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The VCDIFF Generic Differencing and Compression Data Format

Status of this Memo

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Abstract

This memo describes VCDIFF, a general, efficient and portable data format suitable for encoding compressed and/or differencing data so that they can be easily transported among computers.

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1. Executive Summary

Compression and differencing techniques can greatly improve storage and transmission of files and file versions. Since files are often transported across machines with distinct architectures and performance characteristics, such data should be encoded in a form that is portable and can be decoded with little or no knowledge of the encoders. This document describes Vcdiff, a compact portable encoding format designed for these purposes.

Data differencing is the process of computing a compact and invertible encoding of a "target file" given a "source file". Data compression is similar, but without the use of source data. The UNIX utilities diff, compress, and gzip are well-known examples of data differencing and compression tools. For data differencing, the computed encoding is called a "delta file", and for data compression, it is called a "compressed file". Delta and compressed files are good for storage and transmission as they are often smaller than the originals.

Data differencing and data compression are traditionally treated as distinct types of data processing. However, as shown in the Vdelta technique by Korn and Vo [1], compression can be thought of as a special case of differencing in which the source data is empty. The basic idea is to unify the string parsing scheme used in the Lempel-Ziv'77 (LZ'77) style compressors [2] and the block-move technique of Tichy [3]. Loosely speaking, this works as follows:

a. Concatenate source and target data.
b. Parse the data from left to right as in LZ'77 but make sure that a parsed segment starts the target data.
c. Start to output when reaching target data.

Parsing is based on string matching algorithms, such as suffix trees [4] or hashing with different time and space performance characteristics. Vdelta uses a fast string matching algorithm that requires less memory than other techniques [5,6]. However, even with this algorithm, the memory requirement can still be prohibitive for large files. A common way to deal with memory limitation is to partition an input file into chunks called "windows" and process them separately. Here, except for unpublished work by Vo, little has been done on designing effective windowing schemes. Current techniques, including Vdelta, simply use source and target windows with corresponding addresses across source and target files.

String matching and windowing algorithms have great influence on the compression rate of delta and compressed files. However, it is desirable to have a portable encoding format that is independent of such algorithms. This enables the construction of client-server applications in which a server may serve clients with unknown computing characteristics. Unfortunately, all current differencing and compressing tools, including Vdelta, fall short in this respect. Their storage formats are closely intertwined with the implemented string matching and/or windowing algorithms.

The encoding format Vcdiff proposed here addresses the above issues. Vcdiff achieves the characteristics below:

Output compactness:
The basic encoding format compactly represents compressed or delta files. Applications can further extend the basic encoding format with "secondary encoders" to achieve more compression.

Data portability:
The basic encoding format is free from machine byte order and word size issues. This allows data to be encoded on one machine and decoded on a different machine with different architecture.

Algorithm genericity:
The decoding algorithm is independent from string matching and windowing algorithms. This allows competition among implementations of the encoder while keeping the same decoder.

Decoding efficiency:
Except for secondary encoder issues, the decoding algorithm runs in time proportionate to the size of the target file and uses space proportionate to the maximal window size. Vcdiff differs from more conventional compressors in that it uses only byte-aligned data, thus avoiding bit-level operations, which improves decoding speed at the slight cost of compression efficiency.

The combined differencing and compression method is called "delta compression" [14]. As this way of data processing treats compression as a special case of differencing, we shall use the term "delta file" to indicate the compressed output for both cases.

2. Conventions

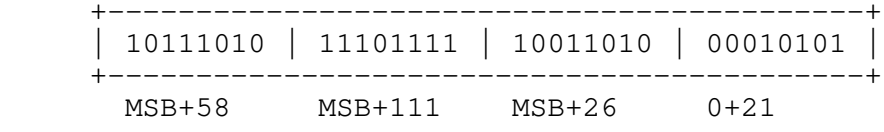
The basic data unit is a byte. For portability, Vcdiff shall limit a byte to its lower eight bits even on machines with larger bytes. The bits in a byte are ordered from right to left so that the least significant bit (LSB) has value 1, and the most significant bit (MSB), has value 128.

For purposes of exposition in this document, we adopt the convention that the LSB is numbered 0, and the MSB is numbered 7. Bit numbers never appear in the encoded format itself.

Vcdiff encodes unsigned integer values using a portable, variable-sized format (originally introduced in the Sfio library [7]). This encoding treats an integer as a number in base 128. Then, each digit in this representation is encoded in the lower seven bits of a byte. Except for the least significant byte, other bytes have their most significant bit turned on to indicate that there are still more digits in the encoding. The two key properties of this integer encoding that are beneficial to a data compression format are:

a. The encoding is portable among systems using 8-bit bytes, and
b. Small values are encoded compactly.

For example, consider the value 123456789, which can be represented with four 7-bit digits whose values are 58, 111, 26, 21 in order from most to least significant. Below is the 8-bit byte encoding of these digits. Note that the MSBs of 58, 111 and 26 are on.



