{x} \wedge z) & \text{for } 0 \leq t < 16, \\ G(x, y, z) = (z \wedge x) \oplus (\bar{z} \wedge y) & \text{for } 16 \leq t < 32, \\ H(x, y, z) = x \oplus y \oplus z & \text{for } 32 \leq t < 48, \\ I(x, y, z) = y \oplus (x \vee \bar{z}) & \text{for } 48 \leq t < 64. \end{cases} \quad (1)$$

The message block  $B$  is partitioned into sixteen consecutive 32-bit words  $m_0, m_1, \dots, m_{15}$  (with little-endian byte ordering), and expanded to 64 words  $W_t$ , for  $0 \leq t < 64$ , of 32 bits each (see also Appendix A):

$$W_t = \begin{cases} m_t & \text{for } 0 \leq t < 16, \\ m_{(1+5t) \bmod 16} & \text{for } 16 \leq t < 32, \\ m_{(5+3t) \bmod 16} & \text{for } 32 \leq t < 48, \\ m_{(7t) \bmod 16} & \text{for } 48 \leq t < 64. \end{cases}$$

We follow the description of the MD5 compression function from Hawkes et al. (2004) because its ‘unrolling’ of the cyclic state facilitates the analysis. For each step  $t$  the compression function algorithm maintains a working register with 4 state words  $Q_t, Q_{t-1}, Q_{t-2}$  and  $Q_{t-3}$  and calculates a new state word  $Q_{t+1}$ . With  $(Q_0, Q_{-1}, Q_{-2}, Q_{-3}) = (b, c, d, a)$ , for  $t = 0, 1, \dots, 63$  in succession  $Q_{t+1}$  is calculated as follows:

$$\begin{aligned} F_t &= f_t(Q_t, Q_{t-1}, Q_{t-2}), \\ T_t &= F_t + Q_{t-3} + AC_t + W_t, \\ R_t &= RL(T_t, RC_t), \\ Q_{t+1} &= Q_t + R_t. \end{aligned} \quad (2)$$

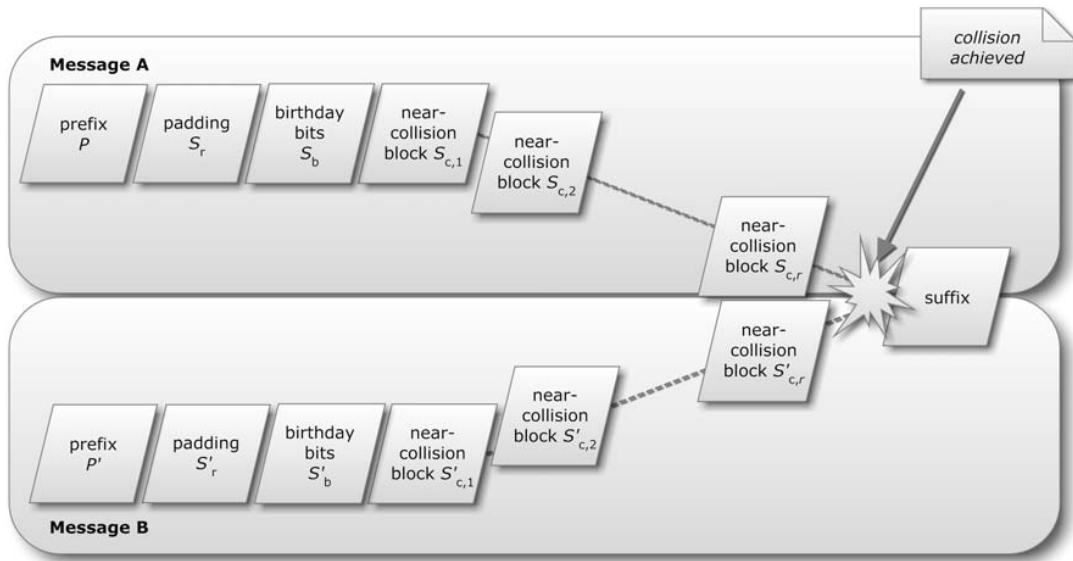
After all steps are computed, the resulting state words are added to the intermediate hash value and returned as output:

$$\begin{aligned} \text{MD5Compress}(\text{IHV}, B) \\ = (a + Q_{61}, b + Q_{64}, c + Q_{63}, d + Q_{62}). \end{aligned} \quad (3)$$

### 3 An overview of chosen-prefix collisions for MD5

Given two arbitrary chosen messages, our purpose is to find appendages such that the extended messages collide under MD5. In this section we give a summary of our method.

Given the two arbitrary messages, we first apply padding to the shorter of the two, if any, to make their lengths equal. This ensures that the Merkle-Damgård strengthening – which is applied after the last bits of the message and involves the message’s bitlength – is identical for the two messages resulting from this construction. We impose the additional requirement that both resulting messages are a specific number of bits (such as 64 or 96) short of a whole number of blocks. In principle this can be avoided, but it leads to an efficient method that allows relatively easy presentation. All these requirements can easily be met, also in applications with stringent formatting restrictions.

**Figure 2** Chosen-prefix collision overview

Given this message pair, we modify a suggestion by Xiaoyun Wang (private communication) by finding a pair of  $k$ -bit values that, when appended to the last incomplete message blocks, results in a specific form of difference vector between the IHVs after application of the MD5 compression function to the extended message pair. Finding the  $k$ -bit appendages can be done using a birthday search procedure.

The specific form of difference vector between the IHVs that is aimed for during the birthday search is such that the difference pattern can relatively easily be removed compared to the more or less random difference pattern one may expect given two arbitrarily chosen prefixes. Removing the difference pattern is done by further appending to the messages a sequence of near-collision blocks. Each pair of near-collision blocks targets a specific subpattern of the remaining differences. For each such subpattern we use an automated, improved version of Wang and Yu's original approach to construct a new differential path, as described in detail in Section 4 below, and subsequently use the differential path to construct a pair of near-collision blocks. Appending those blocks to the two messages results in a new difference vector between the new IHVs from which the targeted subpattern has been eliminated compared to the previous difference vector. The construction continues as long as differences exist. The above process is depicted in Figure 2.

How the various steps involved in this construction are carried out and how their parameters are tuned depends on what needs to be optimised. Extensive birthday searching can be used to create difference patterns that require a small number of pairs of near-collision blocks. When combined with a properly chosen large family of differential paths, a single pair of near-collision blocks suffices to complete the collision right away. However, it may make the actual near-collision block construction quite challenging, which leads to the intuitively expected result that finding very short chosen-prefix collision-causing appendages is

relatively costly. On the other side of the spectrum, fast birthday searching combined with a smaller family of differential paths leads to the need for many successive pairs of near-collision blocks, each of which can quickly be found: if one is willing to accept long chosen-prefix collision-causing appendages, the overall construction can be done quite fast. Between the two extremes almost everything can be varied: number of near-collision blocks, their construction time given the differential path, time to find the full differential path, birthday search time and space requirements, etc., leading to a very wide variety of 'optimal' choices.

The next section contains the details of the various steps in this process, and how the steps are best glued together depending on the circumstances. Application scenarios that impose different restrictions on the chosen-prefix collisions are then presented in Section 5.

#### 4 Chosen-prefix collision construction for MD5, details

In Section 4.1 an outline of the chosen-prefix collision construction is given; this includes a short description of the birthday search referred to in Section 3, the further details of which can be found in Section 4.2. Differential paths are introduced in Section 4.3 and Sections 4.4.1 through 4.4.6 describe how to construct partial and full differential paths. Collision finding — the search for actual near-collision blocks that satisfy a given differential path — is treated in Section 4.5 and an optional differential path preprocessing step to improve collision finding is presented in Section 4.5.3. Section 4.6 gives some details of our implementations and the complexity analysis is treated in Section 4.7. Finally, we present a practical chosen-prefix collision attack using a single near-collision block in Section 4.8.

**Table 2** Family of partial differential paths using  $\delta m_{11} = \pm 2^{p-10 \bmod 32}$ , where  $s_0, \dots, s_{w'} \in \{-1, 0, +1\}$  and  $w' = \min(w, 31 - p)$  for a fixed  $w \geq 0$ 

$t$	$\delta Q_t$	$\delta F_t$	$\delta W_t$	$\delta T_t$	$\delta R_t$	$RC_t$
31	$\mp 2^{p-10 \bmod 32}$					
32	0					
33	0					
34	0	0	$\pm 2^{p-10 \bmod 32}$	0	0	16
35 – 60	0	0	0	0	0	.
61	0	0	$\pm 2^{p-10 \bmod 32}$	$\pm 2^{p-10 \bmod 32}$	$\pm 2^p$	10
62	$\pm 2^p$	0	0	0	0	15
63	$\pm 2^p$	0	0	0	0	21
64	$\pm 2^p$ $+ \sum_{\lambda=0}^{w'} s_\lambda 2^{p+21+\lambda \bmod 32}$					

Note: Interesting values for the parameter  $w$  are between 2 and 5.

#### 4.1 Outline of the collision construction

A chosen-prefix collision for MD5 is a pair of messages  $M$  and  $M'$  that consist of arbitrarily chosen prefixes  $P$  and  $P'$  (not necessarily of the same length), together with constructed suffixes  $S$  and  $S'$ , such that  $M = P\|S$ ,  $M' = P'\|S'$ , and  $\text{MD5}(M) = \text{MD5}(M')$ . The suffixes consist of three parts: padding bitstrings  $S_r, S'_r$ , followed by ‘birthday’ bitstrings  $S_b, S'_b$  both of bitlength  $64 + k$ , where  $0 \leq k \leq 32$  is a parameter, followed by bitstrings  $S_c, S'_c$  each consisting of a sequence of near-collision blocks. The padding bitstrings are chosen such that the bitlengths of  $P\|S_r$  and  $P'\|S'_r$  are both equal to  $512n - 64 - k$  for a positive integer  $n$ . The birthday bitstrings  $S_b, S'_b$  are determined in such a way that application of the MD5 compression function to  $P\|S_r\|S_b$  and  $P'\|S'_r\|S'_b$  results in  $\text{IHV}_n$  and  $\text{IHV}'_n$ , respectively and in the notation from Section 2.3.1, for which  $\delta \text{IHV}_n$  has a certain desirable property that is explained below.

The idea is to eliminate the difference  $\delta \text{IHV}_n$  in  $r$  consecutive steps, for some  $r$ , by writing  $S_c = S_{c,1}\|S_{c,2}\|\dots\|S_{c,r}$  and  $S'_c = S'_{c,1}\|S'_{c,2}\|\dots\|S'_{c,r}$  for  $r$  pairs of near-collision blocks  $(S_{c,j}, S'_{c,j})$  for  $1 \leq j \leq r$ . For each pair of near-collision blocks  $(S_{c,j}, S'_{c,j})$  we need to construct a differential path (see Section 4.3 for an informal definition of this term) such that the difference vector  $\delta \text{IHV}_{n+j}$  has lower weight than  $\delta \text{IHV}_{n+j-1}$ , until after  $r$  pairs we have reached  $\delta \text{IHV}_{n+r} = (0, 0, 0, 0)$ .

Fix some  $j$  and let  $S_{c,j}$  consist of 32-bit words  $m_i$ , for  $0 \leq i < 16$ . We fix fifteen of the  $\delta m_i$  as 0 and allow only  $\delta m_{11}$  to be  $\pm 2^{p-10 \bmod 32}$  with as yet unspecified  $p$  with  $0 \leq p < 32$  (note the slight abuse of notation, since we define message block differences without specifying the message blocks themselves). This was suggested by Xiaoyun Wang because with this type of message difference the number of bitconditions over the final two and a half rounds can be kept low, which turns out to be helpful while constructing collisions. For steps  $t = 34$  up to  $t = 61$  the differential path is fully determined by  $\delta m_{11}$  as illustrated in Table 2. The greater variability for the steps not specified in Table 2 does not need to be fixed at this point. In the last two steps there is a greater degree of freedom specified by the integer  $w \geq 0$  that determines which and how many

IHV differences can be eliminated per pair of near-collision blocks. A larger  $w$  allows more eliminations by means of additional differential paths. The latter have, however, a smaller chance to be satisfied because they depend on more (and thus less likely) carry propagations in  $\Delta Q_{62}$  and  $\Delta Q_{63}$ . This effect contributes to the complexity of finding the near-collision blocks satisfying the differential paths. Varying  $w$  therefore leads to a trade-off between fewer near-collision blocks and increased complexity to find them.

This entire construction of the pair of near-collision blocks  $(S_{c,j}, S'_{c,j})$  will be done in a fully automated way based on the choice of  $w$  and the values of  $\text{IHV}_{n+j-1}$  and  $\text{IHV}'_{n+j-1}$  as specified. It follows from equation (3) and the rows for  $t \geq 61$  in Table 2 that a differential path with  $\delta m_{11} = \pm 2^{p-10 \bmod 32}$  would add a tuple

$$\pm \left( 0, 2^p + \sum_{\lambda=0}^{w'} s_\lambda 2^{p+21+\lambda \bmod 32}, 2^p, 2^p \right)$$

to  $\delta \text{IHV}_{n+j-1}$ , with notation as in Table 2. This is set forth in more detail below. A sequence of such tuples is too restrictive to eliminate arbitrary  $\delta \text{IHV}_n$ : although differences in the  $b$  component can be handled using a number of near-collision block pairs, only identical differences can be removed from the  $c$  and  $d$  components and the  $a$ -component differences are not affected at all. We therefore make sure that  $\delta \text{IHV}_n$  has the desirable property, as referred to above, that it *can* be eliminated using these tuples. This is done in the birthday search step where birthday bitstrings  $S_b$  and  $S'_b$  are determined such that  $\delta \text{IHV}_n = (0, \delta b, \delta c, \delta c)$  for some  $\delta b$  and  $\delta c$ . A  $\delta \text{IHV}_n$  of this form corresponds to a collision  $(a, c - d) = (a', c' - d')$  between  $\text{IHV}_n = (a, b, c, d)$  and  $\text{IHV}'_n = (a', b', c', d')$ . With a search space of only 64 bits, such a collision can easily be found. Since the number of near-collision block pairs and the effort required to find them depends in part on the number of bit differences between  $\delta b$  and  $\delta c$ , it may pay off to lower that number at the cost of extending the birthday search space. For instance, for any  $k$  with  $0 \leq k \leq 32$ , a collision  $(a, c - d, c - b \bmod 2^k) = (a', c' - d', c' - b' \bmod 2^k)$  with a  $(64 + k)$ -bit search space results in  $\delta c - \delta b \equiv 0 \bmod 2^k$  and thus, on average, just  $(32 - k)/3$  bit differences between  $\delta b$  and  $\delta c$ . Determining such  $S_b$  and  $S'_b$

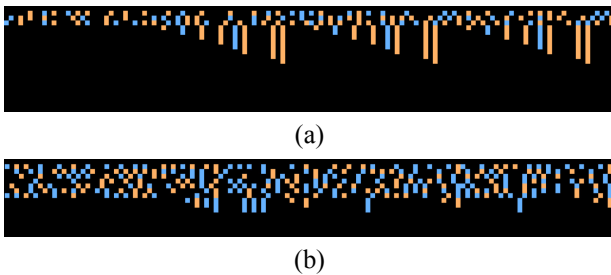


can be expected to require on the order of  $\sqrt{2^{\frac{\pi}{2}2^{64+k}}} = \sqrt{\pi}2^{32+(k/2)}$  calls to the MD5 compression function. More on the birthday search in Section 4.2.

In the conference version (Stevens et al., 2007) of this paper we used only the differential paths with  $\delta Q_{64} = \pm 2^p$ . This forced us to use the harder to satisfy constraint  $\delta \text{IHV}_n = (0, \delta c, \delta c, \delta c)$  with a search space consisting of 96 bits and an expected birthday search cost of  $\sqrt{\pi}2^{48}$  MD5 compression function calls, which is the same as choosing  $k = 32$  above. The top part of Figure 3 visualises the corresponding construction of near-collision blocks for our colliding certificate example from Stevens et al. (2007). The horizontal lines represent the NAFs of  $\delta \text{IHV}_i$  for  $i = 0, 1, \dots, 21$ . In this example  $P \| S_r \| S_b$  consists of 4 blocks (i.e.,  $n = 4$ ), so that three identical groups of bit differences are left at  $i = 4$ . As shown in Figure 3 each of these groups consists of 8 bits. The bits in each group of eight are eliminated simultaneously with the corresponding bits in the other groups of eight by 8 pairs of near-collision blocks, so that at  $i = 12$  a full collision is reached. The blocks after that are identical for the two messages, so that the collision is retained.

The lower part of Figure 3 visualises the improved construction as used for the example from Section 5.2. In that example  $P \| S_r \| S_b$  consists of 8 blocks (i.e.,  $n = 8$ ) and results in a difference vector  $\delta \text{IHV}_n$  of the form  $(0, \delta b, \delta c, \delta c)$ . For any reasonable  $w$ , e.g.,  $w = 2$ , we then select a sequence of differential paths from the family given in Table 2 to eliminate  $\delta \text{IHV}_n$ . For this example, 3 pairs of near-collision blocks sufficed to reach a collision. In the next paragraphs we show how this can be done for general  $\delta \text{IHV}_n$  of the form  $(0, \delta b, \delta c, \delta c)$ .

**Figure 3** (a)  $\delta \text{IHV}$ s for the colliding certificates with different distinguished names (b)  $\delta \text{IHV}$ s for the colliding website certificate and the rogue CA certificate (see online version for colours)



Let, for any such difference vector,  $\delta c = \sum_i k_i 2^i$  and  $\delta b - \delta c = \sum_i l_i 2^i$ , where  $(k_i)_{i=0}^{31}$  and  $(l_i)_{i=0}^{31}$  are NAFs. If  $\delta c \neq 0$ , let  $i$  be such that  $k_i \neq 0$ . Using a differential path from Table 2 with  $\delta m_{11} = -k_i 2^{i-10 \bmod 32}$  we can eliminate the difference  $k_i 2^i$  in  $\delta c$  and  $\delta d$  and simultaneously change  $\delta b$  by

$$k_i 2^i + \sum_{\lambda=i+21 \bmod 32}^{i+21+w' \bmod 32} l_\lambda 2^\lambda,$$

where  $w' = \min(w, 31 - i)$ . Here one needs to be careful that each non-zero  $l_\lambda$  is eliminated only once in

the case when multiple  $i$ 's allow the elimination of  $l_\lambda$ . Doing this for all non-zero  $k_i$ 's in the NAF of  $\delta c$  will result in a difference vector  $(0, \delta \hat{b}, 0, 0)$  where  $\delta \hat{b}$  may be different from  $\delta b$ , and where the weight  $w(\text{NAF}(\delta \hat{b}))$  may be smaller or larger than  $w(\text{NAF}(\delta b))$ . More precisely,  $\delta \hat{b} = \sum_{\lambda=0}^{31} e_\lambda l_\lambda 2^\lambda$ , where  $e_\lambda = 0$  if there exist indices  $i$  and  $j$  with  $0 \leq j \leq \min(w, 31 - i)$  such that  $k_i = \pm 1$  and  $\lambda = 21 + i + j \bmod 32$  and  $e_\lambda = 1$  otherwise.

The bits in  $\delta \hat{b}$  can be eliminated as follows. Let  $(\hat{l}_i)_{i=0}^{31} = \text{NAF}(\delta \hat{b})$  and let  $j$  be such that  $\hat{l}_j = \pm 1$  and  $j - 21 \bmod 32$  is minimal. Then the difference  $\sum_{i=j}^{j+w'} \hat{l}_i 2^i$  with  $w' = \min(w, 31 - (j - 21 \bmod 32))$  can be eliminated from  $\delta \hat{b}$  using  $\delta m_{11} = 2^{j-31 \bmod 32}$ , which introduces a new difference  $2^{j-21 \bmod 32}$  in  $\delta b$ ,  $\delta c$  and  $\delta d$ . This latter difference is eliminated using  $\delta m_{11} = -2^{j-31 \bmod 32}$ , which then leads to a new difference vector  $(0, \delta \bar{b}, 0, 0)$  with  $w(\text{NAF}(\delta \bar{b})) < w(\text{NAF}(\delta \hat{b}))$ . The process is repeated until all differences have been eliminated.

Algorithm 1 summarises the construction of pairs of near-collision blocks set forth above. The details of the construction are described in the sections below.

#### 4.2 Birthday search

A birthday search on a search space  $V$  is generally performed as in (van Oorschot and Wiener, 1999) by iterating a properly chosen deterministic function  $f: V \rightarrow V$  and by assuming that the points of  $V$  thus visited form a ‘random walk’, also called a trail. After approximately  $\sqrt{\pi|V|/2}$  iterations one may expect to have encountered a collision, i.e., different points  $x$  and  $y$  such that  $f(x) = f(y)$ . As the entire trail can in practice not be stored and to take advantage of parallelism, different pseudo-random walks are generated, of which only the startpoints, lengths, and endpoints are kept. The endpoints are ‘distinguished points’, points with an easily recognisable bitpattern depending on  $|V|$ , available storage and other characteristics. The average length of a walk is inversely proportional to the fraction of distinguished points in  $V$ . Since intersecting walks share their endpoints, they can easily be detected. The collision point can then be recomputed given the startpoints and lengths of the two colliding walks. The expected cost (i.e., number of evaluations of  $f$ ) to generate the walks is denoted by  $C_{\text{tr}}$  and the expected cost of the recomputation to determine collision points is denoted by  $C_{\text{coll}}$ .