Henceforth, the terms "byte" and "integer" will refer to a byte and an unsigned integer as described.

Algorithms in the C language are occasionally exhibited to clarify the descriptions. Such C code is meant for clarification only, and is not part of the actual specification of the Vcdiff format.

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14, RFC 2119 [12].

3. Delta Instructions

A large target file is partitioned into non-overlapping sections called "target windows". These target windows are processed separately and sequentially based on their order in the target file.

A target window T, of length t, may be compared against some source data segment S, of length s. By construction, this source data segment S comes either from the source file, if one is used, or from a part of the target file earlier than T. In this way, during decoding, S is completely known when T is being decoded.

The choices of T, t, S and s are made by some window selection algorithm, which can greatly affect the size of the encoding. However, as seen later, these choices are encoded so that no knowledge of the window selection algorithm is needed during decoding.

Assume that S[j] represents the jth byte in S, and T[k] represents the kth byte in T. Then, for the delta instructions, we treat the data windows S and T as substrings of a superstring U, formed by concatenating them like this:

```
S[0]S[1]...S[s-1]T[0]T[1]...T[t-1]
```

The "address" of a byte in S or T is referred to by its location in U. For example, the address of T[k] is s+k.

The instructions to encode and direct the reconstruction of a target window are called delta instructions. There are three types:

- ADD: This instruction has two arguments, a size x and a sequence of x bytes to be copied.
- COPY: This instruction has two arguments, a size x and an address p in the string U. The arguments specify the substring of U that must be copied. We shall assert that such a substring must be entirely contained in either S or T.

RUN: This instruction has two arguments, a size x and a byte b, that will be repeated x times.

Below are example source and target windows and the delta instructions that encode the target window in terms of the source window.

```
a b c d e f g h i j k l m n o p
a b c d w x y z e f g h e f g h e f g h z z z z

COPY  4, 0
ADD   4, w x y z
COPY  4, 4
COPY 12, 24
RUN   4, z
```

Thus, the first letter 'a' in the target window is at location 16 in the superstring. Note that the fourth instruction, "COPY 12, 24", copies data from T itself since address 24 is position 8 in T. This instruction also shows that it is fine to overlap the data to be copied with the data being copied from, as long as the latter starts earlier. This enables efficient encoding of periodic sequences, i.e., sequences with regularly repeated subsequences. The RUN instruction is a compact way to encode a sequence repeating the same byte even though such a sequence can be thought of as a periodic sequence with period 1.

To reconstruct the target window, one simply processes one delta instruction at a time and copies the data, either from the source window or the target window being reconstructed, based on the type of the instruction and the associated address, if any.

4. Delta File Organization

A Vcdiff delta file starts with a Header section followed by a sequence of Window sections. The Header section includes magic bytes to identify the file type, and information concerning data processing beyond the basic encoding format. The Window sections encode the target windows.

Below is the overall organization of a delta file. The indented items refine the ones immediately above them. An item in square brackets may or may not be present in the file depending on the information encoded in the Indicator byte above it.

```
Header
    Header1                                   - byte
    Header2                                   - byte
    Header3                                   - byte
    Header4                                   - byte
    Hdr_Indicator                             - byte
    [Secondary compressor ID]                 - byte
    [Length of code table data]               - integer
    [Code table data]
        Size of near cache                    - byte
        Size of same cache                    - byte
        Compressed code table data
Window1
    Win_Indicator                             - byte
    [Source segment size]                     - integer
    [Source segment position]                 - integer
    The delta encoding of the target window
        Length of the delta encoding          - integer
        The delta encoding
            Size of the target window         - integer
            Delta_Indicator                   - byte
            Length of data for ADDs and RUNs  - integer
            Length of instructions and sizes  - integer
            Length of addresses for COPYs     - integer
            Data section for ADDs and RUNs    - array of bytes
            Instructions and sizes section    - array of bytes
            Addresses section for COPYs       - array of bytes
Window2
...
```

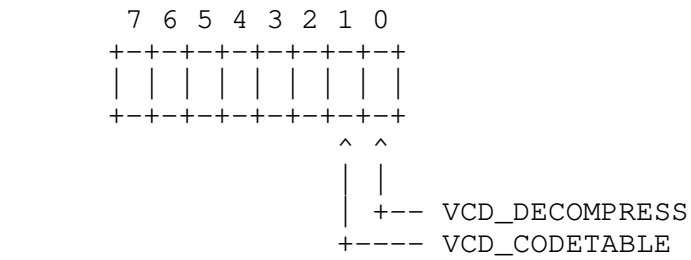
4.1 The Header Section

Each delta file starts with a header section organized as below. Note the convention that square-brackets enclose optional items.

```
Header1                                   - byte = 0xD6
Header2                                   - byte = 0xC3
Header3                                   - byte = 0xC4
Header4                                   - byte
Hdr_Indicator                             - byte
[Secondary compressor ID]                 - byte
[Length of code table data]               - integer
[Code table data]
```

The first three Header bytes are the ASCII characters 'V', 'C' and 'D' with their most significant bits turned on (in hexadecimal, the values are 0xD6, 0xC3, and 0xC4). The fourth Header byte is currently set to zero. In the future, it might be used to indicate the version of Vcdiff.