In our case the search space  $V$  and iteration function  $f$  depend on an integer parameter  $k \in \{0, 1, 2, \dots, 32\}$  as explained in Section 4.1. The birthday collision that we try to find, however, needs to satisfy several additional conditions that cannot be captured by  $V$ ,  $f$ , or  $k$ : the prefixes associated with  $x$  and  $y$  in a birthday collision  $f(x) = f(y)$  must be different, and the required number of pairs of near-collision blocks may be at most  $r$  when allowing differential paths with parameter  $w$ . The probability that a collision satisfies all requirements depends not only on the choice of  $r$  and  $w$ , but also on the

value for  $k$ , and is denoted by  $p_{r,k,w}$ . As a consequence, on average  $1/p_{r,k,w}$  birthday collisions have to be found.

Assuming that  $M$  bytes of memory are available and that a single trail requires 28 bytes of storage (namely 96 bits for the start- and endpoint each, and 32 for the length), this leads to the following expressions for the birthday search costs:

$$C_{\text{tr}}(r, k, w) = \sqrt{\frac{\pi \cdot |V|}{2p_{r,k,w}}},$$

$$C_{\text{coll}}(r, k, w, M) = \frac{2.5 \cdot 28 \cdot C_{\text{tr}}(r, k, w)}{p_{r,k,w} \cdot M},$$

where  $|V| = 2^{64+k}$ , and the factor 2.5 is explained in Section 3 of van Oorschot and Wiener (1999).

For  $M = 70/p_{r,k,w}$  as given in the last column of Table 3 and in the more extensive tables in Appendix C, the two costs are equal, and the overall expected birthday costs becomes  $2C_{\text{tr}}(r, k, w)$ . However, if the cost at run time of finding the trails exceeds the expected cost by a factor  $\lambda$ , then the cost to determine the resulting birthday collisions can be expected to increase by a factor  $\lambda^2$ . Hence, in practice it is advisable to choose  $M$  considerably larger. For  $\epsilon \leq 1$ , using  $M = 70/(p_{r,k,w} \cdot \epsilon)$  bytes of memory will result in  $C_{\text{coll}} \approx \epsilon \cdot C_{\text{tr}}$  and the expected overall birthday search cost will be about  $(1 + \epsilon) \cdot C_{\text{tr}}(r, k, w)$  MD5 compressions.

### 4.3 Differential paths and bitconditions

In step (e) of Algorithm 1, MD5Compress is applied to the respective intermediate hash values IHV and IHV' and message blocks  $B$  and  $B'$ . Here, IHV and IHV' were constructed in such a way that  $\delta\text{IHV}$  has a specific structure, as set forth above. Furthermore, the blocks  $B$  and  $B'$  were constructed such that  $\delta B$  has a pre-specified low-weight value (cf. step (b) of Algorithm 1) and such that throughout the 64 steps of both calls to MD5Compress the propagation of differences between corresponding variables follows a specific precise description, as determined in step (c) of Algorithm 1. In this section we describe how this description, which is called a *differential path* for MD5Compress, is determined based on IHV, IHV' and  $\delta B$ . According to equations (2),

$$\begin{aligned} \delta F_t &= f_t(Q'_t, Q'_{t-1}, Q'_{t-2}) - f_t(Q_t, Q_{t-1}, Q_{t-2}), \\ \delta T_t &= \delta F_t + \delta Q_{t-3} + \delta W_t, \\ \delta R_t &= RL(T'_t, RC_t) - RL(T_t, RC_t), \text{ and} \\ \delta Q_{t+1} &= \delta Q_t + \delta R_t. \end{aligned} \quad (4)$$

#### Algorithm 1 Construction of pairs of near-collision blocks

Given  $n$ -block  $P \| S_r \| S_b$  and  $P' \| S'_r \| S'_b$ , the corresponding resulting IHV <sub>$n$</sub>  and IHV' <sub>$n$</sub> , and a value for  $w$ , a pair of bitstrings  $S_c, S'_c$  is constructed consisting of sequences of near-collision blocks such that  $M = P \| S_r \| S_b \| S_c$  and  $M' = P' \| S'_r \| S'_b \| S'_c$  satisfy  $\text{MD5}(M) = \text{MD5}(M')$ . This is done by performing in succession steps 1, 2 and 3 below.

1. Let  $j = 0$  and let  $S_c$  and  $S'_c$  be two bitstrings of length zero.
2. Let  $\delta\text{IHV}_{n+j} = (0, \delta b, \delta c, \delta c)$ . If  $\delta c = 0$  then proceed to step 3. Let  $(k_i)_{i=0}^{31} = \text{NAF}(\delta c)$  and  $(l_i)_{i=0}^{31} = \text{NAF}(\delta b - \delta c)$ . Choose any  $i$  for which  $k_i \neq 0$  and let  $w' = \min(w, 31 - i)$ . Perform steps (a) through (f):
  - (a) Increase  $j$  by 1.
  - (b) Let  $\delta S_{c,j} = (\delta m_0, \delta m_1, \dots, \delta m_{15})$  with  $\delta m_{11} = -k_i 2^{i-10 \bmod 32}$  and  $\delta m_t = 0$  for  $0 \leq t < 16$  and  $t \neq 11$ .
  - (c) Given  $\delta\text{IHV}_{n+j-1} = \text{IHV}'_{n+j-1} - \text{IHV}_{n+j-1}$  and  $\delta S_{c,j}$ , construct a few differential paths based on Table 2 with
 
$$\delta Q_{61} = 0, \quad \delta Q_{64} = -k_i 2^i - \sum_{\lambda=i+21 \bmod 32}^{i+21+w' \bmod 32} l_\lambda 2^\lambda, \quad \delta Q_{63} = \delta Q_{62} = -k_i 2^i.$$
 How this is done is described in Sections 4.3 and 4.4.
  - (d) Find message blocks  $S_{c,j}$  and  $S'_{c,j} = S_{c,j} + \delta S_{c,j}$  that satisfy one of the constructed differential paths. How this is done is described in Section 4.5. If proper message blocks cannot be found, back up to step (c) to find more differential paths.
  - (e) Compute  $\text{IHV}_{n+j} = \text{MD5Compress}(\text{IHV}_{n+j-1}, S_{c,j})$ ,  
 $\text{IHV}'_{n+j} = \text{MD5Compress}(\text{IHV}'_{n+j-1}, S'_{c,j})$ , and append  $S_{c,j}$  and  $S'_{c,j}$  to  $S_c$  and  $S'_c$ , respectively.
  - (f) Repeat step 2
3. Let  $\delta\text{IHV}_{n+j} = (0, \delta \hat{b}, 0, 0)$ . If  $\delta \hat{b} = 0$  then terminate. Let  $(l_i)_{i=0}^{31} = \text{NAF}(\delta \hat{b})$ . Choose  $i$  such that  $l_i \neq 0$  and  $i - 21 \bmod 32$  is minimal and let  $w' = \min(w, 31 - (i - 21 \bmod 32))$ . Perform steps (a) through (e) as above with  $\delta m_{11} = 2^{i-31 \bmod 32}$  as opposed to  $\delta m_{11} = -k_i 2^{i-10 \bmod 32}$  in step (b) and in steps (c) and (d) with
 
$$\delta Q_{61} = 0, \quad \delta Q_{64} = 2^{i-21 \bmod 32} - \sum_{\lambda=i}^{i+w' \bmod 32} l_\lambda 2^\lambda, \quad \delta Q_{63} = \delta Q_{62} = 2^{i-21 \bmod 32}.$$
 Perform steps (a) through (e) again with  $\delta m_{11} = -2^{i-31 \bmod 32}$  in step (b) and
 
$$\delta Q_{61} = 0, \quad \delta Q_{64} = \delta Q_{63} = \delta Q_{62} = -2^{i-21 \bmod 32}$$
 in steps (c) and (d). Repeat step 3.

**Table 3** Expected birthday costs for  $k = 0$ 

$k = 0$				$w = 0$				$w = 1$				$w = 2$				$w = 3$			
$r$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$	
16	5.9	35.27	1MB	1.75	33.2	1MB		1.01	32.83	1MB		1.	32.83	1MB		1.	32.83	1MB	
15	7.2	35.92	1MB	2.39	33.52	1MB		1.06	32.86	1MB		1.	32.83	1MB		1.	32.83	1MB	
14	8.71	36.68	1MB	3.37	34.01	1MB		1.27	32.96	1MB		1.04	32.84	1MB		1.04	32.84	1MB	
13	10.45	37.55	1MB	4.73	34.69	1MB		1.78	33.22	1MB		1.2	32.93	1MB		1.2	32.93	1MB	
12	12.45	38.55	1MB	6.53	35.59	1MB		2.78	33.71	1MB		1.66	33.16	1MB		1.66	33.16	1MB	
11	14.72	39.68	2MB	8.77	36.71	1MB		4.34	34.5	1MB		2.61	33.63	1MB		2.61	33.63	1MB	
10	17.28	40.97	11MB	11.47	38.06	1MB		6.54	35.6	1MB		4.18	34.42	1MB		4.18	34.42	1MB	
9	20.16	42.4	79MB	14.62	39.64	2MB		9.38	37.02	1MB		6.46	35.56	1MB		6.46	35.56	1MB	
8	23.39	44.02	732MB	18.21	41.43	21MB		12.88	38.76	1MB		9.52	37.09	1MB		9.52	37.09	1MB	
7	26.82	45.73	8GB	22.2	43.43	323MB		17.02	40.83	9MB		13.4	39.02	1MB		13.4	39.02	1MB	
6	31.2	47.92	161GB	26.73	45.69	8GB		21.78	43.22	241MB		18.14	41.4	20MB		18.14	41.4	20MB	
5	35.	49.83	3TB	31.2	47.92	161GB		27.13	45.89	10GB		23.74	44.2	938MB		23.74	44.2	938MB	
4								34.	49.33	2TB		30.19	47.42	81GB		30.19	47.42	81GB	

Notes: The columns  $p$ ,  $C_{tr}$  and  $M$  denote the values of  $-\log_2(p_{r,k,w})$ ,  $\log_2(C_{tr}(r,k,w))$  and the minimum required memory  $M$  such that  $C_{coll}(r,k,w,M) \leq C_{tr}(r,k,w)$ , respectively. The values for  $p_{r,k,w}$  were estimated from Algorithm 1. See Appendix C for more extensive tables.

It follows that neither  $\delta F_t$  nor  $\delta R_t$  is uniquely determined given the input differences  $(\delta Q_t, \delta Q_{t-1}, \delta Q_{t-2})$  and  $\delta T_t$ , respectively. Therefore a more flexible tool is required to describe in a succinct way a valid propagation of differences, starting from  $IHV = (Q_{-3}, Q_0, Q_{-1}, Q_{-2})$ ,  $IHV' = (Q'_{-3}, Q'_0, Q'_{-1}, Q'_{-2})$  and  $\delta B$  and, in our case, resulting in the desired final differences  $(\delta Q_{61}, \delta Q_{62}, \delta Q_{63}, \delta Q_{64})$  as defined in Table 2 and as targeted by step (c) of Algorithm 1.

#### 4.3.1 Bitconditions

Differential paths are described using *bitconditions*  $q_t = (q_t[i])_{i=0}^{31}$  on  $(Q_t, Q'_t)$ , where each bitcondition  $q_t[i]$  specifies a restriction on the bits  $Q_t[i]$  and  $Q'_t[i]$  possibly including values of other bits  $Q_l[i]$ . As we will show in this section, we can specify the values of  $\delta Q_t$ ,  $\delta F_t$  for all  $t$  using bitconditions on  $(Q_t, Q'_t)$ , which also determine  $\delta T_t$  and  $\delta R_t = \delta Q_{t+1} - \delta Q_t$  according to the difference equations (4). Thus, a differential path can be seen as a  $68 \times 32$  matrix  $(q_t)_{t=-3}^{64}$  of bitconditions. In general, the first four rows  $(q_t)_{t=-3}^0$  are fully determined by the values of  $IHV$  and  $IHV'$ . Furthermore, in our specific case where  $\delta B$  consists of just  $\delta m_{11} = \pm 2^d$ , the final 34 rows  $(q_t)_{t=31}^{64}$  correspond to Table 2 and one of the choices made in step (c) of Algorithm 1.

**Table 4** Differential bitconditions,  $\delta Q_t = \sum_{i=0}^{31} 2^i k_i$  and  $\Delta Q_t = (k_i)$ 

$q_t[i]$	Condition on $(Q_t[i], Q'_t[i])$	$k_i$
.	$Q_t[i] = Q'_t[i]$	0
+	$Q_t[i] = 0, Q'_t[i] = 1$	+1
-	$Q_t[i] = 1, Q'_t[i] = 0$	-1

Bitconditions are denoted using symbols such as 0, 1, +, -,  $\wedge$ ,  $\vee$ , ..., as defined in Tables 4 and 5, to facilitate the representation of a differential path. A *direct* bitcondition  $q_t[i]$  does not involve any other indices than  $t$  and  $i$ ,

whereas an *indirect* bitcondition involves one of the row indices  $t \pm 1$  or  $t \pm 2$  as well. Table 4 lists *differential* bitconditions  $q_t[i]$ , which are direct bitconditions that specify the value  $k_i = Q'_t[i] - Q_t[i]$ . A full row of differential bitconditions  $q_t = (k_i)_{i=0}^{31}$  fixes a BSDR of  $\delta Q_t = \sum_{i=0}^{31} 2^i k_i$ . Table 5 lists *boolean function* bitconditions, which are direct or indirect. They are used to resolve a possible ambiguity in

$$\begin{aligned} \Delta F_t[i] &= f_t(Q'_t[i], Q'_{t-1}[i], Q'_{t-2}[i]) \\ &\quad - f_t(Q_t[i], Q_{t-1}[i], Q_{t-2}[i]) \in \{-1, 0, +1\} \end{aligned}$$

that may be caused by different possible values for  $Q_j[i], Q'_j[i]$  given differential bitconditions  $q_j[i]$ . As an example, for  $t = 0$  and  $(q_t[i], q_{t-1}[i], q_{t-2}[i]) = (., +, -)$  (cf. Table 4) there is an ambiguity:

$$\begin{aligned} \text{if } Q_t[i] = Q'_t[i] = 0 \text{ then } f_t(0, 1, 0) - f_t(0, 0, 1) &= -1, \\ \text{if } Q_t[i] = Q'_t[i] = 1 \text{ then } f_t(1, 1, 0) - f_t(1, 0, 1) &= +1. \end{aligned}$$

To resolve this ambiguity the triple of bitconditions  $(., +, -)$  can be replaced by  $(0, +, -)$  or  $(1, +, -)$  for the two cases given above, respectively.

All boolean function bitconditions include the constant bitcondition  $Q_t[i] = Q'_t[i]$ , so boolean function bitconditions do not affect  $\delta Q_t$ . Furthermore, the indirect boolean function bitconditions never involve bitconditions + or -, since those bitconditions can always be replaced by one of the direct ones ., 0 or 1. For the indirect bitconditions we distinguish between ‘forward’ and ‘backward’ ones, because that makes it easier to resolve an ambiguity later on in our step-wise approach. In a valid (partial) differential path one can easily convert forward bitconditions into backward bitconditions and vice versa.

**Table 5** Boolean function bitconditions

$q_t[i]$	Condition on $(Q_t[i], Q'_t[i])$	Direct/indirect	Direction
0	$Q_t[i] = Q'_t[i] = 0$	Direct	
1	$Q_t[i] = Q'_t[i] = 1$	Direct	
$\sim$	$Q_t[i] = Q'_t[i] = Q_{t-1}[i]$	Indirect	Backward
$\vee$	$Q_t[i] = Q'_t[i] = Q_{t+1}[i]$	Indirect	Forward
!	$Q_t[i] = Q'_t[i] = \overline{Q_{t-1}[i]}$	Indirect	Backward
y	$Q_t[i] = Q'_t[i] = \overline{Q_{t+1}[i]}$	Indirect	Forward
m	$Q_t[i] = Q'_t[i] = Q_{t-2}[i]$	Indirect	Backward
w	$Q_t[i] = Q'_t[i] = Q_{t+2}[i]$	Indirect	Forward
#	$Q_t[i] = Q'_t[i] = \overline{Q_{t-2}[i]}$	Indirect	Backward
h	$Q_t[i] = Q'_t[i] = \overline{Q_{t+2}[i]}$	Indirect	Forward
?	$Q_t[i] = Q'_t[i] \wedge (Q_t[i] = 1 \vee Q_{t-2}[i] = 0)$	Indirect	Backward
q	$Q_t[i] = Q'_t[i] \wedge (Q_{t+2}[i] = 1 \vee Q_t[i] = 0)$	Indirect	Forward

When all  $\delta Q_t$  and  $\delta F_t$  have been determined by bitconditions then also  $\delta T_t$  and  $\delta R_t = \delta Q_{t+1} - \delta Q_t$  can be determined, which together describe the bitwise rotation of  $\delta T_t$  in each step. This does, however, not imply that the left rotate of  $\delta T_t$  over  $RC_t$  positions is equal to  $\delta R_t$  or with what probability that happens. See also Section 4.4.4.

The differential paths we constructed for several of our examples can be found at <http://www.win.tue.nl/hashclash/ChosenPrefixCollisions/>.

#### 4.4 Differential path construction

The basic idea to construct a differential path is to construct a partial lower differential path over steps  $t = 0, 1, \dots, 11$  and a partial upper differential path over steps  $t = 63, 62, \dots, 16$ , so that the  $Q_i$  involved in the partial paths meet but do not overlap. Given the two partial paths, we try to connect them over the remaining 4 steps into one full differential path which hopefully succeeds with some non-negligible probability. Using many lower and upper differential paths and trying to connect each combination of a lower and an upper differential path will eventually result in full differential paths. Constructing the partial lower path can be done by starting with bitconditions  $q_{-3}, q_{-2}, q_{-1}, q_0$  that are equivalent to the values of  $IHV, IHV'$  and then extend this step by step. Similarly the partial upper path can be constructed by extending the partial paths in Table 2 step by step. In both constructions the transitions between the steps must be compatible with the targeted message difference  $\delta B$ . To summarise, step (c) of Algorithm 1 in Section 4.1 consists of the following substeps:

- c.1 Given  $IHV$  and  $IHV'$ , determine the corresponding bitconditions  $(q_i)_{i=-3}^0$ .
- c.2 Generate partial lower differential paths by extending  $(q_i)_{i=-3}^0$  forward up to step  $t = 11$ . This is explained in Sections 4.4.1 to 4.4.4.
- c.3 Generate partial upper differential paths by extending the path specified by Table 2 backward from  $t = 31$  down to  $t = 16$ . This is explained in Section 4.4.5.
- c.4 Try to connect all pairs of lower and upper differential

paths over  $t = 12, 13, 14, 15$  to generate as many full differential paths as possible given the outcome of the two previous steps. This is explained in Section 4.4.6.

##### 4.4.1 Extending differential paths forward

In general, when constructing a differential path one must first fix the message block differences  $\delta m_0, \dots, \delta m_{15}$ . In our particular case this is achieved by the choice of  $\delta S_{c,j}$  in step (b) of Algorithm 1. Suppose we have a partial differential path consisting of at least bitconditions  $q_{t-1}$  and  $q_{t-2}$  and that the differences  $\delta Q_t$  and  $\delta Q_{t-3}$  are known. In step c.2 of Algorithm 1, we want to extend this partial differential path forward with step  $t$  resulting in the difference  $\delta Q_{t+1}$ , bitconditions  $q_t$ , and additional bitconditions  $q_{t-1}, q_{t-2}$  (cf. Section 4.4).

We assume that all indirect bitconditions in  $q_{t-1}$  and  $q_{t-2}$  are forward and involve only bits of  $Q_{t-1}$ . If we already have  $q_t$  as opposed to just the value  $\delta Q_t$  (e.g.  $q_0$  resulting from given values  $IHV, IHV'$ ), then we can skip Section 4.4.2 and continue at Section 4.4.3.

##### 4.4.2 Carry propagation

First we select bitconditions  $q_t$  based on the value  $\delta Q_t$ . Since we want to construct differential paths with as few bitconditions as possible, but also want to be able to randomise the process, any low weight BSDR (such as the NAF) of  $\delta Q_t$  may be chosen, which then translates into a possible choice for  $q_t$  as in Table 4. For instance, with  $\delta Q_t = 2^8$ , we may choose  $q_t[8] = '+'$ , or  $q_t[8] = '-'$  and  $q_t[9] = '+'$  (with in either case all other  $q_t[i] = '.'$ ).

##### 4.4.3 Boolean function

For some  $i$ , let  $(a, b, c) = (q_t[i], q_{t-1}[i], q_{t-2}[i])$  be any triple of bitconditions such that all indirect bitconditions involve only  $Q_t[i]$ ,  $Q_{t-1}[i]$  or  $Q_{t-2}[i]$ . For any such triple  $(a, b, c)$  let  $U_{abc}$  denote the set of tuples of values  $(x, x', y, y', z, z') =$

$(Q_t[i], Q'_t[i], Q_{t-1}[i], Q'_{t-1}[i], Q_{t-2}[i], Q'_{t-2}[i])$  satisfying it:

$$U_{abc} = \{(x, x', y, y', z, z') \in \{0, 1\}^6 \mid \text{satisfies bitconditions } (a, b, c)\}.$$

The cardinality of  $U_{abc}$  indicates the amount of freedom left by  $(a, b, c)$ . Triples  $(a, b, c)$  for which  $U_{abc} = \emptyset$  cannot be part of a valid differential path and are thus of no interest. The set of all triples  $(a, b, c)$  as above and with  $U_{abc} \neq \emptyset$  is denoted by  $\mathcal{F}_t$ .

Each  $(a, b, c) \in \mathcal{F}_t$  induces a set  $V_{abc}$  of possible boolean function differences  $\Delta F_t[i] = f_t(x', y', z') - f_t(x, y, z)$ :

$$V_{abc} = \{f_t(x', y', z') - f_t(x, y, z) \mid (x, x', y, y', z, z') \in U_{abc}\} \subset \{-1, 0, +1\}.$$

A triple  $(d, e, f) \in \mathcal{F}_t$  with  $|V_{def}| = 1$  leaves no ambiguity in  $\Delta F_t[i]$  and is therefore called a *solution*. Let  $\mathcal{S}_t \subset \mathcal{F}_t$  be the set of solutions.

For arbitrary  $(a, b, c) \in \mathcal{F}_t$  and for each  $g \in V_{abc}$ , we define  $W_{abc,g}$  as the subset of  $\mathcal{S}_t$  consisting of all solutions that are compatible with  $(a, b, c)$  and that have  $g$  as boolean function difference:

$$W_{abc,g} = \{(d, e, f) \in \mathcal{S}_t \mid U_{def} \subset U_{abc} \wedge V_{def} = \{g\}\}.$$

For each  $g \in V_{abc}$  there is always a triple  $(d, e, f) \in W_{abc,g}$  consisting of direct bitconditions 01+- that suffices, i.e., fixes a certain tuple in  $U_{abc}$ . This implies that  $W_{abc,g} \neq \emptyset$ . Despite this fact, we are specifically interested in bitconditions  $(d, e, f) \in W_{abc,g}$  that maximise  $|U_{def}|$  as such bitconditions maximise the amount of freedom in the bits of  $Q_t, Q_{t-1}, Q_{t-2}$  while fully determining  $\Delta F_t[i]$ .

The direct and forward (resp. backward) boolean function bitconditions were chosen such that for all  $t, i$  and  $(a, b, c) \in \mathcal{F}_t$  and for all  $g \in V_{abc}$  there exists a triple  $(d, e, f) \in W_{abc,g}$  consisting only of direct and forward (resp. backward) bitconditions such that

$$\{(x, x', y, y', z, z') \in U_{abc} \mid f_t(x', y', z') - f_t(x, y, z) = g\} = U_{def}.$$

These boolean function bitconditions allow one to resolve an ambiguity in an optimal way in the sense that they are sufficient and necessary.

If the triple  $(d, e, f)$  is not unique, then for simplicity we prefer direct over indirect bitconditions and short indirect bitconditions (vy~!) over long indirect ones (whqm#?). For given  $t$ , bitconditions  $(a, b, c)$ , and  $g \in V_{abc}$  we define  $FC(t, abc, g) = (d, e, f)$  as the preferred triple  $(d, e, f)$  consisting of direct and forward bitconditions. Similarly, we define  $BC(t, abc, g)$  as the preferred triple consisting of direct and backward bitconditions. These functions are easily determined and should be precomputed. They have been tabulated in Appendix B in Tables B-1, B-2, B-3 and B-4 grouped according to the four different round functions

$F, G, H, I$ , and per table for all 27 possible triples  $(a, b, c)$  of differential bitconditions.

To determine the differences  $\delta F_t = \sum_{i=0}^{31} 2^i g_i$  we proceed as follows. For  $i = 0, 1, 2, \dots, 31$  we assume that we have valid bitconditions  $(a, b, c) = (q_t[i], q_{t-1}[i], q_{t-2}[i])$  where only  $c$  may be indirect. If it is, it must involve  $Q_{t-1}[i]$ . Therefore  $(a, b, c) \in \mathcal{F}_t$ . If  $|V_{abc}| = 1$ , then there is no ambiguity and  $\{g_i\} = V_{abc}$ . Otherwise, if  $|V_{abc}| > 1$ , then we choose  $g_i$  arbitrarily from  $V_{abc}$  and we resolve the ambiguity by replacing bitconditions  $(a, b, c)$  by  $FC(t, abc, g_i)$ . Once all  $g_i$  and thus  $\delta F_t$  have been determined,  $\delta T_t$  is determined as  $\delta F_t + \delta Q_{t-3} + \delta W_t$ .

Note that in the next step  $t + 1$  our assumptions hold again, since  $a$  is a direct bitcondition and if  $b$  is indirect then it is forward and involves  $a$ . Bitconditions  $a$  and  $b$  may be new compared to the previous step, namely if the triple  $(a, b, c)$  was replaced by  $FC(t, abc, g_i)$ .

#### 4.4.4 Bitwise rotation

The integer  $\delta T_t$  as just determined does not uniquely determine  $\delta R_t = RL(T'_t, n) - RL(T_t, n)$ , where  $n = RC_t$  (cf. difference equations (4)). In this section we show how to find the most likely  $\delta R_t$  that corresponds to a given  $\delta T_t$ , i.e., the  $v$  for which  $|\{X \in \mathbb{Z}/2^{32}\mathbb{Z} \mid v = RL(X + \delta T_t, n) - RL(X, n)\}|$  is maximised

Any BSDR  $(k_{31}, \dots, k_{32-n}, k_{31-n}, \dots, k_0)$  of  $\delta T_t$  gives rise to a candidate  $\delta R_t$  given by the BSDR  $RL((k_i), n) = (k_{31-n}, \dots, k_0, k_{31}, \dots, k_{32-n})$ . Two BSDRs  $(k_i)$  and  $(l_i)$  of  $\delta T_t$  result in the same  $\delta R_t$  if

$$\sum_{i=0}^{31-n} 2^i k_i = \sum_{i=0}^{31-n} 2^i l_i \quad \text{and} \quad \sum_{i=32-n}^{31} 2^i k_i = \sum_{i=32-n}^{31} 2^i l_i.$$

This suggests the following approach. We define a *partition* as a pair  $(\alpha, \beta)$  of integers such that  $\alpha + \beta = \delta T_t \bmod 2^{32}$ ,  $|\alpha| < 2^{32-n}$ ,  $|\beta| < 2^{32}$  and  $2^{32-n}|\beta|$ . For any partition  $(\alpha, \beta)$ , values  $k_i \in \{0, \pm 1\}$  for  $0 \leq i < 32$  can be found such that

$$\alpha = \sum_{i=0}^{31-n} 2^i k_i \quad \text{and} \quad \beta = \sum_{i=32-n}^{31} 2^i k_i. \quad (5)$$

With  $\alpha + \beta = \delta T_t \bmod 2^{32}$  it follows that  $(k_i)$  is a BSDR of  $\delta T_t$ . Conversely, with (5) any BSDR  $(k_i)$  of  $\delta T_t$  defines a partition, which we denote  $(k_i) \equiv (\alpha, \beta)$ .

The rotation of a partition  $(\alpha, \beta)$  is defined as

$$RL((\alpha, \beta), n) = (2^n \alpha + 2^{n-32} \beta \bmod 2^{32}).$$

If  $(k_i) \equiv (\alpha, \beta)$ , this matches  $RL((k_i), n)$ . The latter, as seen above, is a candidate  $\delta R_t$ , and we find that different partitions give rise to different  $\delta R_t$  candidates. Thus, to find the most likely  $\delta R_t$ , we define

$$p_{(\alpha, \beta)} = Pr[RL((\alpha, \beta), n) = RL(X + \delta T_t, n) - RL(X, n)]$$

where  $X$  ranges over the 32-bit words, and show how  $p_{(\alpha, \beta)}$  can be calculated.

Let  $x = \delta T_t \bmod 2^{32-n}$  and  $y = (\delta T_t - x) \bmod 2^{32}$  with  $0 \leq x < 2^{32-n}$  and  $0 \leq y < 2^{32}$ . This gives rise to at most 4 partitions:

- $(\alpha, \beta) = (x, y)$ ;
- $(\alpha, \beta) = (x, y - 2^{32})$ , if  $y \neq 0$ ;
- $(\alpha, \beta) = (x - 2^{32-n}, y + 2^{32-n} \bmod 2^{32})$ , if  $x \neq 0$ ;
- $(\alpha, \beta) = (x - 2^{32-n}, (y + 2^{32-n} \bmod 2^{32}) - 2^{32})$ , if  $x \neq 0 \wedge y + 2^{32-n} \neq 2^{32}$ .

These are all possible partitions, so we find that  $\delta T_t$  leads to at most 4 different possibilities for  $\delta R_t$ . It remains to determine  $p_{(\alpha, \beta)}$  for the above partitions. For each of the 4 possibilities this is done by counting the number of 32-bit words  $X$  such that the BSDR defined by  $k_i = (X + \delta T_t)[i] - X[i]$  satisfies  $(k_i) \equiv (\alpha, \beta)$ . Considering the  $(32 - n)$  low-order bits, the probability that a given  $\alpha$  satisfies  $\alpha = \sum_{i=0}^{31-n} k_i$  follows from the number  $r$  of  $Y$ 's with  $0 \leq Y < 2^{32-n}$  such that  $0 \leq \alpha + Y < 2^{32-n}$ : if  $\alpha < 0$  then  $r = 2^{32-n} + \alpha$  and if  $\alpha \geq 0$  then  $r = 2^{32-n} - \alpha$ . Hence  $r = 2^{32-n} - |\alpha|$  out of  $2^{32-n}$   $Y$ 's. Now assuming  $\alpha = \sum_{i=0}^{31-n} k_i$ , there is no carry to the high-order bits and the same argument can be used for  $\beta/2^{32-n}$ . Hence, we conclude

$$p_{(\alpha, \beta)} = \frac{2^{32-n} - |\alpha|}{2^{32-n}} \cdot \frac{2^n - |\beta|2^{n-32}}{2^n}.$$

Note that these probabilities, corresponding to the at most 4 partitions above, indeed add up to 1. An equivalent result was previously stated in Magnus Daum's PhD thesis (Daum, 2005; Section 4.1.3), although we provide a new derivation.

In conclusion, all  $\delta R_t$  that are compatible with a given  $\delta T_t$  can easily be determined, including the probabilities that they occur. In Algorithm 1 we choose a partition  $(\alpha, \beta)$  for which  $p_{(\alpha, \beta)}$  is maximal and take  $\delta R_t = RL((\alpha, \beta), n)$ .

A more straightforward approach (as previously used in practice) would be to use  $\delta R_t = RL(NAF(\delta T_t), n)$ . This is in many cases the most likely choice, and matches our desire to minimise the number of differences in  $\delta Q_t$  and therefore also in  $\delta T_t$  and  $\delta R_t$ . Given  $\delta R_t$ , we finally determine  $\delta Q_{t+1}$  as  $\delta Q_t + \delta R_t$ .

#### 4.4.5 Extending differential paths backward

Having dealt with the forward extension of step c.2 of Algorithm 1 in Sections 4.4.2, 4.4.3 and 4.4.4, we now consider the backward extension of step c.3 of Algorithm 1 (cf. Section 4.4). The backward construction follows the same approach as the forward one. Our description relies on the notation introduced in Section 4.4.3.

Suppose we have a partial differential path consisting of at least bitconditions  $q_t$  and  $q_{t-1}$  and that the differences  $\delta Q_{t+1}$  and  $\delta Q_{t-2}$  are known. In step c.3 of Algorithm 1 we want to extend this partial differential path backward with step  $t$  resulting in the difference  $\delta Q_{t-3}$ , bitconditions  $q_{t-2}$ , and additional bitconditions  $q_t, q_{t-1}$ . We assume that all indirect bitconditions in  $q_t$  and  $q_{t-1}$  are backward and only involve bits of  $Q_{t-1}$ .

We choose a low weight BSDR (such as the NAF) of  $\delta Q_{t-2}$ , which then translates into a possible choice for  $q_{t-2}$  as in Table 4.

As in the last two paragraphs of Section 4.4.3, the differences  $\delta F_t = \sum_{i=0}^{31} 2^i g_i$  are determined by assuming for  $i = 0, 1, \dots, 31$  that we have valid bitconditions  $(a, b, c) = (q_t[i], q_{t-1}[i], q_{t-2}[i])$  where only  $a$  may be indirect. If it is, it must involve  $Q_{t-1}[i]$ . Therefore  $(a, b, c) \in \mathcal{F}_t$ . If  $|V_{abc}| = 1$ , then there is no ambiguity and  $\{g_i\} = V_{abc}$ . Otherwise, if  $|V_{abc}| > 1$ , then we choose  $g_i$  arbitrarily from  $V_{abc}$  and we resolve the ambiguity by replacing bitconditions  $(a, b, c)$  by  $BC(t, abc, g_i)$ .

#### Algorithm 2 Construction of $\mathcal{U}_{i+1}$ from $\mathcal{U}_i$

Suppose  $\mathcal{U}_i$  is given as  $\{(\delta Q_{12}, \delta Q_{13}, \delta F_{12}, \delta F_{13}, \delta F_{14}, \delta F_{15})\}$  if  $i = 0$  or if  $i > 0$  constructed inductively based on  $\mathcal{U}_{i-1}$  by means of this algorithm. For each tuple  $(q_1, q_2, f_1, f_2, f_3, f_4) \in \mathcal{U}_i$  do the following:

1. Let  $\mathcal{U}_{i+1} = \emptyset$  and  $(a, b, e, f) = (q_{15}[i], q_{14}[i], q_{11}[i], q_{10}[i])$
2. For each bitcondition  $d = q_{12}[i] \in \begin{cases} \{.\} & \text{if } q_1[i] = 0 \\ \{-, +\} & \text{if } q_1[i] = 1 \end{cases}$  do
  3. Let  $q'_1 = 0, -1$  or  $+1$  depending on whether  $d = '.', '-',$  or  $+$ , respectively
  4. For each different  $f'_1 \in \{-f_1[i], +f_1[i]\} \cap V_{def}$  do
    5. Let  $(d', e', f') = FC(12, def, f'_1)$
    6. For each bitcondition  $c = q_{13}[i] \in \begin{cases} \{.\} & \text{if } q_2[i] = 0 \\ \{-, +\} & \text{if } q_2[i] = 1 \end{cases}$  do
      7. Let  $q'_2 = 0, -1$  or  $+1$  depending on whether  $c = '.', '-',$  or  $+$ , respectively
      8. For each different  $f'_2 \in \{-f_2[i], +f_2[i]\} \cap V_{cd'e'}$  do
        9. Let  $(c', d'', e'') = FC(13, cd'e', f'_2)$
        10. For each different  $f'_3 \in \{-f_3[i], +f_3[i]\} \cap V_{bc'd''}$  do
          11. Let  $(b', c'', d''') = FC(14, bc'd'', f'_3)$
          12. For each different  $f'_4 \in \{-f_4[i], +f_4[i]\} \cap V_{ab'c''}$  do
            13. Let  $(a', b'', c''') = FC(15, ab'c'', f'_4)$
            14. If  $(q_1 - 2^i q'_1, q_2 - 2^i q'_2, f_1 - 2^i f'_1, f_2 - 2^i f'_2, f_3 - 2^i f'_3, f_4 - 2^i f'_4)$  is not in  $\mathcal{U}_{i+1}$  yet, insert it in  $\mathcal{U}_{i+1}$

To rotate  $\delta R_t = \delta Q_{t+1} - \delta Q_t$  over  $n = 32 - RC_t$  bits, we may follow the framework as set forth in Section 4.4.4 with the roles of  $\delta R_t$  and  $\delta T_t$  reversed: choose a partition  $(\alpha, \beta)$  (of  $\delta R_t$  as opposed to  $\delta T_t$ ) with maximal probability and determine  $\delta T_t = RL((\alpha, \beta), n)$ . Finally, we determine  $\delta Q_{t-3} = \delta T_t - \delta F_t - \delta W_t$  to extend our partial differential path backward with step  $t$ . Note that here also (i.e., as in the last paragraph of Section 4.4.3) in the next step  $t - 1$  our assumptions hold again, since  $c$  is a direct bitcondition and if  $b$  is indirect then it is backward and involves  $c$  (where  $b$  and  $c$  are new if  $(a, b, c)$  was replaced by  $BC(t, abc, g_i)$ ).

#### 4.4.6 Constructing full differential paths

Construction of a full differential path can be done as follows. Assume that for some  $\delta Q_{-3}$  and bitconditions  $q_{-2}, q_{-1}, q_0$  the forward construction as described in Sections 4.4.1, 4.4.2, 4.4.3, and 4.4.4 has been carried out up to step  $t = 11$  (cf. step c.2 in Section 4.4). Furthermore, assume that for some  $\delta Q_{64}$  and bitconditions  $q_{63}, q_{62}, q_{61}$  the backward construction as described in Section 4.4.5 has been carried out down to step  $t = 16$  (cf. step c.3 in Section 4.4). For each combination of forward and backward partial differential paths thus found, this leads to bitconditions  $q_{-2}, q_{-1}, \dots, q_{11}, q_{14}, q_{15}, \dots, q_{63}$  and differences  $\delta Q_{-3}, \delta Q_{12}, \delta Q_{13}, \delta Q_{64}$ .

It remains to try and glue together each of these combinations by finishing steps  $t = 12, 13, 14, 15$  (cf. step c.4 in Section 4.4) until a full differential path is found. First, as in the backward extension in Section 4.4.5, for  $t = 12, 13, 14, 15$  we set  $\delta R_t = \delta Q_{t+1} - \delta Q_t$ , choose the resulting  $\delta T_t$  by left-rotating  $\delta R_t$  over  $n - RC_t$  bits, and determine  $\delta F_t = \delta T_t - \delta W_t - \delta Q_{t-3}$ .

We aim to complete the differential path by finding new bitconditions  $q_{10}, q_{11}, \dots, q_{15}$  that are compatible with the original bitconditions and that result in the required  $\delta Q_{12}, \delta Q_{13}, \delta F_{12}, \delta F_{13}, \delta F_{14}, \delta F_{15}$ .

An efficient way to find the missing bitconditions is to first test if they exist, and if so to backtrack to actually construct them. For  $i = 0, 1, \dots, 32$  we attempt to construct a set  $\mathcal{U}_i$  consisting of all tuples  $(q_1, q_2, f_1, f_2, f_3, f_4)$  of 32-bit integers with  $q_j \equiv f_k \equiv 0 \pmod{2^i}$  for  $j = 1, 2$  and  $k = 1, 2, 3, 4$  such that for all  $\ell = 0, 1, \dots, i - 1$  there

exist compatible bitconditions  $q_{10}[\ell], q_{11}[\ell], \dots, q_{15}[\ell]$  that determine  $\Delta Q_{11+j}[\ell]$  and  $\Delta F_{11+k}[\ell]$  below, and such that

$$\begin{aligned} \delta Q_{11+j} &= q_j + \sum_{\ell=0}^{i-1} 2^\ell \Delta Q_{11+j}[\ell], & j = 1, 2, \\ \delta F_{11+k} &= f_k + \sum_{\ell=0}^{i-1} 2^\ell \Delta F_{11+k}[\ell], & k = 1, 2, 3, 4. \end{aligned} \quad (6)$$

From these conditions it follows that  $\mathcal{U}_0$  must be chosen as  $\{(\delta Q_{12}, \delta Q_{13}, \delta F_{12}, \delta F_{13}, \delta F_{14}, \delta F_{15})\}$ . For  $i = 1, 2, \dots, 32$ , we attempt to construct  $\mathcal{U}_i$  based on  $\mathcal{U}_{i-1}$  using Algorithm 2. Per  $j$  there are at most two  $q_j$ 's and per  $k$  there are at most two  $f_k$ 's that can satisfy the above relations. This implies that  $|\mathcal{U}_i| \leq 2^6$  for each  $i$ ,  $0 \leq i \leq 32$ . On the other hand, for each tuple in  $\mathcal{U}_i$  there may in principle be many different compatible sets of bitconditions.

As soon as we encounter an  $i$  for which  $\mathcal{U}_i = \emptyset$ , we know that the desired bitconditions do not exist, and that we should try another combination of forward and backward partial differential paths. If, however, we find  $\mathcal{U}_{32} \neq \emptyset$  then it must be the case that  $\mathcal{U}_{32} = \{(0, 0, 0, 0, 0, 0)\}$ . Furthermore, in that case, every set of bitconditions that leads to this non-empty  $\mathcal{U}_{32}$  gives rise to a full differential path, since equations (6) hold with  $i = 32$ . Thus, if  $\mathcal{U}_{32} \neq \emptyset$ , there exists at least one valid path  $u_0, u_1, \dots, u_{32}$  with  $u_i \in \mathcal{U}_i$ . For each valid path, the desired new bitconditions  $(q_{15}[i], q_{14}[i], \dots, q_{10}[i])$  are  $(a', b'', c''', d''', e'', f')$ , which can be found at step 13 of Algorithm 2.