The Hdr_Indicator byte shows if there is any initialization data required to aid in the reconstruction of data in the Window sections. This byte MAY have non-zero values for either, both, or neither of the two bits VCD_DECOMPRESS and VCD_CODETABLE below:



If bit 0 (VCD_DECOMPRESS) is non-zero, this indicates that a secondary compressor may have been used to further compress certain parts of the delta encoding data as described in Sections 4.3 and 6. In that case, the ID of the secondary compressor is given next. If this bit is zero, the compressor ID byte is not included.

If bit 1 (VCD_CODETABLE) is non-zero, this indicates that an application-defined code table is to be used for decoding the delta instructions. This table itself is compressed. The length of the data comprising this compressed code table and the data follow next. Section 7 discusses application-defined code tables. If this bit is zero, the code table data length and the code table data are not included.

If both bits are set, then the compressor ID byte is included before the code table data length and the code table data.

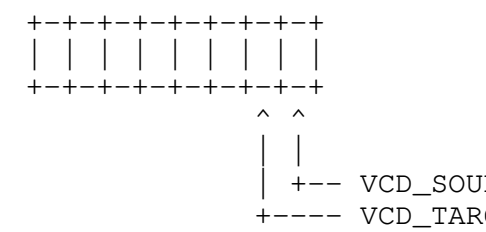
4.2 The Format of a Window Section

Each Window section is organized as follows:

```
Win_Indicator                          - byte
[Source segment length]                - integer
[Source segment position]              - integer
The delta encoding of the target window
```

Below are the details of the various items:

Win_Indicator:
This byte is a set of bits, as shown:



If bit 0 (VCD_SOURCE) is non-zero, this indicates that a segment of data from the "source" file was used as the corresponding source window of data to encode the target window. The decoder will use this same source data segment to decode the target window.

If bit 1 (VCD_TARGET) is non-zero, this indicates that a segment of data from the "target" file was used as the corresponding source window of data to encode the target window. As above, this same source data segment is used to decode the target window.

The Win_Indicator byte MUST NOT have more than one of the bits set (non-zero). It MAY have none of these bits set.

If one of these bits is set, the byte is followed by two integers to indicate respectively, the length and position of the source data segment in the relevant file. If the indicator byte is zero, the target window was compressed by itself without comparing against another data segment, and these two integers are not included.

The delta encoding of the target window:

This contains the delta encoding of the target window, either in terms of the source data segment (i.e., VCD_SOURCE or VCD_TARGET was set) or by itself if no source window is specified. This data format is discussed next.

4.3 The Delta Encoding of a Target Window

The delta encoding of a target window is organized as follows:

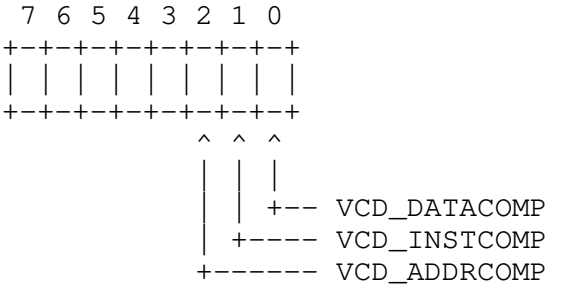
```
Length of the delta encoding            - integer
The delta encoding
    Length of the target window         - integer
    Delta_Indicator                     - byte
    Length of data for ADDs and RUNs    - integer
    Length of instructions section      - integer
    Length of addresses for COPYs       - integer
    Data section for ADDs and RUNs      - array of bytes
    Instructions and sizes section      - array of bytes
    Addresses section for COPYs         - array of bytes
```

Length of the delta encoding:
This integer gives the total number of remaining bytes that comprise the data of the delta encoding for this target window.

The delta encoding:
This contains the data representing the delta encoding which is described next.

Length of the target window:
This integer indicates the actual size of the target window after decompression. A decoder can use this value to allocate memory to store the uncompressed data.

Delta_Indicator:
This byte is a set of bits, as shown:



VCD_DATACOMP: bit value 1.
VCD_INSTCOMP: bit value 2.
VCD_ADDRCOMP: bit value 4.

As discussed, the delta encoding consists of COPY, ADD and RUN instructions. The ADD and RUN instructions have accompanying unmatched data (that is, data that does not specifically match any data in the source window or in some earlier part of the target window) and the COPY instructions have addresses of where the matches occur. OPTIONALLY, these types of data MAY be further compressed using a secondary compressor. Thus, Vcdiff separates the encoding of the delta instructions into three parts:

a. The unmatched data in the ADD and RUN instructions,
b. The delta instructions and accompanying sizes, and
c. The addresses of the COPY instructions.