#### 4.5 Collision finding

Collision finding is the process of finding an actual message block pair  $S_{c,j}, S'_{c,j}$  that satisfies a given  $\delta S_{c,j}$  and a differential path based on a given  $\text{IHV}_{n+j-1}, \text{IHV}'_{n+j-1}$ , cf. step (d) of Algorithm 1. The differential paths as originally considered by Wang and Yu (2005) consisted of only 28 bitconditions. In that case, collision finding can now be done in the equivalent of a mere  $2^{24.8}$  expected MD5 compression function calls, for arbitrary IHV (Stevens, 2007). For chosen-prefix collisions, however, the number of bitconditions is substantially larger, thereby

**Table 6** Collision finding tunnels for MD5

<i>Tunnel</i>	<i>Change</i>	<i>Affected</i>	<i>Extra bitconditions*</i>
$\mathcal{T}_1$	$Q_4[b]$	$m_3..m_5, m_7, Q_{21}..Q_{64}$	$Q_5[b] = 1, Q_6[b] = 1$
$\mathcal{T}_2$	$Q_5[b]$	$m_4, m_5, m_7, m_8, Q_{21}..Q_{64}$	$Q_6[b] = 0$
$\mathcal{T}_3$	$Q_{14}[b]$	$m_{13}..m_{15}, m_6, Q_3, m_2..m_5, Q_{21}..Q_{64}$	$Q_{15}[b] = Q_{16}[b], Q_3[b]$ free <sup>†</sup>
$\mathcal{T}_4$	$Q_9[b]$	$m_8..m_{10}, m_{12}, Q_{22}..Q_{64}$	$Q_{10}[b] = 1, Q_{11}[b] = 1$
$\mathcal{T}_5$	$Q_{10}[b]$	$m_9, m_{10}, m_{12}, m_{13}, Q_{22}..Q_{64}$	$Q_{11}[b] = 0$
$\mathcal{T}_6$	$Q_8[b]$	$m_7..m_9, Q_{12}, m_{12}..m_{15}, Q_{23}..Q_{64}$	$Q_{10}[b] = 1, RR(Q_{12}, 22)[b]$ free <sup>‡</sup>
$\mathcal{T}_7$	$Q_4[b]$	$m_3, m_4, m_7, Q_{24}..Q_{64}$	$Q_5[b] = 0, Q_6[b] = 1$
$\mathcal{T}_8$	$Q_9[b]$	$m_8, m_9, m_{12}, Q_{25}..Q_{64}$	$Q_{10}[b] = 0, Q_{11}[b] = 1$

Notes: \* The extra bitconditions refer only to  $Q_t[b]$  and not to  $Q'_t[b]$ , so e.g.  $Q_6[b] = 0$  is met by both  $q_6[b] = '0'$  and  $q_6[b] = '+'$ .

<sup>†</sup> Bitcondition  $q_3[b] = '.'$  and no other indirect bitconditions may involve  $Q_3[b]$ . Set  $Q_3[b] = Q_{14}[b]$  to avoid carries in  $Q_3$ .

<sup>‡</sup> Bitcondition  $q_{12}[b - 22 \bmod 32] = '.'$  and no other indirect bitconditions may involve  $Q_{12}[b - 22 \bmod 32]$ .

Set  $Q_{12}[b - 22 \bmod 32] = Q_8[b]$  to avoid carries in  $Q_{12}$ .

complicating collision finding. For instance, in one of our earliest chosen-prefix collision constructions the differential path has 71 bitconditions on  $Q_{20}$  up to  $Q_{63}$ .

#### 4.5.1 Tunnels

To find collisions for these more difficult differential paths, we make extensive use of so-called *tunnels* (Klima, 2006). A tunnel allows one to make small changes in a certain first round  $Q_t$ , in specific bits of  $Q_t$  that are determined by the full differential path  $q_{-3}, q_{-2}, \dots, q_{64}$  under consideration, while causing changes in the second round only after some step  $l$  that depends on the tunnel. However, each tunnel implies that additional first-round bitconditions have to be taken into account in the differential path, while leaving freedom of choice for some of the bits in  $Q_t$  that may be changed. A tunnel's *strength* is the number of independent bits that can be changed in this first round  $Q_t$ . Thus, a tunnel of strength  $k$  allows us to generate  $2^k$  different message blocks that all satisfy the differential path up to and including step  $l$  in the second round.

The tunnels used in our collision finding algorithm are shown in Table 6. For example, the first tunnel ( $\mathcal{T}_1$ ) allows changes in bits of  $Q_4$ , in such a way that if  $Q_4[b]$  is changed for some bit position  $b$  with  $0 \leq b < 32$ , this causes extra bitconditions  $Q_5[b] = 1$  and  $Q_6[b] = 1$ , which have to be incorporated in the differential path. Furthermore, because tunnel  $\mathcal{T}_1$  affects after the first round only  $Q_{21}$  through  $Q_{64}$  we have that  $l = 20$ , and  $\mathcal{T}_1$  can be used to change message blocks  $m_3, m_4, m_5$ , and  $m_7$ . To determine the strength of a tunnel one first needs to incorporate the tunnel's extra bitconditions in the full differential path, and then count the remaining amount of freedom in the first round  $Q_t$  that is changed by the tunnel. Given its dependence on the differential path, a tunnel's strength can thus not be tabulated.

The most effective tunnel is  $\mathcal{T}_8$ . As indicated in the table, it affects after the first round only  $Q_{25}, \dots, Q_{64}$ . Over these rounds, Wang and Yu's original differential paths have 20 bitconditions whereas the chosen-prefix collision differential paths that we manage to construct have approximately 27 bitconditions. It follows that, given enough tunnel strength, especially for  $\mathcal{T}_7$  and  $\mathcal{T}_8$ , collision finding can be done efficiently.

#### 4.5.2 Algorithm

In our construction we performed the collision finding using Algorithm 2. The conditions on the differential path imposed by Algorithm 3 can easily be met because, as mentioned in Section 4.3.1, forward and backward bitconditions in the differential path are interchangeable. Steps 10 through 15 of Algorithm 3 are its most computationally intensive part, in particular for the toughest differential paths in a chosen-prefix collision, so they should be optimised. Greater tunnel strength significantly reduces the time spent there, because after step 15 all tunnels are used.

In practice, in step c.4 of Algorithm 1 (cf. Section 4.4) we keep only those full differential paths for which tunnels  $\mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_4$  and  $\mathcal{T}_5$  satisfy a certain lower bound on their strength. Furthermore, of the full differential paths kept, we select those with the best properties such as high tunnel strength and a low number of bitconditions on  $Q_{18}, \dots, Q_{63}$ .

#### 4.5.3 Rotation bitconditions

As mentioned below Algorithm 3, it is assumed there that all rotations in the first round will be correct with probability very close to 1. In Algorithm 3,  $Q_1, \dots, Q_{16}$  are chosen in a non-sequential order and also changed at various steps in the algorithm. Ensuring correct rotations in the first round would be cumbersome and it would hardly avoid wasting time in a state where one or more rotations in the first round would fail due to the various tunnels. However, as shown in Stevens (2006), if we use additional bitconditions  $q_t[i]$  we can (almost) ensure correct rotations in the first round, thereby (almost) eliminating both the effort to verify rotations and the wasted computing time. This is explained below.

We use the notation introduced in Section 4.4.4. Given  $\delta T_t$  and  $\delta R_t$  it is easy to determine which partition  $(\alpha, \beta)$  satisfies  $RL((\alpha, \beta), RC_t) = \delta R_t$ . The probability that this correct rotation holds is not necessarily  $p_{(\alpha, \beta)}$  because it may be assumed that bitconditions  $q_t$  and  $q_{t+1}$  hold and these directly affect  $R_t = Q_{t+1} - Q_t$  and thus  $T_t = RR(R_t, RC_t)$ . Hence, using bitconditions  $q_t$  and  $q_{t+1}$  we can try and increase the probability of a correct rotation in step  $t$  to (almost) 1 in the following way.

The other three partitions (of the four listed in Section 4.4.4) correspond to the incorrect rotations. Those partitions are of the form

$$(\hat{\alpha}, \hat{\beta}) = (\alpha - \lambda_0 2^{32-RC_t}, \beta + \lambda_0 2^{32-RC_t} + \lambda_{RC_t} 2^{32}),$$

$$\lambda_0, \lambda_{RC_t} \in \{-1, 0, +1\}$$

where either  $\lambda_0 \neq 0$  or  $\lambda_{RC_t} \neq 0$ . They result in incorrect  $\widehat{\delta R_t}$  of the form

$$\widehat{\delta R_t} = RL((\hat{\alpha}, \hat{\beta}), RC_t) = \delta R_t + \lambda_0 2^0 + \lambda_{RC_t} 2^{RC_t}.$$

They are caused by a carry when adding  $\delta T_t$  to  $T_t$  that does or does not propagate: from bit position  $32 - RC_t - 1$  to  $32 - RC_t$  for  $\lambda_0 \neq 0$  and from bit position 31 to 32 for  $\lambda_{RC_t} \neq 0$ . Since we chose the partition  $(\alpha, \beta)$  with highest probability, this usually means that we have to prevent instead of ensure those propagations in order to decrease the probability that  $\lambda_0 \neq 0$  or  $\lambda_{RC_t} \neq 0$ .

To almost guarantee proper rotations in each step of Algorithm 3, additional bitconditions can be determined by hand, as shown in Stevens (2006). It was seen that adding bitconditions on  $Q_t, Q_{t+1}$  around bit positions  $31 - RC_t + i$  and lower helps preventing  $\lambda_i \neq 0$ . This can be automated using a limited brute-force search, separately handling the cases  $\lambda_0 \neq 0$  and  $\lambda_{RC_t} \neq 0$ .



**Algorithm 3** Collision finding algorithm

Given a full differential path  $q_{-3}, \dots, q_{64}$  consisting of only direct and backward bitconditions and the set  $\mathcal{T}_1, \dots, \mathcal{T}_8$  of tunnels from Table 6, perform the following steps:

1. Determine for all tunnels for which bits  $b$  the extra bitconditions as shown in Table 6 can be met. For each possible case, apply compatible bitconditions to enforce the extra bitconditions and change the bitconditions  $q_t[b]$  of the changed or affected  $Q_t[b]$  in the first round from ‘.’ to ‘0’.
2. Perform the steps below until a collision block has been found.
3. Select  $Q_1, Q_2, Q_{13}, \dots, Q_{16}$  such that  $q_1, q_2, q_{13}, \dots, q_{16}$  hold.
4. Compute  $m_1, Q_{17}$ .
5. If  $q_{17}$  holds and the rotation for  $t = 16$  is successful, then proceed.
6. Store the set  $\mathcal{Z}$  of all pairs  $(Q_1, Q_2)$  meeting  $q_1, q_2$  that do not change  $m_1$  and bits of  $Q_2$  involved in  $q_3$ .
7. For all  $Q_3, \dots, Q_7$  meeting  $q_3, \dots, q_7$  do:
8.     Compute  $m_6, Q_{18}$ .
9.     If  $q_{18}$  holds and the rotation for  $t = 17$  is successful, then proceed.
10.    For all  $Q_8, \dots, Q_{12}$  meeting  $q_8, \dots, q_{12}$  do:
11.     Compute  $m_{11}, Q_{19}$ .
12.     If  $q_{19}$  holds and the rotation for  $t = 18$  is successful, then proceed.
13.    For all  $(Q_1, Q_2)$  in  $\mathcal{Z}$  do:
14.     Compute  $m_0, Q_{20}$ .
15.     If  $q_{20}$  holds and the rotation for  $t = 19$  is successful, then proceed.
16.    For all values of the bits of tunnels  $\mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3$  do:
17.     Set the bits to those values and compute  $m_5, Q_{21}$ .
18.     If  $q_{21}$  holds and the rotation for  $t = 20$  is successful, then proceed.
19.    For all values of the bits of tunnels  $\mathcal{T}_4, \mathcal{T}_5$  do:
20.     Set the bits to those values and compute  $m_{10}, Q_{22}$ .
21.     If  $q_{22}$  holds and the rotation for  $t = 21$  is successful, then proceed.
22.    For all values of the bits of tunnel  $\mathcal{T}_6$  do:
23.     Set the bits to those values and compute  $m_{15}, Q_{23}$ .
24.     If  $q_{23}$  holds and the rotation for  $t = 22$  is successful, then proceed.
25.    For all values of the bits of tunnel  $\mathcal{T}_7$  do:
26.     Set the bits to those values and compute  $m_4, Q_{24}$ .
27.     If  $q_{24}$  holds and the rotation for  $t = 23$  is successful, then proceed.
28.    For all values of the bits of tunnel  $\mathcal{T}_8$  do:
29.     Set the bits to those values and compute  $m_9, Q_{25}$ .
30.     If  $q_{25}$  holds and the rotation for  $t = 24$  is successful, then proceed.
31.     Compute  $m_0, \dots, m_{15}, Q_{26}, \dots, Q_{64}$  and  $Q'_1, \dots, Q'_{64}$ .
32.     If  $\widehat{\delta Q_t} = Q'_t - Q_t$  agrees with  $q_t$  for  $t = 61, 62, 63, 64$ , return  $M, M'$ .

Computation of  $m_i$  and  $Q_i$  is performed at  $t = i$  and  $t = i - 1$ , respectively.

We assume that the rotations in the first round have probability very close to 1 to be correct, and therefore do not verify them.

This is further explained in Section 4.5.3.

Let  $i \in \{0, RC_t\}$ . Given bitconditions  $q_t, q_{t+1}$ , we estimate  $Pr[\lambda_i \neq 0 | q_t, q_{t+1}]$  by sampling a small set of  $\widehat{Q}_t, \widehat{Q}_{t+1}$  satisfying  $q_t, q_{t+1}$ , e.g. of size  $2^{11}$ , and determining the fraction where  $\lambda_i = \text{NAF}(\widehat{\delta R_t} - \delta R_t)[i] \neq 0$  using

$$\widehat{\delta R_t} = RL(RR(\widehat{Q}_{t+1} - \widehat{Q}_t, RC_t) + \delta T_t, RC_t).$$

Using this approach, we estimate the probability that  $\lambda_i = 0$  by selecting a small search bound  $B$  and exhaustively trying all combinations of additional bitconditions on  $Q_t[b], Q_{t+1}[b]$  for  $b = 31 - RC_t + i - B, \dots, 31 - RC_t + i$ . Finally, if there are any bitconditions  $(q'_t, q'_{t+1})$  for which  $Pr[\lambda_i \neq 0 | q'_t, q'_{t+1}]$  is negligible, we select the pair  $(q'_t, q'_{t+1})$  that leads to the smallest number of additional bitconditions and for which  $Pr[\lambda_0 = \lambda_{RC_t} =$

$0 | q_{t-1}, q'_t]$  and  $Pr[\lambda_0 = \lambda_{RC_t} = 0 | q'_{t+1}, q_{t+2}]$  do not decrease significantly for step  $t - 1$  and  $t + 1$ , respectively.

#### 4.6 Implementation remarks

Our software to construct chosen-prefix collisions consists of five main components that perform the following tasks:

- 1 the birthday search (with a special implementation for Sony's PlayStation 3)
- 2 forward extension of a given set of partial lower differential paths by a given step  $t$ , saving only the paths with the fewest bitconditions

- 3 backward extension of a given set of partial upper differential paths by a given step  $t$ , saving only the paths with the fewest bitconditions
- 4 attempt to connect all combinations of given lower and upper differential paths
- 5 coordinate the four earlier tasks by preparing the required inputfiles, collect the outputs, and search for near-collision blocks.

These tasks are carried out as described in the earlier sections. A few remarks are in order. The first task is the most computationally expensive one and consists mostly of simple applications of the MD5 compression function. It turns out that the Cell processor, contained in the PlayStation 3 game console, can be made to perform this task about 30 times faster than a regular 32-bit PC core. More details on the peculiarities of the PlayStation 3 implementation are described in Section 5.2.2.

For the second and third task we exhaustively try all limited weight BSDRs of  $\delta Q_t$ , all possible  $\delta F_t$ 's, and we use the highest-probability rotation. We keep at most a preset number of paths with the lowest number of bitconditions that have a preset minimum total strength over tunnels  $\mathcal{T}_1$ ,  $\mathcal{T}_2$ ,  $\mathcal{T}_4$ , and  $\mathcal{T}_5$ . Each of the programs is designed to execute several separate but parallel threads.

#### 4.7 Complexity analysis

The overall complexity of the chosen-prefix collision attack depends on the parameters used for the birthday search and the construction of pairs of near-collision blocks. This involves various trade-offs and is described in this section.

The birthday search complexity depends on the parameter  $w$  (defining the family of differential paths), the upper bound on the number  $r$  of pairs of near-collision blocks, the size  $2^{64+k}$  of the search space, and the amount of available memory  $M$ . For various parameter choices of  $r$ ,  $k$  and  $w$  we have tabulated the heuristically determined expected birthday search complexities and memory requirements in Appendix C (in practice it is advisable to use a small factor more memory than required to achieve  $C_{\text{coll}} \ll C_{\text{tr}}$ ). Given  $r$ ,  $w$  and  $M$ , the optimal value for  $k$  and the resulting birthday complexity can thus easily be looked up. When  $r$  is left free, one can balance the birthday complexity and the complexity of constructing  $r$  pairs of near-collision blocks.

Each pair of near-collision blocks requires construction of a set of full differential paths followed by the actual construction of the pair of near-collision blocks. The complexity of the former construction depends on several parameter choices, such as the size of the sets of lower and upper differential paths, and the restraints used when selecting BSDRs for a  $\delta Q_t$ . Naturally, a higher overall quality of the resulting complete differential paths, i.e., a low number of overall bitconditions and a high total tunnel strength, generally results when more effort is put into the construction. For practical purposes we have found parameters sufficient for almost all cases (as applicable to

the chosen-prefix collision attack) that have an average total complexity equivalent to roughly  $2^{35}$  MD5 compressions.

The complexity of the collision finding, i.e., the construction of a pair of near-collision blocks, depends on the parameter  $w$ , the total tunnel strength and the number of bitconditions in the last 2.5 rounds. For small  $w = 0, 1, 2$  and paths based on Table 2, the construction requires on average roughly the equivalent of  $2^{34}$  MD5 compressions. Combined with the construction of the differential paths, this leads to the rough overall estimate of about  $2^{35.6}$  MD5 compressions to find a single pair of near-collision blocks for a chosen-prefix collision attack.

With  $w = 2$  and optimising for overall complexity this leads to the optimal parameter choices  $r = 9$  and  $k = 0$ . For these choices, the birthday search cost is about  $2^{37}$  MD5 compressions and constructing the  $r = 9$  pairs of near-collision blocks costs about  $2^{38.8}$  MD5 compressions. The overall complexity is thus estimated at roughly  $2^{39.1}$  MD5 compressions, which takes about 35 hours on a single PC-core. For this parameter choice the memory requirements for the birthday search are very low, even negligible compared to the several hundreds of MBs required for the construction of the differential paths.

With more specific demands, such as a small number  $r$  of near-collision blocks possibly in combination with a relatively low  $M$ , the overall complexity will increase. As an example, our rogue CA construction required at most  $r = 3$  near-collision blocks, and using  $M = 5\text{TB}$  this results in an overall complexity of about  $2^{49}$  MD5 compressions.

#### 4.8 Single-block chosen-prefix collision

Using a different approach it is even possible to construct a chosen-prefix collision using only a single pair of near-collision blocks. Together with 84 birthday bits, the chosen-prefix collision-causing appendages are only  $84 + 512 = 596$  bits long. This approach is based on an even richer family of differential paths that allows elimination using a single pair of near-collision blocks of a set of  $\delta\text{IHVs}$  that is bounded enough so that finding the near-collision blocks is still feasible, but large enough that such a  $\delta\text{IHV}$  can be found efficiently by a birthday search. Instead of using the family of differential paths based on  $\delta m_{11} = \pm 2^i$ , we use the fastest known collision attack for MD5 and vary the last few steps to find a large family of differential paths.

We first present a new collision attack for MD5 with complexity of approximately  $2^{16}$  MD5 compressions improving upon the  $2^{20.96}$  MD5 compressions required in Xie et al. (2008). Our starting point is the partial differential path for MD5 given in Table 7. It is based on message differences  $\delta m_2 = 2^8$ ,  $\delta m_4 = \delta m_{14} = 2^{31}$  and  $\delta m_{11} = 2^{15}$  which is very similar to those used by Wang and Yu (2005) for the first collision attack against MD5. This partial differential path can be used for a near-collision attack with complexity of approximately  $2^{14.8}$  MD5 compressions.

**Table 7** Partial differential path for fast near-collision attack

$t$	$\delta Q_t$	$\delta F_t$	$\delta W_t$	$\delta T_t$	$\delta R_t$	$RC_t$
26	$-2^8$					
27	0					
28	0					
29	0	0	$2^8$	0	0	9
30 – 33	0	0	0	0	0	.
34	0	0	$2^{15}$	$2^{15}$	$2^{31}$	16
35	$2^{31}$	$2^{31}$	$2^{31}$	0	0	23
36	$2^{31}$	0	0	0	0	4
37	$2^{31}$	$2^{31}$	$2^{31}$	0	0	11
38 – 46	$2^{31}$	$2^{31}$	0	0	0	.
47	$2^{31}$	$2^{31}$	$2^8$	$2^8$	$2^{31}$	23
48	0	0	0	0	0	6
49	0	0	0	0	0	10
50	0	0	$2^{31}$	0	0	15
51 – 59	0	0	0	0	0	.
60	0	0	$2^{31}$	$2^{31}$	$-2^5$	6
61	$-2^5$	0	$2^{15}$	$2^{15}$	$2^{25}$	10
62	$-2^5 + 2^{25}$	0	$2^8$	$2^8$	$2^{23}$	15
63	$-2^5 + 2^{25} + 2^{23}$	$2^5 - 2^{23}$	0	$2^5 - 2^{23}$	$2^{26} - 2^{14}$	21
64	$-2^5 + 2^{25} + 2^{23} + 2^{26} - 2^{14}$					

Notes: Partial differential path for  $t = 29, \dots, 63$  using message differences  $\delta m_2 = 2^8$ ,  $\delta m_4 = \delta m_{14} = 2^{31}$ ,  $\delta m_{11} = 2^{15}$ .  
The probability that it is satisfied is approximately  $2^{-14.5}$ .