If the bit VCD_DECOMPRESS (Section 4.1) was on, each of these sections may have been compressed using the specified secondary compressor. The bit positions 0 (VCD_DATACOMP), 1 (VCD_INSTCOMP), and 2 (VCD_ADDRCOMP) respectively indicate, if non-zero, that the corresponding parts are compressed. Then, these parts MUST be decompressed before decoding the delta instructions.

Length of data for ADDs and RUNs:
This is the length (in bytes) of the section of data storing the unmatched data accompanying the ADD and RUN instructions.

Length of instructions section:
This is the length (in bytes) of the delta instructions and accompanying sizes.

Length of addresses for COPYs:
This is the length (in bytes) of the section storing the addresses of the COPY instructions.

Data section for ADDs and RUNs:
This sequence of bytes encodes the unmatched data for the ADD and RUN instructions.

Instructions and sizes section:
This sequence of bytes encodes the instructions and their sizes.

Addresses section for COPYs:
This sequence of bytes encodes the addresses of the COPY instructions.

5. Delta Instruction Encoding

The delta instructions described in Section 3 represent the results of string matching. For many data differencing applications in which the changes between source and target data are small, any straightforward representation of these instructions would be adequate. However, for applications including differencing of binary files or data compression, it is important to encode these instructions well to achieve good compression rates. The keys to this achievement is to efficiently encode the addresses of COPY instructions and the sizes of all delta instructions.

5.1 Address Encoding Modes of COPY Instructions

Addresses of COPY instructions are locations of matches and often occur close by or even exactly equal to one another. This is because data in local regions are often replicated with minor changes. In turn, this means that coding a newly matched address against some recently matched addresses can be beneficial. To take advantage of this phenomenon and encode addresses of COPY instructions more efficiently, the Vcdiff data format supports the use of two different types of address caches. Both the encoder and decoder maintain these caches, so that decoder's caches remain synchronized with the encoder's caches.

a. A "near" cache is an array with "s_near" slots, each containing an address used for encoding addresses nearby to previously encoded addresses (in the positive direction only). The near cache also maintains a "next_slot" index to the near cache. New entries to the near cache are always inserted in the next_slot index, which maintains a circular buffer of the s_near most recent addresses.

b. A "same" cache is an array with "s_same", with a multiple of 256 slots, each containing an address. The same cache maintains a hash table of recent addresses used for repeated encoding of the exact same address.

By default, the parameters s_near and s_same are respectively set to 4 and 3. An encoder MAY modify these values, but then it MUST encode the new values in the encoding itself, as discussed in Section 7, so that the decoder can properly set up its own caches.

At the start of processing a target window, an implementation (encoder or decoder) initializes all of the slots in both caches to zero. The next_slot pointer of the near cache is set to point to slot zero.

Each time a COPY instruction is processed by the encoder or decoder, the implementation's caches are updated as follows, where "addr" is the address in the COPY instruction.

a. The slot in the near cache referenced by the next_slot index is set to addr. The next_slot index is then incremented modulo s_near.

b. The slot in the same cache whose index is addr%(s_same*256) is set to addr. [We use the C notations of % for modulo and * for multiplication.]

5.2 Example code for maintaining caches

To make clear the above description, below are examples of cache data structures and algorithms to initialize and update them:

```
typedef struct _cache_s
{
    int*  near;      /* array of size s_near        */
    int   s_near;
    int   next_slot; /* the circular index for near */
    int*  same;      /* array of size s_same*256    */
    int   s_same;
} Cache_t;

cache_init(Cache_t* ka)
{
    int   i;

    ka->next_slot = 0;
    for(i = 0; i < ka->s_near; ++i)
         ka->near[i] = 0;

    for(i = 0; i < ka->s_same*256; ++i)
         ka->same[i] = 0;
}

cache_update(Cache_t* ka, int addr)
{
    if(ka->s_near > 0)
    {   ka->near[ka->next_slot] = addr;
        ka->next_slot = (ka->next_slot + 1) % ka->s_near;
    }

    if(ka->s_same > 0)
        ka->same[addr % (ka->s_same*256)] = addr;
}
```

5.3 Encoding of COPY instruction addresses

The address of a COPY instruction is encoded using different modes, depending on the type of cached address used, if any.

Let "addr" be the address of a COPY instruction to be decoded and "here" be the current location in the target data (i.e., the start of the data about to be encoded or decoded). Let near[j] be the jth element in the near cache, and same[k] be the kth element in the same cache. Below are the possible address modes:

VCD_SELF: This mode has value 0. The address was encoded by itself as an integer.

VCD_HERE: This mode has value 1. The address was encoded as the integer value "here - addr".

Near modes: The "near modes" are in the range [2,s_near+1]. Let m be the mode of the address encoding. The address was encoded as the integer value "addr - near[m-2]".

Same modes: The "same modes" are in the range [s_near+2,s_near+s_same+1]. Let m be the mode of the encoding. The address was encoded as a single byte b such that "addr == same[(m - (s_near+2))*256 + b]".