This leads in the usual fashion to an identical-prefix collision attack for MD5 that requires approximately  $2^{16}$  MD5 compressions, since one has to do it twice: first to add differences to  $\delta\text{IHV}$  and then to eliminate them again. It should be noted that usually bitconditions are required on the  $\text{IHV}$  and  $\text{IHV}'$  between the two collision blocks which imply an extra factor in complexity. In the present case, however, we can construct a large set of differential paths for the second near-collision block that will cover all bitconditions that are likely to occur, thereby avoiding the extra complexity.

By properly tuning the birthday search, the same partial differential path leads to the construction of a single near-collision block chosen-prefix collision for MD5. By varying the last steps of the differential path and by allowing the collision finding complexity to grow by a factor of about  $2^{26}$ , we have found a set  $\mathcal{S}$  of about  $2^{23.3}$  different  $\delta\text{IHV} = (\delta a, \delta b, \delta c, \delta d)$  of the form  $\delta a = -2^5$ ,  $\delta d = -2^5 + 2^{25}$ ,  $\delta c = -2^5 \bmod 2^{20}$  that can be eliminated. Such  $\delta\text{IHVs}$  can be found using an 84-bit birthday search with step function  $f : \{0, 1\}^{84} \rightarrow \{0, 1\}^{84}$  of the form

$$f(x) = \begin{cases} \phi(\text{MD5compress}(\text{IHV}, B\|x) + \widehat{\delta\text{IHV}}) & \text{if } \sigma(x) = 0 \\ \phi(\text{MD5compress}(\text{IHV}', B'\|x)) & \text{if } \sigma(x) = 1, \end{cases}$$

where  $\widehat{\delta\text{IHV}}$  is of the required form,  $\sigma : x \mapsto \{0, 1\}$  is a balanced selector function and  $\phi(a, b, c, d) \mapsto a\|d\|(c \bmod 2^{20})$ . There are  $2^{128-84} = 2^{44}$  possible  $\delta\text{IHVs}$  of this form, of which only about  $2^{23.3}$  are in the allowed set  $\mathcal{S}$ . It follows that a birthday collision has probability  $p = 2^{23.3}/(2^{44} \cdot 2) = 2^{-21.7}$  to be useful, where the additional

factor 2 stems from the fact that different prefixes are required.

A useful birthday collision can be expected after  $\sqrt{\pi 2^{84}/(2p)} \approx 2^{53.2}$  MD5 compressions, requires 400MB of storage and takes about 3 days on 215 PS3s. The expected complexity of finding the actual near-collision blocks is bounded by about  $2^{14.8+26} = 2^{40.8}$  MD5 compressions.

**Table 8** Example single-block chosen-prefix collision.

Message 1															
4F	64	65	64	20	47	6F	6C	64	72	65	69	63	68	0A	4F
64	65	64	20	47	6F	6C	64	72	65	69	63	68	0A	4F	64
65	64	20	47	6F	6C	64	72	65	69	63	68	0A	4F	64	65
64	20	47	6F	D8	05	0D	00	19	BB	93	18	92	4C	AA	96
DC	E3	5C	B8	35	B3	49	E1	44	E9	8C	50	C2	2C	F4	61
24	4A	40	64	BF	1A	FA	EC	C5	82	0D	42	8A	D3	8D	6B
EC	89	A5	AD	51	E2	90	63	DD	79	B1	6C	F6	7C	12	97
86	47	F5	AF	12	3D	E3	AC	F8	44	08	5C	D0	25	B9	56
Message 2															
4E	65	61	6C	20	4B	6F	62	6C	69	74	7A	0A	4E	65	61
6C	20	4B	6F	62	6C	69	74	7A	0A	4E	65	61	6C	20	4B
6F	62	6C	69	74	7A	0A	4E	65	61	6C	20	4B	6F	62	6C
69	74	7A	0A	75	B8	0E	00	35	F3	D2	C9	09	AF	1B	AD
DC	E3	5C	B8	35	B3	49	E1	44	E8	8C	50	C2	2C	F4	61
24	4A	40	E4	BF	1A	FA	EC	C5	82	0D	42	8A	D3	8D	6B
EC	89	A5	AD	51	E2	90	63	DD	79	B1	6C	F6	FC	11	97
86	47	F5	AF	12	3D	E3	AC	F8	44	08	DC	D0	25	B9	56

In Table 8 two 128-byte messages are given both consisting of a 52-byte chosen prefix and a 76-byte single-block chosen-prefix collision suffix and with colliding MD5 hash value D320B6433D8EBC1AC65711705721C2E1.

## 5 Applications of chosen-prefix collisions

When exploiting collisions in real world applications two major obstacles must be overcome.

- The problem of *meaningful collisions*. Given current methods, collisions require appendages consisting of unpredictable and mostly uncontrollable bitstrings. These must be hidden in the usually heavily formatted application data structure without raising suspicion.
- The problem of *realistic attack scenarios*. As we do not have effective attacks against MD5's (second) preimage resistance but only collision attacks, we cannot target existing MD5-values. In particular, the colliding data structures must be generated simultaneously, along with their shared hash, by the adversary.

In Section 5.1 several chosen-prefix collision applications are surveyed where these problems are addressed with varying degrees of success. Sections 5.2, 5.3, and 5.4 describe the three most prominent applications in more detail.

### 5.1 A survey of potential applications

We mention some potential applications of chosen-prefix collisions.

#### 5.1.1 Digital certificates

Given how heavily they rely on cryptographic hash functions, digital certificates are the first place to look for applications of chosen-prefix collisions. Two X.509 certificates are said to collide if their to-be-signed parts have the same hash and consequently their digital signatures, as provided by the CA, are identical. In earlier work (Lenstra and de Weger, 2005), we have shown how identical-prefix collisions can be used to construct colliding X.509 certificates with different RSA moduli but identical Distinguished Names. Here the RSA moduli absorbed the random-looking near-collision blocks, thus inconspicuously and elegantly solving the meaningfulness problem. Allowing different Distinguished Names required chosen-prefix collisions, as shown in Stevens et al. (2007). The certificates resulting from both constructions do not contain spurious bits, so superficial inspection at bit level of either of the certificates will not reveal the existence of a sibling certificate that collides with it signature-wise. Nevertheless, for these constructions to work the entire to-be-signed parts, and thus the signing CA, must be fully under our own control, thereby limiting the practical attack potential.

A related but in detail rather different construction was carried out in collaboration with Alexander Sotirov, Jacob Appelbaum, David Molnar, and Dag Arne Osvik, as reported on <http://www.win.tue.nl/hashclash/rogue-ca/> and in Stevens et al. (2009). Although in practice a

certificate's to-be-signed part cannot be for 100% under control of the party that submits the certification request, for some commercial CAs (that still used MD5 for their digital signature generation) the entire to-be-signed part could be predicted reliably enough to make the following guess-and-check approach practically feasible: prepare the prefix of the to-be-signed part of a legitimate certification request including a guess for the part that will be included by the CA upon certification, prepare a rogue to-be-signed prefix, determine different collision-causing and identical collision-maintaining appendages to complete two colliding to-be-signed parts, and submit the legitimate one for certification. If upon receipt of the legitimate certificate the guess turns out to have been correct, then the rogue certificate can be completed by pasting the CA's signature of the legitimate data onto the rogue data: because the data collide, the signature will be equally valid for both. Otherwise, if the guess is incorrect, another attempt is made. Using this approach we managed (upon the 4th attempt) to trick a commercial CA into providing a signature valid for a rogue CA certificate. For the intricate details of the construction we refer to Section 5.2.

A few additional remarks about this construction are in order here. We created not just a rogue certificate, but a rogue CA certificate, containing identifying information and public key material for a rogue CA. The private key of this rogue CA is under our control. As the commercial CA's signature is valid for the rogue CA certificate, all certificates issued by the rogue CA are trusted by anybody trusting the commercial CA. As the commercial CA's root certificate is present in all major browsers, this gives us in principle the possibility to impersonate any certificate owner. This is certainly a realistic attack scenario. The price that we have to pay is that the meaningfulness problem is only adequately – and most certainly not elegantly – solved: as further explained in the next paragraph, one of the certificates contains a considerable number of suspicious-looking bits. It must be noted here that browser vendors such as Microsoft, Mozilla and Google and other software companies, can revoke the trust in any CA certificate in their products if deemed necessary.

To indicate that a certificate is a CA certificate, a certain bit has to be set in the certificate's to-be-signed-part. According to the X.509v3 standard (Cooper et al., 2008), this bit comes after the public key field. It is unlikely that a commercial CA will accept a certification request where the CA bit is set. Therefore, the bit must not be set in the legitimate request. For our rogue CA certificate construction, the fact that the two to-be-signed parts must contain a different bit *after* the public key field causes an incompatibility with our 'usual' colliding certificate construction as in Lenstra and de Weger (2005) and Stevens et al. (2007). In that construction the collision-causing appendages correspond to the high order bits of RSA moduli, and they are followed by identical collision-maintaining appendages that transform the two appendages into valid RSA moduli. Anything following after the moduli must remain identical lest the collision property goes lost. As a consequence, the appendages on

the rogue side can no longer be hidden in the public key field and some other field must be found for them. Such a field may be specially defined for this purpose, or an existing (proprietary) extension may be used. The Netscape Comment extension is a good example of the latter, as we found that it is ignored by the major certificate processing software. The upshot is, however, that as the appendages have non-negligible length, it will be hard to define a field that will not look suspicious to someone who looks at the rogue certificate at bit level.

### 5.1.2 Colliding documents

In Daum and Lucks (2005) (see also Gebhardt et al., 2005), it was shown how to construct a pair of PostScript files that collide under MD5, but that display different messages when viewed or printed. These constructions use identical-prefix collisions, and therefore they have to rely on the presence of both messages in each of the colliding files and on macro-functionalities of the document format used. Obviously, this raises suspicion upon inspection at bit level. With chosen-prefix collisions, one message per colliding document suffices and macro-functionalities are no longer required. For example, using a document format that allows insertion of color images (such as Microsoft Word or Adobe PDF), inserting one message per document, two documents can be made to collide by appending carefully crafted color images after the messages. A short one pixel wide line will do – for instance hidden inside a layout element, a company logo, or a nicely colored barcode – and preferably scaled down to hardly visible size (or completely hidden from view, as possible in PDF). An extension of this construction is presented in the paragraphs below and set forth in detail in Section 5.3.

### 5.1.3 Hash based commitments

Kelsey and Kohno (2006) presented a method to first commit to a hash value, and next to construct faster than by a trivial pre-image attack a document with the committed hash value, and with any message of one's choice as a prefix. The method applies to any Merkle-Damgård hash function, such as MD5, that given an IHV and a suffix produces some IHV. Omitting details involving message lengths and Merkle-Damgård strengthening, the idea is to commit to a hash value based on an IHV at the root of a tree, either that IHV itself or calculated as the hash of that IHV and some suffix at the root. The tree is a complete binary tree and is calculated from its leaves up to the root, so the IHV at the root will be one of the last values calculated. This is done in such a way that each node of the tree is associated with an IHV along with a suffix that together hash to the IHV associated with the node's parent. Thus, two siblings have IHVs and suffixes that collide under the hash function. The IHVs at the leaves may be arbitrarily chosen but are, preferably, all different. Given a prefix of one's choice one performs a brute-force search for a suffix that, when appended to the prefix and

along with the standard IHV, results in the IHV at one of the leaves (or nodes) of the tree. Appending the suffixes one encounters on one's way from that leave or node to the root, results in a final message with the desired prefix and committed hash value.

Originally based on a birthday search, the construction of the tree can be done more efficiently by using chosen-prefix collisions to construct sibling node suffixes based on their IHVs. For MD5, however, it remains far from feasible to carry out the entire construction in practice. In a variant that *is* feasible, one commits to a prediction by publishing its hash value. In due time one reveals the correct prediction, chosen from among a large enough preconstructed collection of documents that, due to tree-structured chosen-prefix collision appendages, all share the same published hash value. In section 5.3 we present an example involving 12 documents.

### 5.1.4 Software integrity checking

In Kaminsky (2004) and Mikle (2004), it was shown how any existing MD5 collision, such as the ones originally presented by Xiaoyun Wang at the CRYPTO 2004 rump session, can be abused to mislead integrity checking software that uses MD5. A similar application, using freshly made collisions, was given on <http://www.mathstat.dal.ca/~selinger/md5collision/>. See also Gauravaram et al. (2006). As shown on <http://blog.didierstevens.com/2009/01/17/> this can even be done within the framework of Microsoft's Authenticode code signing program. All these results use identical-prefix collisions and, similar to the colliding PostScript application mentioned earlier, differences in the colliding inputs are used to construct deviating execution flows.

Chosen-prefix collisions allow a more elegant approach, since common operating systems ignore bitstrings that are appended to executables: the programs will run unaltered. Thus, using tree-structured chosen-prefix collision appendages as above, any number of executables can be made to have the same MD5 hash value or MD5-based digital signature. See Section 5.4 for an example.

One can imagine two executables: a 'good' one (say Word.exe) and a bad one (the attacker's Worse.exe). A chosen-prefix collision for those executables is computed, and the collision-causing bitstrings are appended to both executables. The resulting altered file Word.exe, functionally equivalent to the original Word.exe, can be offered to a code signing program such as Microsoft's Authenticode and receive an 'official' MD5-based digital signature. This signature will then be equally valid for the attacker's Worse.exe, and the attacker might be able to replace Word.exe by his Worse.exe (renamed to Word.exe) on the appropriate download site. This construction affects a common functionality of MD5 hashing and may pose a practical threat. It also allows people to get many executables signed at once and for free by getting a single executable signed, bypassing verification of any

kind (e.g. authenticity, quality, compatibility, non-spyware, non-malware) by the signing party.

### 5.1.5 Computer forensics

In computer forensics so-called *hash sets* are used to quickly identify known files. For example, when a hard disk is seized by law enforcement officers, they may compute the hashes of all files on the disk, and compare those hashes to hashes in existing hash sets: a whitelist (for known harmless files such as operating system and other common software files) and a blacklist (for previously identified harmful files). Only files whose hashes do not occur in either hash set have to be inspected further. A useful feature of this method of recognising files is that the file name itself is irrelevant, since only the content of the file is hashed.

MD5 is a popular hash function for this application. Examples are NIST's National Software Reference Library Reference Data Set (<http://www.nsl.nist.gov/>) and the US Department of Justice's Hashkeeper application (<http://www.usdoj.gov/ndic/domex/hashkeeper.htm>).

A conceivable, and rather obvious, attack on this application of hashes is to produce a harmless file (e.g. an innocent picture) and a harmful one (e.g. an illegal picture), and insert collision blocks that will not be noticed by common application software or human viewers. In a learning phase the harmless file might be submitted to the hash set and thus the common hash may end up on the whitelist. The harmful file will be overlooked from then on.

### 5.1.6 Peer to peer software

Hash sets are also used in peer to peer software. A site offering content may maintain a list of pairs (file name, hash). The file name is local only, and the peer to peer software uniquely identifies the file's content by means of its hash. Depending on how the hash is computed such systems may be vulnerable to a chosen-prefix attack. Software such as eDonkey and eMule use MD4 to hash the content in a two stage manner: the identifier of the content  $c_1 || c_2 || \dots || c_n$  is  $\text{MD4}(\text{MD4}(c_1) || \dots || \text{MD4}(c_n))$ , where the chunks  $c_i$  are about 9 MB each. One-chunk files, i.e., files not larger than 9 MB, are most likely vulnerable; whether multi-chunk files are vulnerable is open for research. We have not worked out the details of a chosen-prefix collision attack against MD4, but this seems very well doable by adapting our methods and should result in an attack that is considerably faster than our present one against MD5.

### 5.1.7 Content addressed storage

In recent years *content addressed storage* is gaining popularity as a means of storing fixed content at a physical location of which the address is directly derived from the content itself. For example, a hash of the content may be used as the file name. See Primmer and D'Halluin (2005) for an example. Clearly, chosen-prefix collisions can be

used by an attacker to fool such storage systems, e.g. by first preparing colliding pairs of files, by then storing the harmless-looking first one, and later overwriting it with the harmful second one.

Further investigations are required to assess the impact of chosen-prefix collisions. We leave it to others to study to what extent commonly used protocols and message formats such as TLS, S/MIME (CMS), IPsec and XML Signatures (see Bellovin and Rescorla, 2006; Hoffman and Schneier, 2005) allow insertion of random looking data that may be overlooked by some or all implementations. The threat posed by identical-prefix collisions is not well understood either: their application may be more limited, but for MD5 they can be generated almost instantaneously and thus allow real-time attacks on the execution of cryptographic protocols, and, more importantly, for SHA-1 they may soon be feasible.

## 5.2 Creating a rogue Certification Authority certificate

This section contains an in-depth discussion of the practical dangers posed by rogue Certification Authority certificates, followed by a detailed description of how we managed to construct such a certificate.

The work reported here was carried out in close collaboration with Alexander Sotirov and Dag Arne Osvik, and was triggered by email exchanges with Alexander Sotirov, Jacob Appelbaum and David Molnar.

### 5.2.1 Attack potential of rogue CA certificates

In the conference version (Stevens et al., 2007; Section 4.1) of this paper we daydreamed:

"Ideally, a realistic attack targets the core of PKI: provide a relying party with trust, beyond reasonable cryptographic doubt, that the person indicated by the Distinguished Name field has exclusive control over the private key corresponding to the public key in the certificate. The attack should also enable the attacker to cover his trails."

Our dream scenario has been, mostly, realised with the construction of a rogue CA certificate. With the private key of a CA under our control, and the public key appearing in a certificate with a valid signature of a commercial CA that is trusted by all major browsers, we can create 'trusted' certificates at will. When scrutinised at bit level, however, our rogue CA certificate may look suspicious which may, ultimately, expose us. Bit level inspection is not something many users will engage in – if they know the difference between https and http to begin with – and, obviously, the software that is supposed to inspect a certificate's bits is expertly guided around the suspicious ones. So, it may be argued that our construction has a non-negligible attack potential. Below we discuss some possibilities in this direction. Upfront, however, we like to point out that our rogue CA is nothing more than a proof of concept that is incapable of doing much harm, because it expired, on purpose, in September of 2004, i.e., more than 4 years before it was created.

Any website secured using TLS can be impersonated using a rogue certificate issued by a rogue CA. This is irrespective of which CA issued the website's true certificate and of any property of that certificate (such as the hash function it is based upon – SHA-256 is not any better in this context than MD4). Combined with redirection attacks where `http` requests are redirected to rogue web servers, this leads to virtually undetectable phishing attacks.

But any application involving a Certification Authority that provides MD5-based certificates with sufficiently predictable serial number and validity period may be vulnerable. In contexts different from TLS this may include signing or encryption of e-mail or software, non-repudiation services, etc.

As pointed out earlier, bit-level inspection of our rogue CA certificate will reveal a relatively large number of bits that may look suspicious – and that *are* suspicious. This could have been avoided if we had chosen to create a rogue certificate for a regular website, as opposed to a rogue CA certificate, because in that case we could have hidden all collision causing bits inside the public keys. Nevertheless, even if each resulting certificate by itself looks unsuspicious, as soon as a dispute arises, the rogue certificate's legitimate sibling can be located with the help of the CA, and the fraud becomes apparent by putting the certificates alongside, thus exposing the party responsible for the fraud.

Our attack relies on our ability to predict the content of the certificate fields inserted by the CA upon certification: if our prediction is correct with non-negligible probability, a rogue certificate can be generated with the same non-negligible probability. Irrespective of the weaknesses, known or unknown, of the cryptographic hash function used for digital signature generation, our type of attack becomes effectively impossible if the CA adds a sufficient amount of fresh randomness to the certificate fields before the public key fields. Relying parties, however, cannot verify this randomness and also the trustworthiness of certificates should not crucially depend on such secondary and circumstantial aspects. We would be in favor of a more fundamental solution – along with a strong cryptographic hash function – possibly along the lines as proposed in Halevi and Krawczyk (2006). Generally speaking, it is advisable not to sign data that is completely determined by some other party. Put differently, a signer should always make a few trivial and unpredictable modifications before digitally signing a document provided by someone else.

Based on our previous work (Stevens et al., 2007), the issue in the previous paragraph was recognised and the possibility of the attack presented in this paper anticipated in the catalogue (BSI, 2007) of algorithms suitable for the German Signature Law ('*Signaturgesetz*'). This catalogue includes conditions and time frames for cryptographic hash algorithms to be used in legally binding digital signatures in Germany. One of the changes introduced in the 2008 version of the catalog is an explicit condition on the usage of SHA-1: only until 2010, and only for so-called "qualified certificates" that contain at least 20 bits of entropy in their serial numbers. We are grateful to Prof. Werner Schindler of

the BSI for bringing this to our attention and for confirming that this change was introduced to thwart exactly the type of rogue certificates that we present here for MD5.