5.4 Example code for encoding and decoding of COPY instruction addresses

We show example algorithms below to demonstrate the use of address modes more clearly. The encoder has the freedom to choose address modes, the sample addr_encode() algorithm merely shows one way of picking the address mode. The decoding algorithm addr_decode() will uniquely decode addresses, regardless of the encoder's algorithm choice.

Note that the address caches are updated immediately after an address is encoded or decoded. In this way, the decoder is always synchronized with the encoder.

```
int addr_encode(Cache_t* ka, int addr, int here, int* mode)
{
    int  i, d, bestd, bestm;

    /* Attempt to find the address mode that yields the
     * smallest integer value for "d", the encoded address
     * value, thereby minimizing the encoded size of the
     * address. */

    bestd = addr; bestm = VCD_SELF;      /* VCD_SELF == 0 */

    if((d = here-addr) < bestd)
        { bestd = d; bestm = VCD_HERE; } /* VCD_HERE == 1 */

    for(i = 0; i < ka->s_near; ++i)
        if((d = addr - ka->near[i]) >= 0 && d < bestd)
            { bestd = d; bestm = i+2; }

    if(ka->s_same > 0 && ka->same[d = addr%(ka->s_same*256)] == addr)
        { bestd = d%256; bestm = ka->s_near + 2 + d/256; }

    cache_update(ka,addr);

    *mode = bestm; /* this returns the address encoding mode */
    return  bestd; /* this returns the encoded address       */
}
```

Note that the addr_encode() algorithm chooses the best address mode using a local optimization, but that may not lead to the best encoding efficiency because different modes lead to different instruction encodings, as described below.

The functions addrint() and addrbyte() used in addr_decode(), obtain from the "Addresses section for COPYs" (Section 4.3), an integer or a byte, respectively. These utilities will not be described here. We simply recall that an integer is represented as a compact variable-sized string of bytes, as described in Section 2 (i.e., base 128).

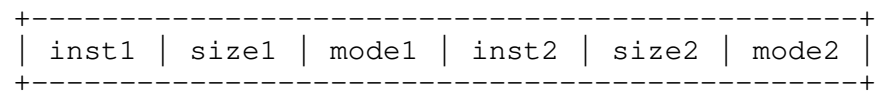
```
int addr_decode(Cache_t* ka, int here, int mode)
{   int  addr, m;

    if(mode == VCD_SELF)
         addr = addrint();
    else if(mode == VCD_HERE)
         addr = here - addrint();
    else if((m = mode - 2) >= 0 && m < ka->s_near) /* near cache */
         addr = ka->near[m] + addrint();
    else /* same cache */
    {    m = mode - (2 + ka->s_near);
         addr = ka->same[m*256 + addrbyte()];
    }

    cache_update(ka, addr);

    return addr;
}
```

5.4 Instruction Codes

Matches are often short in lengths and separated by small amounts of unmatched data. That is, the lengths of COPY and ADD instructions are often small. This is particularly true of binary data such as executable files or structured data, such as HTML or XML. In such cases, compression can be improved by combining the encoding of the sizes and the instruction types, as well as combining the encoding of adjacent delta instructions with sufficiently small data sizes. Effective choices of when to perform such combinations depend on many factors including the data being processed and the string matching algorithm in use. For example, if many COPY instructions have the same data sizes, it may be worthwhile to encode these instructions more compactly than others.

The Vcdiff data format is designed so that a decoder does not need to be aware of the choices made in encoding algorithms. This is achieved with the notion of an "instruction code table", containing 256 entries. Each entry defines, either a single delta instruction or a pair of instructions that have been combined. Note that the code table itself only exists in main memory, not in the delta file (unless using an application-defined code table, described in Section 7). The encoded data simply includes the index of each instruction and, since there are only 256 indices, each index can be represented as a single byte.

Each instruction code entry contains six fields, each of which is a single byte with an unsigned value:



Each triple (inst,size,mode) defines a delta instruction. The meanings of these fields are as follows:

inst: An "inst" field can have one of the four values: NOOP (0), ADD (1), RUN (2) or COPY (3) to indicate the instruction types. NOOP means that no instruction is specified. In this case, both the corresponding size and mode fields will be zero.

size: A "size" field is zero or positive. A value zero means that the size associated with the instruction is encoded separately as an integer in the "Instructions and sizes section" (Section 6). A positive value for "size" defines the actual data size. Note that since the size is restricted to a byte, the maximum value for any instruction with size implicitly defined in the code table is 255.

mode: A "mode" field is significant only when the associated delta instruction is a COPY. It defines the mode used to encode the associated addresses. For other instructions, this is always zero.

5.6 The Code Table

Following the discussions on address modes and instruction code tables, we define a "Code Table" to have the data below:

s_near: the size of the near cache,
s_same: the size of the same cache,
i_code: the 256-entry instruction code table.