We stress that our attack on MD5 is not a preimage or second preimage attack. We cannot create a rogue certificate having a signature in common with a certificate that was not especially crafted using our chosen-prefix collision. In particular, we cannot target any existing, independently created certificate and forge a rogue certificate that shares its digital signature with the digital signature of the targeted certificate. However, given any certificate with an MD5-based digital signature, a relying party cannot easily recognise if it is trustworthy or, on the contrary, crafted by our method. Therefore we repeat our urgent recommendation not to use MD5 for new X.509 certificates. How existing MD5 certificates should be handled is a subject of further research. We also urgently recommend to reconsider usage of MD5 in other applications. Proper alternatives are available; but compatibility with existing applications is obviously another matter. Given potential developments related to SHA-1 (see de Cannière and Rechberger, 2006) and <http://www.iaik.tugraz.at/content/research/krypto/sha1/>) we feel that usage of SHA-1 in certificate generation should be reassessed as well.

### 5.2.2 Certificate construction

Our first colliding X.509 certificate construction was based on an identical-prefix collision, and resulted in two certificates with different public keys, but identical Distinguished Name fields (Lenstra and de Weger, 2005). As a first application of chosen-prefix collisions we showed how the Distinguished Name fields could be chosen differently as well (Stevens et al., 2007). In this section we describe the details of a colliding certificate construction that goes one step further by also allowing different "basic constraints" fields. This allows us to construct one of the certificates as an ordinary website certificate, but the other one as a CA certificate. As already pointed out in Section 5.1, this additional difference required a radical departure from our traditional construction method from Lenstra and de Weger (2005) and Stevens et al. (2007). Furthermore, unlike our previous colliding certificate constructions where the CA was under our control, a commercial CA provided the digital signature for the (legitimate) website certificate. This required us to sufficiently accurately predict its serial number and validity period well before the certification request was submitted to the signing CA.

We exploited the following weaknesses of the commercial CA that carried out the legitimate certification request:

- Its usage of the cryptographic hash function MD5 to generate digital signatures for new certificates.

- Its fully automated way to process online certification requests that fails to recognise anomalous behavior of requesting parties.
- Its usage of sequential serial numbers and its usage of validity periods that are determined entirely by the date and time in seconds at which the certification request is processed.
- Its failure to enforce, by means of the “basic constraints” field in its own certificate, a limit on the length of the chain of certificates that it can sign.

The first three points are further discussed below. The last point, if properly handled, could have crippled our rogue CA certificate but does not affect its construction. A certificate contains a “basic constraints” field where a bit is set to indicate if the certificate is a CA certificate. With the bit set, a “path length constraint” subfield may be present, specifying an integer that indicates how many CAs may occur in the chain between the CA certificate in question and end-user certificates. The commercial CA that we interacted with failed to use this option in its own certificate, implying that any number of intermediate CAs is permitted. If the “path length constraint” would have been present and set at 0 (zero), then our rogue CA certificate could still have been constructed. But whether or not the rogue CA certificate or certificates signed by it can then also be used depends on (browser-)software actually checking the “path length constraint” subfields in chains of certificates. Thus a secondary “defense in depth” mechanism was present that could have foiled our attack, but failed to do so simply because it was not used.

Before describing the construction of the colliding certificates, we briefly discuss the parameter choices used for the chosen-prefix collision search. The 2048-bit upper bound on the length of RSA moduli, as enforced by some CAs, combined with other limitations of our certificate construction, implied we could allow for at most 3 near-collision blocks. Opting for the least difficult possibility (namely, 3 near-collision blocks), we had to decide on values for  $k$  and the aimed for value for  $w$ , determining the costs of the birthday search and the near-collision block constructions (cf. Sections 4.2 and 4.1), respectively. Obviously, our choices were influenced by our computational resources, namely a cluster of 215 PlayStation 3 (PS3) game consoles. When running Linux on a PS3, applications have access to 6 Synergistic Processing Units (SPUs), a general purpose CPU, and about 150MB of RAM per PS3. For the birthday search, the  $6 \times 215$  SPUs are computationally equivalent to approximately 8600 regular 32-bit cores, due to each SPU’s  $4 \times 32$ -bit wide SIMD architecture. The other parts of the chosen-prefix collision construction are not suitable for the SPUs, but we were able to use the 215 PS3 CPUs for the construction of the actual near-collision blocks. With these resources, the choice  $w = 5$  still turned out to be acceptable despite the 1000-fold increase in the cost of the actual near-collision block construction. This is the case even for the hard cases with many differences between IHV and IHV’:

as a consequence the differential paths contain many bitconditions, which leaves little space for the tunnels, thereby complicating the near-collision block construction.

For the targeted 3 near-collision blocks, the entries for  $w = 5$  in the first table in Appendix C show the time-memory tradeoff when the birthday search space is varied with  $k$ . With 150MB at our disposal per PS3, for a total of about 30GB, we decided to use  $k = 8$  as this optimises the overall birthday complexity for the plausible case that the birthday search takes  $\sqrt{2}$  times longer than expected. The resulting overall chosen-prefix collision construction takes on average less than a day on the PS3-cluster. In theory we could have used 1TB (or more) of hard drive space, in which case it would have been optimal to use  $k = 0$  for a birthday search of about 20 PS3 days.

We summarise the construction of the colliding certificates in the sequence of steps below, and then describe each step in more detail.

- 1 Construction of templates for the two to-be-signed parts, as outlined in Figure 4. Note that we distinguish between a ‘legitimate’ to-be-signed part on the left hand side, and a ‘rogue’ to-be-signed part on other side.
- 2 Prediction of serial number and validity period for the legitimate part, thereby completing the chosen prefixes of both to-be-signed parts.
- 3 Computation of the two different collision-causing appendages.
- 4 Computation of a single collision-maintaining appendage that will be appended to both sides, thereby completing both to-be-signed parts.
- 5 Preparation of the certification request for the legitimate to-be-signed part.
- 6 Submission of the certification request and receipt of the new certificate.
- 7 If serial number and validity period of the newly received certificate are as predicted, then the rogue certificate can be completed. Otherwise return to Step 2.

**Figure 4** The to-be-signed parts of the colliding certificates

legitimate website certificate		rogue CA certificate	
serial number	chosen prefixes	serial number	<div>commercial CA name</div> <div>validity period</div> <div>rogue CA name</div> <div>1024 bit RSA public key</div> <div>v3 extensions</div> <div>"CA = TRUE"</div>
commercial CA name		commercial CA name	
validity period		validity period	
domain name	collision bits	rogue CA name	
2048 bit RSA public key		1024 bit RSA public key	<div>tumor</div>
v3 extensions	identical suffixes	v3 extensions	
"CA = FALSE"		"CA = TRUE"	



### 5.2.2.1 Step 1. Templates for the to-be-signed parts

In this step all bits are set in the two to-be-signed parts, except for bits that will be determined in later steps. For the latter bits space will be reserved here. On the legitimate side the parts to be filled in later are the predictions for the serial number and validity period, and most bits of the public key. On the rogue side the largest part of the content of an extension field of the type “Netscape Comment” is for the moment left undetermined. The following roughly describes the sequence of steps.

- On the legitimate side, the chosen prefix contains space for serial number and validity period, along with the exact Distinguished Name of the commercial CA where the certification request will be submitted. This is followed by a subject Distinguished Name that contains a legitimate website domain name (owned by one of us) consisting of as many characters as allowed by the commercial CA (in our case 64), and concluded by the first 208 bits of an RSA modulus, the latter all chosen at random after the leading ‘1’-bit. These sizes were chosen in order to have as many corresponding bits as possible on the rogue side, while fixing as few bits as possible of the RSA modulus on the legitimate side (see Step 4 for the reason why).
- The corresponding bits on the rogue side contain an arbitrarily chosen serial number, the same commercial CA’s Distinguished Name, an arbitrarily chosen validity period (actually chosen as indicating “August 2004”, to avoid abuse of the rogue certificate), a short rogue CA name, a 1024-bit RSA public key generated using standard software, and the beginning of the X.509v3 extension fields. One of these fields is the “basic constraints” field, a bit that we set to indicate that the rogue certificate will be a CA certificate (in Figure 4 this bit is denoted by “CA=TRUE”).
- At this point the entire chosen prefix is known on the rogue side, but on the legitimate side predictions for the serial number and validity period still need to be inserted. That will be done in Step 2.
- The various field sizes were selected so that on both sides the chosen prefixes are now 96 bits short of the same MD5 block boundary. On both sides these 96 bit positions are reserved for the birthday bits. As only  $64 + k = 72$  birthday search bits per side will be needed (and appended in Step 3) the first 24 bits at this point are set to 0. On the legitimate side these 96 bits are part of the RSA modulus, on the rogue side they are part of an extension field of the type ‘Netscape Comment’, denoted as ‘tumor’ in Figure 4.
- From here on forward, everything that goes to the rogue side is part of the ‘Netscape Comment’ field, as it is not meaningful for the rogue CA certificate but only appended to cause and maintain a collision with bits added to the legitimate side. On the legitimate side we first make space for 3 near-collision blocks of 512

bits each (calculated in Step 3) and for 208 bits used to complete a 2048-bit RSA modulus (determined in Step 4), and then set the RSA public exponent (for which we took the common choice 65537) and the X.509v3 extensions including the bit indicating that the legitimate certificate will be an end-user certificate (in Figure 4 denoted by “CA=FALSE”).

### 5.2.2.2 Step 2. Prediction of serial number and validity period

Based on repeated certification requests submitted to the targeted commercial CA, it turned out that the validity period can very reliably be predicted as the period of precisely one year plus one day, starting exactly six seconds after a request is submitted. So, to control that field, all we need to do is select a validity period of the right length, and submit the legitimate certification request precisely six seconds before it starts. Though occasional accidents may happen in the form of one-second shifts, this was the easy part.

Predicting the serial number is harder but not impossible. In the first place, it was found that the targeted commercial CA uses sequential serial numbers. Being able to predict the next serial number, however, is not enough: the construction of the collision can be expected to take at least a day, before which the serial number and validity period have to be fixed, and only after which the to-be-signed part of the certificate will be entirely known. As a consequence, there will have been a substantial and uncertain increment in the serial number by the time the collision construction is finished. So, another essential ingredient of our construction was the fact that the CA’s weekend workload is quite stable: it was observed during several weekends that the increment in serial number over a weekend does not vary a lot. This allowed us to pretty reliably predict Monday morning’s serial numbers on the Friday afternoon before. Thus, on Friday afternoon we selected a number at the high end of the predicted range for the next Monday morning, and inserted it in the legitimate to-be-signed part along with a validity period starting that same Monday morning at the time corresponding to our serial number prediction. See Step 6 how we then managed, after the weekend, to target precisely the selected serial number and validity period.

### 5.2.2.3 Step 3. Computation of the collision

At this point both chosen prefixes have been fully determined so the chosen-prefix collision can be computed: first the 72 birthday bits per side, calculated in parallel on the 1290 SPUs of a cluster of 215 PS3s, followed by the calculation of 3 pairs of 512-bit near-collision blocks on the 215 PS3 CPUs. The entire calculation takes on average about a day.

Given that we had a weekend available, and that the calculation can be expected to take just a day, we sequentially processed a number of chosen-prefixes, each

corresponding to different serial numbers and validity periods (targeting both Monday and Tuesday mornings). So, a near-collision block calculation on the CPUs would always run simultaneously with a birthday search on the SPUs for the ‘next’ attempt.

#### 5.2.2.4 Step 4. Finishing the to-be-signed parts

At this point the legitimate and rogue sides collide under MD5, so that from here on only identical bits may be appended to both sides.

With  $208 + 24 + 72 + 3 \cdot 512 = 1840$  bits set, the remaining  $2048 - 1840 = 208$  bits need to be set for the 2048-bit RSA modulus on the legitimate side. Since in the next step the RSA private exponent corresponding to the RSA public exponent is needed, the full factorisation of the RSA modulus needs to be known, and the factors must be compatible with the choice of the RSA public exponent. Common CAs (including our targeted commercial CA) do not check for compositeness of RSA moduli in certification requests, implying that we could simply have added 208 bits to make the RSA modulus a prime. We found that approach unsatisfactory, and opted for the rather crude but trivial to program method sketched below that results in a 224-bit prime factor with a prime 1824-bit cofactor. Given that at the time this work was done the largest factor found using the elliptic curve integer factorisation method was 222 bits long, a 224-bit smallest prime factor keeps the resulting modulus out of reach of common factoring efforts. We could have used a relatively advanced lattice-based method to try and squeeze in a 312-bit prime factor along with a prime 1736-bit cofactor. Given only 208 bits of freedom to select a 2048-bit RSA modulus, it is unlikely that a more balanced solution can efficiently be found. Thus the reason why as few bits as possible should be fixed in Step 1, is that it allows us to construct a slightly less unbalanced RSA modulus.

Let  $N$  be the 2048-bit integer consisting of the 1840 already determined bits of the RSA modulus-to-be, followed by 208 one bits. We select a 224-bit integer  $p$  at random until  $N \bmod p$  is less than  $2^{208}$ , and keep doing this until both  $p$  and  $q = \lfloor N/p \rfloor$  are prime and the RSA public exponent is coprime to  $(p-1)(q-1)$ . Once such primes  $p$  and  $q$  have been found, the number  $pq$  will be the legitimate side’s RSA modulus, the leading 1840 bits of which are already present in the legitimate side’s to-be-signed part, and the 208 least significant bits of which are inserted in both to-be-signed parts.

To analyse the required effort somewhat more in general,  $2^{k-208}$  integers of  $k$  bits (with  $k > 208$ ) need to be selected on average for  $pq$  to have the desired 1840 leading bits. Since an  $\ell$ -bit integer is prime with probability approximately  $1/\log(2^\ell)$ , a total of  $k(2048 - k)2^{k-208}(\log 2)^2$  attempts may be expected before a suitable RSA modulus is found. The coprimality requirement is a lower order effect that we disregard. Note that for  $k(k-2048)(\log 2)^2$  of the attempts the  $k$ -bit number  $p$  has to be tested for primality, and that for  $(2048 - k) \log 2$  of those  $q$  needs to be tested as well (on

average, obviously). For  $k = 224$  this turned out to be doable in a few minutes on a standard PC.

This completes the to-be-signed parts on both sides. Now it remains to be hoped that the legitimate part that actually will be signed corresponds, bit for bit, with the legitimate to-be-signed part that we concocted.

#### 5.2.2.5 Step 5. Preparing the certification request

Using the relevant information from the legitimate side’s template, i.e., the subject Distinguished Name and the public key, a PKCS#10 Certificate Signing Request is prepared. The CA requires proof of possession of the private key corresponding to the public key in the request. This is done by signing the request using the private key – this is the sole reason that we need the RSA private exponent.

#### 5.2.2.6 Step 6. Submission of the certification request

The targeted legitimate to-be-signed part contains a very specific validity period that leaves no choice for the moment at which the certification request needs to be submitted to the CA. Just hoping that at that time the serial number would have precisely the predicted value is unlikely to work, so a somewhat more elaborate approach is used. About half an hour before the targeted submission moment, the same request is submitted, and the serial number in the resulting certificate is inspected. If it is already too high, the entire attempt is abandoned. Otherwise, the request is repeatedly submitted, with a frequency depending on the gap that may still exist between the serial number received and the targeted one, and taking into account possible certification requests by others. In this way the serial number is slowly nudged toward the right value at the right time. Although there is nothing illegal about repeated certification requests, it should be possible for a CA to recognise the somewhat anomalous behavior sketched above and to take appropriate countermeasures (such as random delays or jumps in serial numbers) if it occurs.

Various types of accidents may happen, of course, and we experienced some of them, such as another CA customer ‘stealing’ our targeted serial number just a few moments before our attempt to get it, thereby wasting that weekend’s calculations. But, after the fourth weekend it worked as planned, and we managed to get an actually signed part that exactly matched our predicted legitimate to-be-signed part.

#### 5.2.2.7 Step 7. Creation of the rogue certificate

Given the perfect match between the actually signed part and the hoped for one, and the MD5 collision between the latter and the rogue side’s to-be-signed part, the MD5-based digital signature present in the legitimate certificate as provided by the commercial CA is equally valid for the rogue side. To finish the rogue CA certificate it suffices to copy the digital signature to the right spot in the rogue CA certificate.

The full details of the above construction, including both certificates, can be found on <http://www.win.tue.nl/hashclash/rogue-ca/>.

### 5.3 Nostradamus attack

In the original Nostradamus attack from Kelsey and Kohno (2006) one first commits to a certain hash value, and afterwards for any message constructs a document that not only contains that message but also has under MD5 the committed hash value. So far, this attack is, in its full generality, infeasible for MD5 because space and time requirements are beyond what can be handled at his point. It is easily doable, though, if a limited size message space has been defined upfront.

Suppose there are messages  $m_1, m_2, \dots, m_r$ , then using  $r - 1$  chosen-prefix collisions we can construct  $r$  suffixes  $s_1, s_2, \dots, s_r$  such that the  $r$  documents  $d_i = m_i || s_i$  all have the same hash. After committing to the common hash, afterwards any of the  $r$  documents  $d_1, d_2, \dots, d_r$  can be shown, possibly to achieve some malicious goal. The other documents will remain hidden and their contents, i.e., the  $m_i$ -parts, cannot be derived – with overwhelming probability – from the single published document or from the common hash value.

To show the practicality of this variant, we have made an example consisting of 12 different PDF documents with a common MD5-hash, where each document predicts a different outcome of the 2008 US presidential elections. The PDF format is convenient for this purpose because it allows insertion of extra image objects that are unreferenced in the resulting document and thus invisible in any common PDF reader. See the next section for more on the PDF related details of the construction and <http://www.win.tue.nl/hashclash/Nostradamus/> for the actual documents, one of which correctly predicted the outcome one year before the elections took place. For each of the 11 collisions required for this example we used a 64-bit birthday search (on a single PS3) aiming for about 11 near-collision blocks (constructed on a quad-core PC). It took less than 2 days per chosen-prefix collision. Since we performed those computations our methods have improved as described in this paper, so this attack would now run much faster.

#### 5.3.1 PDF construction

Given the structure of PDF documents it is not entirely straightforward how to insert different chosen-prefix

collision blocks, while keeping the parts following those blocks identical in order to maintain the collision. The relevant details of both the PDF structure and our construction are covered here.

A PDF document is built up from the following four consecutive parts: a fixed header, a part consisting of an arbitrary number of numbered objects, an object lookup table and, finally, a trailer. The trailer specifies the number of objects, which of the objects is the unique root object (containing the document content) and which is the info object (containing the document's meta information such as authors and title etc.), and contains a filepointer to the start of the object lookup table.

Given a file containing a PDF document, additional numbered objects can be inserted, as long as they are added to the object lookup table and the corresponding changes are made to the number of objects and the filepointer in the trailer. A template for an image object is given in Table 9. With the exception of the binary image, the format is entirely text based. The binary image is put between single line-feed characters (ASCII code 10) and the result is encapsulated by the keywords `stream` and `endstream`. The keyword `/Length` must specify the byte length of the image. As the image is uncompressed and each pixel requires three bytes ('RGB'), the image byte length must be three times the product of the specified width and height. The object number (42 in the example object header) must be set to the next available object number.

When constructing colliding PDF files they must be equal after the collision-causing data (cf. the "suffix" in Figure 2). The object lookup tables and trailers for all files must therefore be the same. This was achieved as follows:

- As all documents must have the same number of objects, dummy objects are inserted where necessary.
- Since all root objects must have the same object number, they can be copied if necessary to objects with the next available object number.
- The info objects are treated in the same way as the root objects.
- To make sure that all object lookup tables and filepointers are identical, the objects can be sorted by object number and if necessary padded with spaces after their `obj` keyword to make sure that all objects with the same object number have the same file position and byte length in all files.

**Table 9** A numbered image object in the PDF format

Part	Contents
object header	42 0 obj
image header	<< /ColorSpace /DeviceRGB /Subtype /Image
image size	/Length 9216 /Width 64 /Height 48 /BitsPerComponent 8
image contents	>> stream...endstream
object footer	endobj

- Finally, the object lookup tables and trailers need to be adapted to reflect the new situation – as a result they should be identical for all files.

Although this procedure works for basic PDF files (such as PDF version 1.4 as we produced using pdfflatex), it should be noted that the PDF document format allows additional features that may cause obstructions, the details of which are irrelevant for this article.

Given  $r$   $\LaTeX$  files with the desired subtle differences (such as names of  $r$  different candidates),  $r$  different PDF files are produced using a version of  $\LaTeX$  that is suitable for our purposes (cf. above). In all these files a hidden image object with a fixed object number is then inserted, and the approach sketched above is followed to make the lookup tables and trailers for all files identical. To ensure that the files are identical after the hidden image contents, their corresponding objects were made the last objects in the files. This then leads to  $r$  chosen prefixes consisting of the leading parts of the PDF files up to and including the keyword `stream` and the first line-feed character. After determining  $r - 1$  chosen-prefix collisions resulting in  $r$  collision-causing appendages, the appendages are put in the proper binary image parts, after which all files are completed with a line-feed character, the keywords `endstream` and `endobj`, and the identical lookup tables and trailers.