Vcdiff itself defines a "default code table" in which s_near is 4 and s_same is 3. Thus, there are 9 address modes for a COPY instruction. The first two are VCD_SELF (0) and VCD_HERE (1). Modes 2, 3, 4 and 5 are for addresses coded against the near cache. And modes 6, 7 and 8, are for addresses coded against the same cache.

	TYPE	SIZE	MODE	TYPE	SIZE	MODE	INDEX
1.	RUN	0	0	NOOP	0	0	0
2.	ADD	0, [1,17]	0	NOOP	0	0	[1,18]
3.	COPY	0, [4,18]	0	NOOP	0	0	[19,34]
4.	COPY	0, [4,18]	1	NOOP	0	0	[35,50]
5.	COPY	0, [4,18]	2	NOOP	0	0	[51,66]
6.	COPY	0, [4,18]	3	NOOP	0	0	[67,82]
7.	COPY	0, [4,18]	4	NOOP	0	0	[83,98]
8.	COPY	0, [4,18]	5	NOOP	0	0	[99,114]
9.	COPY	0, [4,18]	6	NOOP	0	0	[115,130]
10.	COPY	0, [4,18]	7	NOOP	0	0	[131,146]
11.	COPY	0, [4,18]	8	NOOP	0	0	[147,162]
12.	ADD	[1,4]	0	COPY	[4,6]	0	[163,174]
13.	ADD	[1,4]	0	COPY	[4,6]	1	[175,186]
14.	ADD	[1,4]	0	COPY	[4,6]	2	[187,198]
15.	ADD	[1,4]	0	COPY	[4,6]	3	[199,210]
16.	ADD	[1,4]	0	COPY	[4,6]	4	[211,222]
17.	ADD	[1,4]	0	COPY	[4,6]	5	[223,234]
18.	ADD	[1,4]	0	COPY	4	6	[235,238]
19.	ADD	[1,4]	0	COPY	4	7	[239,242]
20.	ADD	[1,4]	0	COPY	4	8	[243,246]
21.	COPY	4	[0,8]	ADD	1	0	[247,255]

The default instruction code table is depicted above, in a compact representation that we use only for descriptive purposes. See section 7 for the specification of how an instruction code table is represented in the Vcdiff encoding format. In the depiction, a zero value for size indicates that the size is separately coded. The mode of non-COPY instructions is represented as 0, even though they are not used.

In the depiction, each numbered line represents one or more entries in the actual instruction code table (recall that an entry in the instruction code table may represent up to two combined delta instructions.) The last column ("INDEX") shows which index value, or range of index values, of the entries are covered by that line. (The notation [i,j] means values from i through j, inclusively.) The first 6 columns of a line in the depiction, describe the pairs of instructions used for the corresponding index value(s).

If a line in the depiction includes a column entry using the [i,j] notation, this means that the line is instantiated for each value in the range from i to j, inclusively. The notation "0, [i,j]" means that the line is instantiated for the value 0 and for each value in the range from i to j, inclusively.

If a line in the depiction includes more than one entry using the [i,j] notation, implying a "nested loop" to convert the line to a range of table entries, the first such [i,j] range specifies the outer loop, and the second specifies the inner loop.

The below examples should make clear the above description:

Line 1 shows the single RUN instruction with index 0. As the size field is 0, this RUN instruction always has its actual size encoded separately.

Line 2 shows the 18 single ADD instructions. The ADD instruction with size field 0 (i.e., the actual size is coded separately) has index 1. ADD instructions with sizes from 1 to 17 use code indices 2 to 18 and their sizes are as given (so they will not be separately encoded.)

Following the single ADD instructions are the single COPY instructions ordered by their address encoding modes. For example, line 11 shows the COPY instructions with mode 8, i.e., the last of the same cache. In this case, the COPY instruction with size field 0 has index 147. Again, the actual size of this instruction will be coded separately.

Lines 12 to 21 show the pairs of instructions that are combined together. For example, line 12 depicts the 12 entries in which an ADD instruction is combined with an immediately following COPY instruction. The entries with indices 163, 164, 165 represent the pairs in which the ADD instructions all have size 1, while the COPY instructions have mode 0 (VCD_SELF) and sizes 4, 5 and 6 respectively.

The last line, line 21, shows the eight instruction pairs, where the first instruction is a COPY and the second is an ADD. In this case, all COPY instructions have size 4 with mode ranging from 0 to 8 and all the ADD instructions have size 1. Thus, the entry with the largest index 255 combines a COPY instruction of size 4 and mode 8 with an ADD instruction of size 1.

The choice of the minimum size 4 for COPY instructions in the default code table was made from experiments that showed that excluding small matches (less then 4 bytes long) improved the compression rates.