Note that the `Length` etc. fields have to be set before collision finding, and that the value of `Length` will grow logarithmically with  $r$  and linearly in the number of near-collision blocks one is aiming for.

#### 5.4 Colliding executables

Using the same set-up as used for the Nostradamus attack reported in Section 5.3, i.e., 64-bit birthday searching on a PS3 followed by the construction of about 12 near-collision blocks on a quad-core PC, it took us less than 2 days to create two different Windows executables with the same MD5 hash. Initially both 40960 bytes large,  $13 \times 64$  bytes had to be appended to each executable, for a resulting size of just 41792 bytes each, to let the files collide under MD5 without changing their functionality. See <http://www.win.tue.nl/hashclash/SoftIntCodeSign/> for details. As noted above, it has been shown on <http://blog.didierstevens.com/2009/01/17/> that this attack can be elevated to one on a code signing scheme.

As usual, the following remarks apply:

- An existing executable with a known and published hash value not resulting from this construction cannot be targeted by this attack (Gauravaram et al., 2006): our attack is not a preimage or second preimage attack. In order to attack a software integrity protection or code signing scheme using this approach, the attacker must be able to manipulate the files before they are hashed (and, possibly, signed). Given the level of access

required to realise the attack an attacker can probably do more harm in other simpler and more traditional ways.

- On the other hand, there is no guarantee that a downloaded file with the proper hash or correct signature is not the evil sibling of the intended file. Especially when software integrity verification takes place under the hood, users may be lured into installing – and trusting – malware. Until a tool is available that would also be able to distinguish potentially malicious MD5-based certificates, all a relying party can do is resorting to bit-level inspection of each executable; the latter requires more expertise than most users can be expected to have, in particular if the collision blocks are hidden at a less conspicuous place than at the very end of the executable.
- Any number  $r$  of executables can be made to collide, at the cost of  $r - 1$  chosen-prefix collisions and an  $O(\log r)$ -byte appendage to each of the  $r$  original executables.

A countermeasure thwarting our attack would be the inclusion of a self-checking component in software, i.e., where the software would check the integrity of its own executable as the first step of the execution. It is better, however, not to rely on cryptographic primitives such as MD5 that fail to meet their design criteria.

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## Appendix A

**Table A1** MD5 compression function constants

$t$	$AC_t$	$RC_t$	$W_t$
0	d76aa478 <sub>16</sub>	7	$m_0$
1	e8c7b756 <sub>16</sub>	12	$m_1$
2	242070db <sub>16</sub>	17	$m_2$
3	c1bdceee <sub>16</sub>	22	$m_3$
4	f57c0faf <sub>16</sub>	7	$m_4$
5	4787c62a <sub>16</sub>	12	$m_5$
6	a8304613 <sub>16</sub>	17	$m_6$
7	fd469501 <sub>16</sub>	22	$m_7$
8	698098d8 <sub>16</sub>	7	$m_8$
9	8b44f7af <sub>16</sub>	12	$m_9$
10	ffff5bb1 <sub>16</sub>	17	$m_{10}$
11	895cd7be <sub>16</sub>	22	$m_{11}$
12	6b901122 <sub>16</sub>	7	$m_{12}$
13	fd987193 <sub>16</sub>	12	$m_{13}$
14	a679438e <sub>16</sub>	17	$m_{14}$
15	49b40821 <sub>16</sub>	22	$m_{15}$
16	f61e2562 <sub>16</sub>	5	$m_1$
17	c040b340 <sub>16</sub>	9	$m_6$
18	265e5a51 <sub>16</sub>	14	$m_{11}$
19	e9b6c7aa <sub>16</sub>	20	$m_0$
20	d62f105d <sub>16</sub>	5	$m_5$
21	02441453 <sub>16</sub>	9	$m_{10}$
22	d8a1e681 <sub>16</sub>	14	$m_{15}$
23	e7d3fbc8 <sub>16</sub>	20	$m_4$
24	21e1cde6 <sub>16</sub>	5	$m_9$
25	c33707d6 <sub>16</sub>	9	$m_{14}$
26	f4d50d87 <sub>16</sub>	14	$m_3$
27	455a14ed <sub>16</sub>	20	$m_8$
28	a9e3e905 <sub>16</sub>	5	$m_{13}$
29	fcefa3f8 <sub>16</sub>	9	$m_2$
30	676f02d9 <sub>16</sub>	14	$m_7$

**Table A1** MD5 compression function constants (continued)

$t$	$AC_t$	$RC_t$	$W_t$
31	8d2a4c8a <sub>16</sub>	20	$m_{12}$
32	fffa3942 <sub>16</sub>	4	$m_5$
33	8771f681 <sub>16</sub>	11	$m_8$
34	6d9d6122 <sub>16</sub>	16	$m_{11}$
35	fde5380c <sub>16</sub>	23	$m_{14}$
36	a4beea44 <sub>16</sub>	4	$m_1$
37	4bdecfa9 <sub>16</sub>	11	$m_4$
38	f6bb4b60 <sub>16</sub>	16	$m_7$
39	beefbc70 <sub>16</sub>	23	$m_{10}$
40	289b7ec6 <sub>16</sub>	4	$m_{13}$
41	eaal27fa <sub>16</sub>	11	$m_0$
42	d4ef3085 <sub>16</sub>	16	$m_3$
43	04881d05 <sub>16</sub>	23	$m_6$
44	d9d4d039 <sub>16</sub>	4	$m_9$
45	e6db99e5 <sub>16</sub>	11	$m_{12}$
46	1fa27cf8 <sub>16</sub>	16	$m_{15}$
47	c4ac5665 <sub>16</sub>	23	$m_2$
48	f4292244 <sub>16</sub>	6	$m_0$
49	432aff97 <sub>16</sub>	10	$m_7$
50	ab9423a7 <sub>16</sub>	15	$m_{14}$
51	fc93a039 <sub>16</sub>	21	$m_5$
52	655b59c3 <sub>16</sub>	6	$m_{12}$
53	8f0ccc92 <sub>16</sub>	10	$m_3$
54	ffefff47d <sub>16</sub>	15	$m_{10}$
55	85845dd1 <sub>16</sub>	21	$m_1$
56	6fa87e4f <sub>16</sub>	6	$m_8$
57	fe2ce6e0 <sub>16</sub>	10	$m_{15}$
58	a3014314 <sub>16</sub>	15	$m_6$
59	4e0811a1 <sub>16</sub>	21	$m_{13}$
60	f7537e82 <sub>16</sub>	6	$m_4$
61	bd3af235 <sub>16</sub>	10	$m_{11}$
62	2ad7d2bb <sub>16</sub>	15	$m_2$
63	eb86d391 <sub>16</sub>	21	$m_9$

## Appendix B

### Boolean function bitconditions

The 4 tables in this appendix correspond to rounds 1 through 4, respectively, i.e.,  $0 \leq t < 16$ ,  $16 \leq t < 32$ ,  $32 \leq t < 48$  and  $48 \leq t < 64$ . The ‘ $abc$ ’ in each of the first columns denotes the three differential bitconditions  $(q_t[i], q_{t-1}[i], q_{t-2}[i])$  for the relevant  $t$  and  $0 \leq i \leq 31$ , with each table containing all 27 possible triples. Columns 2, 3, 4 contain forward bitconditions  $FC(t, abc, g)$  for  $g = 0, +1, -1$ , respectively, and columns 5, 6, 7 contain backward bitconditions  $BC(t, abc, g)$  for those same  $g$ ’s, respectively. The parenthesised number next to a triple  $def$  is  $|U_{def}|$ , the amount of freedom left. An entry is left empty if  $g \notin V_{abc}$ . See Section 4.4.3 for more details.

**B.1** Bitconditions applied to boolean function  $F$ **Table B1** Round 1 ( $0 \leq t < 16$ ) bitconditions applied to boolean function  $F$ :

$$F(X, Y, Z) = (X \wedge Y) \oplus (\overline{X} \wedge Z)$$

<i>DB</i> <i>abc</i>	<i>Forward bitconditions</i>			<i>Backward bitconditions</i>		
	$g = 0$	$g = +1$	$g = -1$	$g = 0$	$g = +1$	$g = -1$
... (8)	... (8)			... (8)		
..+ (4)	1.+ (2)	0.+ (2)		1.+ (2)	0.+ (2)	
..- (4)	1.- (2)		0.- (2)	1.- (2)		0.- (2)
.+. (4)	0+. (2)	1+. (2)		0+. (2)	1+. (2)	
+++ (2)		+++ (2)			+++ (2)	
+-+ (2)		1+- (1)	0+- (1)		1+- (1)	0+- (1)
.-. (4)	0-. (2)		1-. (2)	0-. (2)		1-. (2)
.-+ (2)		0-+ (1)	1-+ (1)		0-+ (1)	1-+ (1)
--- (2)			--- (2)			--- (2)
+. . (4)	+.V (2)	+10 (1)	+01 (1)	+ . (2)	+10 (1)	+01 (1)
+. + (2)	+0+ (1)	+1+ (1)		+0+ (1)	+1+ (1)	
+. - (2)	+1- (1)		+0- (1)	+1- (1)		+0- (1)
++. (2)	++1 (1)	++0 (1)		++1 (1)	++0 (1)	
+++ (1)		+++ (1)			+++ (1)	
++- (1)	++- (1)			++- (1)		
+- . (2)	+ -0 (1)		+ -1 (1)	+ -0 (1)		+ -1 (1)
+++ (1)	+++ (1)			+++ (1)		
+++ (1)			+++ (1)			+++ (1)
-. . (4)	-.V (2)	-01 (1)	-10 (1)	- . (2)	-01 (1)	-10 (1)
-. + (2)	-1+ (1)	-0+ (1)		-1+ (1)	-0+ (1)	
-. - (2)	-0- (1)		-1- (1)	-0- (1)		-1- (1)
-+. (2)	-+0 (1)	-+1 (1)		-+0 (1)	-+1 (1)	
++ + (1)		++ + (1)			++ + (1)	
++ - (1)	++ - (1)			++ - (1)		
--. (2)	--1 (1)		--0 (1)	--1 (1)		--0 (1)
--- (1)	--- (1)			--- (1)		
--- (1)			--- (1)			--- (1)

**B.2** Bitconditions applied to boolean function  $G$ **Table B2** Round 2 ( $16 \leq t < 32$ ) bitconditions applied to boolean function  $G$ :

$$G(X, Y, Z) = (Z \wedge X) \oplus (\overline{Z} \wedge Y)$$

<i>DB</i> <i>abc</i>	<i>Forward bitconditions</i>			<i>Backward bitconditions</i>		
	$g = 0$	$g = +1$	$g = -1$	$g = 0$	$g = +1$	$g = -1$
... (8)	... (8)			... (8)		
..+ (4)	.V+ (2)	10+ (1)	01+ (1)	^ . + (2)	10+ (1)	01+ (1)
..- (4)	.V- (2)	01- (1)	10- (1)	^ . - (2)	01- (1)	10- (1)
.+. (4)	.+1 (2)	.+0 (2)		.+1 (2)	.+0 (2)	
++. (2)	0++ (1)	1++ (1)		0++ (1)	1++ (1)	
+-+ (2)	1+- (1)	0+- (1)		1+- (1)	0+- (1)	
.-. (4)	.-1 (2)		.-0 (2)	.-1 (2)		.-0 (2)
.-+ (2)	1-+ (1)		0-+ (1)	1-+ (1)		0-+ (1)
--- (2)	0-- (1)		1-- (1)	0-- (1)		1-- (1)
+. . (4)	+ .0 (2)	+ .1 (2)		+ .0 (2)	+ .1 (2)	
+. + (2)	+1+ (1)	+0+ (1)		+1+ (1)	+0+ (1)	
+. - (2)	+0- (1)	+1- (1)		+0- (1)	+1- (1)	
++. (2)		++ . (2)			++ . (2)	
+++ (1)		+++ (1)			+++ (1)	
++- (1)		++- (1)			++- (1)	
+- . (2)		+ -1 (1)	+ -0 (1)		+ -1 (1)	+ -0 (1)
+++ (1)	+++ (1)			+++ (1)		
+++ (1)	+++ (1)			+++ (1)		
-. . (4)	-.0 (2)		-.1 (2)	-.0 (2)		-.1 (2)
-. + (2)	-0+ (1)		-1+ (1)	-0+ (1)		-1+ (1)
-. - (2)	-1- (1)		-0- (1)	-1- (1)		-0- (1)
-+. (2)		-+0 (1)	-+1 (1)		-+0 (1)	-+1 (1)
++ + (1)	++ + (1)			++ + (1)		
++ - (1)	++ - (1)			++ - (1)		
--. (2)			--. (2)			--. (2)
--- (1)			--- (1)			--- (1)
--- (1)			--- (1)			--- (1)

B.3 Bitconditions applied to boolean function  $H$ **Table B3** Round 3 ( $32 \leq t < 48$ ) bitconditions applied to boolean function  $H$ :

$$H(X, Y, Z) = X \oplus Y \oplus Z$$

DB abc	Forward bitconditions			Backward bitconditions		
	$g = 0$	$g = +1$	$g = -1$	$g = 0$	$g = +1$	$g = -1$
... (8)	... (8)			... (8)		
..+ (4)		.V+ (2)	.Y+ (2)		^+. (2)	!.+ (2)
..- (4)		.Y- (2)	.V- (2)		!.- (2)	^-.- (2)
+. (4)		.+W (2)	.+H (2)		m+. (2)	#+. (2)
++ (2)	++ (2)			++ (2)		
+- (2)	+- (2)			+- (2)		
.- (4)		.-H (2)	.-W (2)		#-. (2)	m-. (2)
.-+ (2)	.-+ (2)			.-+ (2)		
.-. (2)	.-. (2)			.-. (2)		
+. (4)		+.V (2)	+.Y (2)		+^-. (2)	+!. (2)
++ (2)	++ (2)			++ (2)		
+- (2)	+- (2)			+- (2)		
++ (2)	++ (2)			++ (2)		
+++ (1)		+++ (1)		+++ (1)		
++- (1)			++- (1)		++- (1)	
+- (2)	+- (2)			+- (2)		
++ (1)		++ (1)		++ (1)		
++ (1)		++ (1)		++ (1)		
-. (4)		-.Y (2)	-.V (2)		-!. (2)	-^-. (2)
-.+ (2)	-.+ (2)			-.+ (2)		
-. (2)	-. (2)			-. (2)		
-. (2)	-. (2)			-. (2)		
++ (1)		++ (1)		++ (1)		
++ (1)		++ (1)		++ (1)		
-. (2)	-. (2)			-. (2)		
-. (1)		-. (1)		-. (1)		
-. (1)		-. (1)		-. (1)		

B.4 Bitconditions applied to boolean function  $I$ **Table B4** Round 4 ( $48 \leq t < 64$ ) bitconditions applied to boolean function  $I$ :

$$I(X, Y, Z) = Y \oplus (X \vee \bar{Z})$$

DB abc	Forward bitconditions			Backward bitconditions		
	$g = 0$	$g = +1$	$g = -1$	$g = 0$	$g = +1$	$g = -1$
... (8)	... (8)			... (8)		
..+ (4)	1.+ (2)	01+ (1)	00+ (1)	1.+ (2)	01+ (1)	00+ (1)
..- (4)	1.- (2)	00- (1)	01- (1)	1.- (2)	00- (1)	01- (1)
+. (4)		0+1 (1)	.+Q (3)		0+1 (1)	?+. (3)
++ (2)	0++ (1)		1++ (1)	0++ (1)		1++ (1)
+- (2)	0+- (1)		1+- (1)	0+- (1)		1+- (1)
.- (4)		.-Q (3)	0-1 (1)		?-. (3)	0-1 (1)
.-+ (2)	0-+ (1)	1-+ (1)		0-+ (1)	1-+ (1)	
.-. (2)	0-- (1)	1-- (1)		0-- (1)	1-- (1)	
+. (4)	+0 (2)	+01 (1)	+11 (1)	+0 (2)	+01 (1)	+11 (1)
++ (2)	++ (2)			++ (2)		
+- (2)		+0- (1)	+1- (1)		+0- (1)	+1- (1)
++ (2)	++ (1)		++ (1)	++ (1)		++ (1)
+++ (1)			+++ (1)			+++ (1)
++- (1)	++- (1)			++- (1)		
+- (2)	+-1 (1)	+-0 (1)		+-1 (1)	+-0 (1)	
++ (1)		++ (1)			++ (1)	
++ (1)	++ (1)			++ (1)		
-. (4)	-.0 (2)	-11 (1)	-01 (1)	-.0 (2)	-11 (1)	-01 (1)
-.+ (2)		-1+ (1)	-0+ (1)		-1+ (1)	-0+ (1)
-. (2)	-. (2)			-. (2)		
-. (2)	-. (2)			-. (2)		
++ (1)	++ (1)		++ (1)	++ (1)		++ (1)
++ (1)	++ (1)			++ (1)		
-. (2)	-.1 (1)	-.0 (1)		-.1 (1)	-.0 (1)	
-. (1)	-. (1)			-. (1)		
-. (1)	-. (1)			-. (1)		



## Appendix C

### C.1 Birthday cost

In this appendix notation and variables are as in Section 4.2. The columns  $p$ ,  $C_{\text{tr}}$  and  $M$  denote the values  $-\log_2(p_{r,k,w})$ ,  $\log_2(C_{\text{tr}}(r,k,w))$  and the minimum required memory such that  $C_{\text{coll}}(r,k,w,M) \leq C_{\text{tr}}(r,k,w)$ , respectively.

$r = 3$				$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0															
4													34.01	51.33	2TB
8									33.42	53.03	748GB		31.31	51.98	174GB
12	34.01	55.33	2TB	32.42	54.53	374GB			30.55	53.6	103GB		28.24	52.44	21GB
16	31.	55.83	141GB	29.65	55.15	55GB			27.36	54.01	12GB		25.6	53.13	4GB
20	27.51	56.08	13GB	26.18	55.42	5GB			24.53	54.59	2GB		23.26	53.96	673MB
24	24.33	56.49	2GB	23.35	56.	714MB			22.17	55.41	315MB		21.19	54.92	160MB
28	21.11	56.88	152MB	20.56	56.6	103MB			19.98	56.32	70MB		19.57	56.11	52MB
32	17.88	57.26	17MB	17.88	57.27	17MB			17.89	57.27	17MB		17.88	57.27	17MB
$r = 3$				$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0				31.68	48.17	225GB			30.25	47.45	84GB		28.01	46.33	18GB
4	32.2	50.43	323GB	29.92	49.29	67GB			28.06	48.36	19GB		26.2	47.43	6GB
8	28.83	50.74	32GB	27.33	49.99	11GB			25.88	49.26	5GB		24.47	48.56	2GB
12	26.63	51.64	7GB	25.14	50.9	3GB			23.96	50.3	2GB		22.94	49.8	537MB
16	24.31	52.48	2GB	23.27	51.96	675MB			22.49	51.57	394MB		21.86	51.26	255MB
20	22.28	53.46	340MB	21.62	53.13	215MB			21.14	52.9	155MB		20.73	52.69	117MB
24	20.53	54.59	102MB	20.01	54.33	71MB			19.65	54.15	55MB		19.38	54.01	46MB
28	19.25	55.95	42MB	19.02	55.83	36MB			18.82	55.74	31MB		18.65	55.65	28MB
32	17.88	57.27	17MB	17.88	57.27	17MB			17.88	57.27	17MB		17.88	57.27	17MB
$r = 4$				$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0									34.	49.33	2TB		30.19	47.42	81GB
4				33.42	51.04	749GB			30.36	49.51	90GB		27.59	48.12	14GB
8	35.	53.83	3TB	30.3	51.48	87GB			27.21	49.93	11GB		24.87	48.76	2GB
12	29.58	53.12	53GB	27.53	52.09	13GB			24.59	50.62	2GB		22.47	49.56	388MB
16	26.26	53.45	6GB	24.36	52.51	2GB			22.06	51.36	292MB		20.38	50.51	91MB
20	23.16	53.91	628MB	21.5	53.08	199MB			19.72	52.19	58MB		18.54	51.6	26MB
24	20.25	54.45	84MB	19.09	53.87	38MB			17.8	53.23	16MB		16.86	52.76	8MB
28	17.26	54.95	11MB	16.63	54.64	7MB			16.02	54.34	5MB		15.6	54.13	4MB
32	14.29	55.47	2MB	14.29	55.47	2MB			14.29	55.47	2MB		14.29	55.47	2MB
$r = 4$				$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	26.98	45.81	9GB	24.45	44.55	2GB			22.14	43.4	310MB		20.33	42.49	88MB
4	24.95	46.8	3GB	22.82	45.73	493MB			21.04	44.84	144MB		19.55	44.1	52MB
8	22.63	47.64	432MB	20.92	46.79	133MB			19.58	46.12	53MB		18.56	45.61	26MB
12	20.67	48.66	112MB	19.41	48.03	47MB			18.45	47.55	24MB		17.71	47.18	15MB
16	19.08	49.86	37MB	18.19	49.42	21MB			17.56	49.1	13MB		17.08	48.86	10MB
20	17.66	51.16	14MB	17.09	50.87	10MB			16.7	50.67	8MB		16.39	50.52	6MB
24	16.25	52.45	6MB	15.82	52.24	4MB			15.54	52.09	4MB		15.33	51.99	3MB
28	15.31	53.98	3MB	15.09	53.87	3MB			14.93	53.79	3MB		14.78	53.72	2MB
32	14.29	55.47	2MB	14.29	55.47	2MB			14.29	55.47	2MB		14.29	55.47	2MB