6. Decoding a Target Window

Section 4.3 discusses that the delta instructions and associated data are encoded in three arrays of bytes:

```
Data section for ADDs and RUNs,
Instructions and sizes section, and
Addresses section for COPYs.
```

Further, these data sections may have been further compressed by some secondary compressor. Assuming that any such compressed data has been decompressed so that we now have three arrays:

```
inst: bytes coding the instructions and sizes.
data: unmatched data associated with ADDs and RUNs.
addr: bytes coding the addresses of COPYs.
```

These arrays are organized as follows:

inst: a sequence of (index, [size1], [size2]) tuples, where "index" is an index into the instruction code table, and size1 and size2 are integers that MAY or MAY NOT be included in the tuple as follows. The entry with the given "index" in the instruction code table potentially defines two delta instructions. If the first delta instruction is not a VCD_NOOP and its size is zero, then size1 MUST be present. Otherwise, size1 MUST be omitted and the size of the instruction (if it is not VCD_NOOP) is as defined in the table. The presence or absence of size2 is defined similarly with respect to the second delta instruction.

data: a sequence of data values, encoded as bytes.

addr: a sequence of address values. Addresses are normally encoded as integers as described in Section 2 (i.e., base 128). However, since the same cache emits addresses in the range [0,255], same cache addresses are always encoded as a single byte.

To summarize, each tuple in the "inst" array includes an index to some entry in the instruction code table that determines:

a. Whether one or two instructions were encoded and their types.

b. If the instructions have their sizes encoded separately, these sizes will follow, in order, in the tuple.

c. If the instructions have accompanying data, i.e., ADDs or RUNs, their data will be in the array "data".

d. Similarly, if the instructions are COPYs, the coded addresses are found in the array "addr".

The decoding procedure simply processes the arrays by reading one code index at a time, looking up the corresponding instruction code entry, then consuming the respective sizes, data and addresses following the directions in this entry. In other words, the decoder maintains an implicit next-element pointer for each array; "consuming" an instruction tuple, data, or address value implies incrementing the associated pointer.

For example, if during the processing of the target window, the next unconsumed tuple in the inst array has an index value of 19, then the first instruction is a COPY, whose size is found as the immediately following integer in the inst array. Since the mode of this COPY instruction is VCD_SELF, the corresponding address is found by consuming the next integer in the addr array. The data array is left intact. As the second instruction for code index 19 is a NOOP, this tuple is finished.

7. APPLICATION-DEFINED CODE TABLES

Although the default code table used in Vcdiff is good for general purpose encoders, there are times when other code tables may perform better. For example, to code a file with many identical segments of data, it may be advantageous to have a COPY instruction with the specific size of these data segments, so that the instruction can be encoded in a single byte. Such a special code table MUST then be encoded in the delta file so that the decoder can reconstruct it before decoding the data.

Vcdiff allows an application-defined code table to be specified in a delta file with the following data:

```
Size of near cache          - byte
Size of same cache          - byte
Compressed code table data
```

The "compressed code table data" encodes the delta between the default code table (source) and the new code table (target) in the same manner as described in Section 4.3 for encoding a target window in terms of a source window. This delta is computed using the following steps:

a. Convert the new instruction code table into a string, "code", of 1536 bytes using the below steps in order:

   i. Add in order the 256 bytes representing the types of the first instructions in the instruction pairs.
   ii. Add in order the 256 bytes representing the types of the second instructions in the instruction pairs.
   iii. Add in order the 256 bytes representing the sizes of the first instructions in the instruction pairs.
   iv. Add in order the 256 bytes representing the sizes of the second instructions in the instruction pairs.
   v. Add in order the 256 bytes representing the modes of the first instructions in the instruction pairs.
   vi. Add in order the 256 bytes representing the modes of the second instructions in the instruction pairs.

b. Similarly, convert the default code table into a string "dflt".

c. Treat the string "code" as a target window and "dflt" as the corresponding source data and apply an encoding algorithm to compute the delta encoding of "code" in terms of "dflt". This computation MUST use the default code table for encoding the delta instructions.

The decoder can then reverse the above steps to decode the compressed table data using the method of Section 6, employing the default code table, to generate the new code table. Note that the decoder does not need to know about the details of the encoding algorithm used in step (c). It is able to decode the new code table because the Vcdiff format is independent from the choice of encoding algorithm, and because the encoder in step (c) uses the known, default code table.

8. Performance

The encoding format is compact. For compression only, using the LZ-77 string parsing strategy and without any secondary compressors, the typical compression rate is better than Unix compress and close to gzip. For differencing, the data format is better than all known methods in terms of its stated goal, which is primarily decoding speed and encoding efficiency.

We compare the performance of compress, gzip and Vcdiff using the archives of three versions of the Gnu C compiler, gcc-2.95.1.tar, gcc-2.95.2.tar and gcc-2.95.3.tar. Gzip was used at its default compression level. The Vcdiff data were obtained using the Vcodex/Vcdiff software (Section 13).

Below are the different Vcdiff runs:

Vcdiff: vcdiff is used as a compressor only.