$r = 5$				$w = 0$				$w = 1$				$w = 2$				$w = 3$			
$k$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$	
0	35.	49.83	3TB	31.2	47.92	161GB		27.13	45.89	10GB		23.74	44.2	938MB					
4	33.42	51.04	749GB	28.47	48.56	25GB		24.63	46.64	2GB		21.58	45.12	210MB					
8	28.61	50.63	27GB	25.61	49.13	4GB		22.	47.33	280MB		19.39	46.02	46MB					
12	25.43	51.04	3GB	22.74	49.7	468MB		19.66	48.15	56MB		17.53	47.09	13MB					
16	22.36	51.51	360MB	20.02	50.34	72MB		17.59	49.12	14MB		15.95	48.3	5MB					
20	19.38	52.01	46MB	17.48	51.07	13MB		15.67	50.16	4MB		14.55	49.6	2MB					
24	16.68	52.66	7MB	15.35	52.	3MB		14.06	51.36	2MB		13.17	50.91	1MB					
28	13.92	53.29	2MB	13.22	52.93	1MB		12.61	52.63	1MB		12.21	52.43	1MB					
32	11.2	53.92	1MB	11.2	53.93	1MB		11.2	53.92	1MB		11.2	53.93	1MB					
$r = 5$				$w = 4$				$w = 5$				$w = 6$				$w = 7$			
$k$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$	
0	20.53	42.59	102MB	18.03	41.34	18MB		16.17	40.41	5MB		14.92	39.79	3MB					
4	18.94	43.79	34MB	17.	42.82	9MB		15.57	42.11	4MB		14.53	41.59	2MB					
8	17.27	44.96	11MB	15.79	44.22	4MB		14.75	43.7	2MB		14.01	43.33	2MB					
12	15.92	46.28	5MB	14.84	45.75	2MB		14.09	45.37	2MB		13.56	45.11	1MB					
16	14.8	47.73	2MB	14.06	47.35	2MB		13.55	47.1	1MB		13.18	46.92	1MB					
20	13.79	49.22	1MB	13.31	48.98	1MB		12.99	48.82	1MB		12.76	48.7	1MB					
24	12.64	50.64	1MB	12.29	50.47	1MB		12.07	50.36	1MB		11.91	50.28	1MB					
28	11.95	52.3	1MB	11.76	52.2	1MB		11.62	52.14	1MB		11.5	52.07	1MB					
32	11.2	53.92	1MB	11.2	53.93	1MB		11.2	53.92	1MB		11.2	53.93	1MB					

$r = 6$				$w = 0$				$w = 1$				$w = 2$				$w = 3$			
$k$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$	
0	31.2	47.92	161GB	26.73	45.69	8GB		21.78	43.22	241MB		18.14	41.4	20MB					
4	28.18	48.42	20GB	23.89	46.27	2GB		19.56	44.11	52MB		16.46	42.55	6MB					
8	24.66	48.66	2GB	21.17	46.91	158MB		17.37	45.01	12MB		14.79	43.72	2MB					
12	21.67	49.16	224MB	18.6	47.62	27MB		15.43	46.04	3MB		13.4	45.03	1MB					
16	18.82	49.74	31MB	16.21	48.43	6MB		13.74	47.2	1MB		12.23	46.44	1MB					
20	16.03	50.34	5MB	13.97	49.31	2MB		12.2	48.43	1MB		11.18	47.92	1MB					
24	13.54	51.1	1MB	12.11	50.38	1MB		10.86	49.75	1MB		10.04	49.35	1MB					
28	11.03	51.84	1MB	10.28	51.47	1MB		9.69	51.17	1MB		9.33	50.99	1MB					
32	8.56	52.6	1MB	8.56	52.6	1MB		8.56	52.6	1MB		8.56	52.6	1MB					
$r = 6$				$w = 4$				$w = 5$				$w = 6$				$w = 7$			
$k$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$		$p$	$C_{tr}$	$M$	
0	15.12	39.88	3MB	13.05	38.85	1MB		11.73	38.19	1MB		10.91	37.78	1MB					
4	14.05	41.35	2MB	12.44	40.55	1MB		11.39	40.02	1MB		10.7	39.68	1MB					
8	12.92	42.79	1MB	11.73	42.19	1MB		10.95	41.8	1MB		10.44	41.54	1MB					
12	12.01	44.33	1MB	11.14	43.9	1MB		10.57	43.61	1MB		10.2	43.42	1MB					
16	11.25	45.95	1MB	10.64	45.64	1MB		10.24	45.45	1MB		9.98	45.32	1MB					
20	10.53	47.59	1MB	10.14	47.39	1MB		9.89	47.27	1MB		9.72	47.19	1MB					
24	9.59	49.12	1MB	9.31	48.98	1MB		9.14	48.9	1MB		9.04	48.85	1MB					
28	9.09	50.87	1MB	8.93	50.79	1MB		8.82	50.74	1MB		8.73	50.69	1MB					
32	8.56	52.6	1MB	8.56	52.6	1MB		8.56	52.6	1MB		8.56	52.6	1MB					

$r = 7$	$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$
0	26.82	45.73	8GB	22.2	43.43	323MB	17.02	40.83	9MB	13.4	39.02	1MB
4	24.02	46.34	2GB	19.68	44.16	56MB	15.16	41.9	3MB	12.18	40.41	1MB
8	21.1	46.88	151MB	17.23	44.94	11MB	13.37	43.01	1MB	10.97	41.81	1MB
12	18.32	47.49	22MB	14.96	45.8	3MB	11.82	44.24	1MB	9.98	43.31	1MB
16	15.67	48.16	4MB	12.87	46.76	1MB	10.48	45.56	1MB	9.13	44.89	1MB
20	13.1	48.88	1MB	10.93	47.79	1MB	9.26	46.95	1MB	8.35	46.5	1MB
24	10.82	49.74	1MB	9.32	48.99	1MB	8.15	48.4	1MB	7.43	48.04	1MB
28	8.56	50.6	1MB	7.78	50.22	1MB	7.23	49.94	1MB	6.91	49.78	1MB
32	6.34	51.5	1MB	6.34	51.5	1MB	6.34	51.5	1MB	6.34	51.5	1MB

$r = 7$	$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$	$p$	$C_{tr}$	$M$
0	10.8	37.73	1MB	9.25	36.95	1MB	8.35	36.5	1MB	7.84	36.25	1MB
4	10.13	39.39	1MB	8.9	38.78	1MB	8.17	38.41	1MB	7.74	38.19	1MB
8	9.42	41.03	1MB	8.5	40.57	1MB	7.94	40.3	1MB	7.61	40.13	1MB
12	8.82	42.74	1MB	8.15	42.4	1MB	7.74	42.19	1MB	7.48	42.07	1MB
16	8.31	44.48	1MB	7.84	44.24	1MB	7.55	44.1	1MB	7.37	44.01	1MB
20	7.82	46.23	1MB	7.51	46.08	1MB	7.32	45.99	1MB	7.21	45.93	1MB
24	7.06	47.86	1MB	6.84	47.75	1MB	6.72	47.69	1MB	6.66	47.65	1MB
28	6.71	49.68	1MB	6.58	49.62	1MB	6.5	49.58	1MB	6.43	49.54	1MB
32	6.34	51.5	1MB	6.34	51.5	1MB	6.34	51.5	1MB	6.34	51.5	1MB

$r = 8$	$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	23.39	44.02	732MB	18.21	41.43	21MB	12.88	38.76	1MB	9.52	37.09	1MB
4	20.57	44.61	105MB	15.94	42.29	5MB	11.39	40.02	1MB	8.69	38.67	1MB
8	17.91	45.28	17MB	13.77	43.21	1MB	9.99	41.32	1MB	7.86	40.26	1MB
12	15.35	46.	3MB	11.78	44.22	1MB	8.79	42.72	1MB	7.17	41.91	1MB
16	12.91	46.78	1MB	10.	45.32	1MB	7.75	44.2	1MB	6.59	43.62	1MB
20	10.56	47.61	1MB	8.35	46.5	1MB	6.81	45.73	1MB	6.03	45.34	1MB
24	8.49	48.57	1MB	6.97	47.81	1MB	5.91	47.28	1MB	5.29	46.97	1MB
28	6.48	49.56	1MB	5.71	49.18	1MB	5.21	48.93	1MB	4.93	48.79	1MB
32	4.54	50.6	1MB	4.54	50.6	1MB	4.54	50.6	1MB	4.54	50.6	1MB

$r = 8$	$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	7.45	36.05	1MB	6.37	35.51	1MB	5.8	35.23	1MB	5.5	35.08	1MB
4	7.06	37.85	1MB	6.18	37.42	1MB	5.71	37.18	1MB	5.45	37.05	1MB
8	6.63	39.64	1MB	5.96	39.31	1MB	5.6	39.12	1MB	5.39	39.02	1MB
12	6.26	41.46	1MB	5.77	41.21	1MB	5.49	41.07	1MB	5.34	40.99	1MB
16	5.94	43.29	1MB	5.59	43.12	1MB	5.39	43.02	1MB	5.28	42.97	1MB
20	5.61	45.13	1MB	5.38	45.01	1MB	5.25	44.95	1MB	5.18	44.92	1MB
24	5.01	46.83	1MB	4.85	46.75	1MB	4.77	46.71	1MB	4.73	46.69	1MB
28	4.78	48.71	1MB	4.68	48.67	1MB	4.62	48.64	1MB	4.58	48.62	1MB
32	4.54	50.6	1MB	4.54	50.6	1MB	4.54	50.6	1MB	4.54	50.6	1MB

$r = 9$	$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	20.16	42.4	79MB	14.62	39.64	2MB	9.38	37.02	1MB	6.46	35.56	1MB
4	17.56	43.1	13MB	12.63	40.64	1MB	8.26	38.45	1MB	5.93	37.29	1MB
8	15.09	43.87	3MB	10.75	41.7	1MB	7.2	39.92	1MB	5.41	39.03	1MB
12	12.73	44.69	1MB	9.06	42.86	1MB	6.3	41.47	1MB	4.96	40.81	1MB
16	10.51	45.58	1MB	7.57	44.11	1MB	5.53	43.09	1MB	4.57	42.61	1MB
20	8.39	46.52	1MB	6.2	45.43	1MB	4.83	44.74	1MB	4.2	44.42	1MB
24	6.53	47.59	1MB	5.05	46.85	1MB	4.12	46.39	1MB	3.63	46.14	1MB
28	4.77	48.71	1MB	4.05	48.35	1MB	3.61	48.13	1MB	3.4	48.02	1MB
32	3.14	49.9	1MB	3.14	49.9	1MB	3.14	49.9	1MB	3.14	49.9	1MB
$r = 9$	$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	4.95	34.8	1MB	4.25	34.45	1MB	3.92	34.28	1MB	3.76	34.21	1MB
4	4.73	36.69	1MB	4.15	36.4	1MB	3.87	36.26	1MB	3.74	36.2	1MB
8	4.49	38.57	1MB	4.04	38.35	1MB	3.82	38.24	1MB	3.72	38.18	1MB
12	4.28	40.47	1MB	3.94	40.3	1MB	3.78	40.21	1MB	3.69	40.17	1MB
16	4.09	42.37	1MB	3.85	42.25	1MB	3.73	42.19	1MB	3.67	42.16	1MB
20	3.88	44.27	1MB	3.72	44.19	1MB	3.64	44.15	1MB	3.6	44.13	1MB
24	3.42	46.04	1MB	3.32	45.99	1MB	3.27	45.96	1MB	3.25	45.95	1MB
28	3.28	47.97	1MB	3.21	47.93	1MB	3.18	47.92	1MB	3.16	47.9	1MB
32	3.14	49.9	1MB	3.14	49.9	1MB	3.14	49.9	1MB	3.14	49.9	1MB

$r = 10$	$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	17.28	40.97	11MB	11.47	38.06	1MB	6.54	35.6	1MB	4.18	34.42	1MB
4	14.87	41.76	3MB	9.77	39.21	1MB	5.73	37.19	1MB	3.87	36.26	1MB
8	12.6	42.63	1MB	8.18	40.42	1MB	4.97	38.81	1MB	3.56	38.11	1MB
12	10.45	43.55	1MB	6.79	41.72	1MB	4.34	40.49	1MB	3.3	39.97	1MB
16	8.45	44.55	1MB	5.57	43.11	1MB	3.8	42.22	1MB	3.06	41.86	1MB
20	6.56	45.61	1MB	4.48	44.56	1MB	3.31	43.98	1MB	2.83	43.74	1MB
24	4.92	46.79	1MB	3.53	46.09	1MB	2.78	45.71	1MB	2.42	45.53	1MB
28	3.44	48.04	1MB	2.78	47.72	1MB	2.44	47.54	1MB	2.28	47.47	1MB
32	2.13	49.39	1MB	2.13	49.39	1MB	2.13	49.39	1MB	2.13	49.39	1MB
$r = 10$	$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	3.17	33.91	1MB	2.77	33.71	1MB	2.6	33.62	1MB	2.53	33.59	1MB
4	3.06	35.85	1MB	2.72	35.69	1MB	2.58	35.62	1MB	2.52	35.59	1MB
8	2.94	37.8	1MB	2.68	37.66	1MB	2.56	37.61	1MB	2.51	37.58	1MB
12	2.83	39.74	1MB	2.63	39.64	1MB	2.54	39.6	1MB	2.5	39.58	1MB
16	2.73	41.69	1MB	2.59	41.62	1MB	2.52	41.59	1MB	2.49	41.57	1MB
20	2.61	43.63	1MB	2.51	43.58	1MB	2.47	43.56	1MB	2.45	43.55	1MB
24	2.28	45.47	1MB	2.22	45.44	1MB	2.2	45.42	1MB	2.19	45.42	1MB
28	2.2	47.43	1MB	2.16	47.41	1MB	2.15	47.4	1MB	2.14	47.39	1MB
32	2.13	49.39	1MB	2.13	49.39	1MB	2.13	49.39	1MB	2.13	49.39	1MB

$r = 11$	$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	14.72	39.68	2MB	8.77	36.71	1MB	4.34	34.5	1MB	2.61	33.63	1MB
4	12.5	40.58	1MB	7.36	38.	1MB	3.8	36.23	1MB	2.45	35.55	1MB
8	10.43	41.54	1MB	6.06	39.36	1MB	3.3	37.98	1MB	2.29	37.47	1MB
12	8.49	42.57	1MB	4.94	40.8	1MB	2.89	39.77	1MB	2.15	39.4	1MB
16	6.7	43.68	1MB	3.98	42.32	1MB	2.54	41.59	1MB	2.02	41.34	1MB
20	5.06	44.86	1MB	3.15	43.9	1MB	2.22	43.44	1MB	1.89	43.27	1MB
24	3.64	46.15	1MB	2.42	45.54	1MB	1.86	45.25	1MB	1.63	45.14	1MB
28	2.44	47.54	1MB	1.91	47.28	1MB	1.66	47.16	1MB	1.56	47.11	1MB
32	1.49	49.07	1MB	1.49	49.07	1MB	1.49	49.07	1MB	1.49	49.07	1MB

$r = 11$	$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	2.02	33.33	1MB	1.82	33.24	1MB	1.75	33.2	1MB	1.73	33.19	1MB
4	1.97	35.31	1MB	1.81	35.23	1MB	1.75	35.2	1MB	1.72	35.19	1MB
8	1.92	37.29	1MB	1.79	37.22	1MB	1.74	37.2	1MB	1.72	37.19	1MB
12	1.87	39.26	1MB	1.77	39.21	1MB	1.73	39.19	1MB	1.72	39.19	1MB
16	1.83	41.24	1MB	1.75	41.2	1MB	1.73	41.19	1MB	1.72	41.18	1MB
20	1.76	43.21	1MB	1.71	43.18	1MB	1.7	43.17	1MB	1.69	43.17	1MB
24	1.55	45.1	1MB	1.52	45.09	1MB	1.52	45.08	1MB	1.51	45.08	1MB
28	1.52	47.09	1MB	1.5	47.08	1MB	1.49	47.07	1MB	1.49	47.07	1MB
32	1.49	49.07	1MB	1.49	49.07	1MB	1.49	49.07	1MB	1.49	49.07	1MB

$r = 12$	$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	12.45	38.55	1MB	6.53	35.59	1MB	2.78	33.71	1MB	1.66	33.16	1MB
4	10.43	39.54	1MB	5.39	37.02	1MB	2.45	35.55	1MB	1.59	35.12	1MB
8	8.55	40.6	1MB	4.37	38.51	1MB	2.15	37.4	1MB	1.52	37.09	1MB
12	6.81	41.73	1MB	3.51	40.08	1MB	1.91	39.28	1MB	1.46	39.06	1MB
16	5.24	42.95	1MB	2.8	41.72	1MB	1.71	41.18	1MB	1.41	41.03	1MB
20	3.85	44.25	1MB	2.2	43.43	1MB	1.54	43.09	1MB	1.35	43	1MB
24	2.66	45.66	1MB	1.69	45.17	1MB	1.32	44.98	1MB	1.2	44.93	1MB
28	1.75	47.2	1MB	1.37	47.01	1MB	1.23	46.94	1MB	1.18	46.92	1MB
32	1.15	48.9	1MB	1.15	48.9	1MB	1.15	48.9	1MB	1.15	48.9	1MB

$r = 12$	$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	1.38	33.02	1MB	1.3	32.98	1MB	1.28	32.97	1MB	1.28	32.96	1MB
4	1.36	35.01	1MB	1.3	34.98	1MB	1.28	34.97	1MB	1.28	34.96	1MB
8	1.35	37	1MB	1.3	36.97	1MB	1.28	36.97	1MB	1.28	36.96	1MB
12	1.33	38.99	1MB	1.29	38.97	1MB	1.28	38.96	1MB	1.27	38.96	1MB
16	1.31	40.98	1MB	1.29	40.97	1MB	1.28	40.96	1MB	1.27	40.96	1MB
20	1.29	42.97	1MB	1.27	42.96	1MB	1.26	42.96	1MB	1.26	42.95	1MB
24	1.17	44.91	1MB	1.16	44.91	1MB	1.16	44.91	1MB	1.16	44.91	1MB
28	1.16	46.91	1MB	1.16	46.9	1MB	1.15	46.9	1MB	1.15	46.9	1MB
32	1.15	48.9	1MB	1.15	48.9	1MB	1.15	48.9	1MB	1.15	48.9	1MB

$r = 13$				$w = 0$			$w = 1$			$w = 2$			$w = 3$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	10.45	37.55	1MB	4.73	34.69	1MB	1.78	33.22	1MB	1.2	32.93	1MB			
4	8.62	38.64	1MB	3.86	36.26	1MB	1.62	35.13	1MB	1.18	34.91	1MB			
8	6.93	39.79	1MB	3.09	37.87	1MB	1.47	37.06	1MB	1.15	36.9	1MB			
12	5.41	41.03	1MB	2.47	39.56	1MB	1.35	39.	1MB	1.13	38.89	1MB			
16	4.06	42.35	1MB	1.98	41.31	1MB	1.26	40.95	1MB	1.12	40.88	1MB			
20	2.91	43.78	1MB	1.59	43.12	1MB	1.18	42.92	1MB	1.1	42.87	1MB			
24	1.96	45.31	1MB	1.27	44.96	1MB	1.08	44.87	1MB	1.04	44.85	1MB			
28	1.33	46.99	1MB	1.11	46.88	1MB	1.05	46.85	1MB	1.03	46.84	1MB			
32	1.03	48.84	1MB	1.03	48.84	1MB	1.03	48.84	1MB	1.03	48.84	1MB			

$r = 13$				$w = 4$			$w = 5$			$w = 6$			$w = 7$		
$k$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$	$p$	$C_{\text{tr}}$	$M$
0	1.1	32.88	1MB	1.08	32.87	1MB	1.08	32.86	1MB	1.08	32.86	1MB	1.08	32.86	1MB
4	1.1	34.87	1MB	1.08	34.87	1MB	1.08	34.86	1MB	1.08	34.86	1MB	1.08	34.86	1MB
8	1.09	36.87	1MB	1.08	36.87	1MB	1.08	36.86	1MB	1.08	36.86	1MB	1.08	36.86	1MB
12	1.09	38.87	1MB	1.08	38.87	1MB	1.08	38.86	1MB	1.08	38.86	1MB	1.08	38.86	1MB
16	1.09	40.87	1MB	1.08	40.86	1MB	1.08	40.86	1MB	1.08	40.86	1MB	1.08	40.86	1MB
20	1.08	42.86	1MB	1.07	42.86	1MB	1.07	42.86	1MB	1.07	42.86	1MB	1.07	42.86	1MB
24	1.03	44.84	1MB	1.03	44.84	1MB	1.03	44.84	1MB	1.03	44.84	1MB	1.03	44.84	1MB
28	1.03	46.84	1MB	1.03	46.84	1MB	1.03	46.84	1MB	1.03	46.84	1MB	1.03	46.84	1MB
32	1.03	48.84	1MB	1.03	48.84	1MB	1.03	48.84	1MB	1.03	48.84	1MB	1.03	48.84	1MB