Vcdiff-d: vcdiff is used as a differencer only. That is, it only compares target data against source data. Since the files involved are large, they are broken into windows. In this case, each target window, starting at some file offset in the target file, is compared against a source window with the same file offset (in the source file). The source window is also slightly larger than the target window to increase matching opportunities.

Vcdiff-dc: This is similar to Vcdiff-d, but vcdiff can also compare target data against target data as applicable. Thus, vcdiff both computes differences and compresses data. The windowing algorithm is the same as above. However, the above hint is recinded in this case.

Vcdiff-dcw: This is similar to Vcdiff-dc but the windowing algorithm uses a content-based heuristic to select a source window that is more likely to match with a given target window. Thus, the source data segment selected for a target window often will not be aligned with the file offsets of this target window.

	gcc-2.95.1	gcc-2.95.2	gcc-2.95.3
1. raw size	55,746,560	55,797,760	55,787,520
2. compress	-	19,939,390	19,939,453
3. gzip	-	12,973,443	12,998,097
4. Vcdiff	-	15,358,786	15,371,737
5. Vcdiff-d	-	100,971	26,383,849
6. Vcdiff-dc	-	97,246	14,461,203
7. Vcdiff-dcw	-	256,445	1,248,543

The above table shows the raw sizes of the tar files and the sizes of the compressed results. The differencing results in the gcc-2.95.2 column were obtained by compressing gcc-2.95.2, given gcc-2.95.1. The same results for the column gcc-2.95.3 were obtained by compressing gcc-2.95.3, given gcc-2.95.2.

Rows 2, 3 and 4 show that, for compression only, the compression rate from Vcdiff is worse than gzip and better than compress.

The last three rows in the column gcc-2.95.2 show that when two file versions are very similar, differencing can give dramatically good compression rates. Vcdiff-d and Vcdiff-dc use the same simple window selection method of aligning by file offsets, but Vcdiff-dc also does compression so its output is slightly smaller. Vcdiff-dcw uses a content-based algorithm to search for source data that likely will match a given target window. Although it does a good job, the algorithm does not always find the best matches, which in this case, are given by the simple algorithm of Vcdiff-d. As a result, the output size for Vcdiff-dcw is slightly larger.

The situation is reversed in the gcc-2.95.3 column. Here, the files and their contents were sufficiently rearranged or changed between the making of the gcc-2.95.3.tar archive and the gcc-2.95.2 archive so that the simple method of aligning windows by file offsets no longer works. As a result, Vcdiff-d and Vcdiff-dc do not perform well. By allowing compression, along with differencing, Vcdiff-dc manages to beat Vcdiff-c, which does compression only. The content-based window matching algorithm in Vcdiff-dcw is effective in matching the right source and target windows so that Vcdiff-dcw is the overall winner.

9. Further Issues

This document does not address a few issues:

Secondary compressors:

As discussed in Section 4.3, certain sections in the delta encoding of a window may be further compressed by a secondary compressor. In our experience, the basic Vcdiff format is adequate for most purposes so that secondary compressors are seldom needed. In particular, for normal use of data differencing, where the files to be compared have long stretches of matches, much of the gain in compression rate is already achieved by normal string matching. Thus, the use of secondary compressors is seldom needed in this case. However, for applications beyond differencing of such nearly identical files, secondary compressors may be needed to achieve maximal compressed results.

Therefore, we recommend leaving the Vcdiff data format defined as in this document so that the use of secondary compressors can be implemented when they become needed in the future. The formats of the compressed data via such compressors or any compressors that may be defined in the future are left open to their implementations. These could include Huffman encoding, arithmetic encoding, and splay tree encoding [8,9].

Large file system vs. small file system:
As discussed in Section 4, a target window in a large file may be compared against some source window in another file or in the same file (from some earlier part). In that case, the file offset of the source window is specified as a variable-sized integer in the delta encoding. There is a possibility that the encoding was computed on a system supporting much larger files than in a system where the data may be decoded (e.g., 64-bit file systems vs. 32-bit file systems). In that case, some target data may not be recoverable. This problem could afflict any compression format, and ought to be resolved with a generic negotiation mechanism in the appropriate protocol(s).

10. Summary

We have described Vcdiff, a general and portable encoding format for compression and differencing. The format is good in that it allows implementing a decoder without knowledge of the encoders. Further, ignoring the use of secondary compressors not defined within the format, the decoding algorithms run in linear time and requires working space proportional to window size.

11. Acknowledgements

Thanks are due to Balachander Krishnamurthy, Jeff Mogul and Arthur Van Hoff who provided much encouragement to publicize Vcdiff. In particular, Jeff helped in clarifying the description of the data format presented here.

12. Security Considerations

Vcdiff only provides a format to encode compressed and differenced data. It does not address any issues concerning how such data are, in fact, stored in a given file system or the run-time memory of a computer system. Therefore, we do not anticipate any security issues with respect to Vcdiff.

13. Source Code Availability

Vcdiff is implemented as a data transforming method in Phong Vo's Vcodex library. AT&T Corp. has made the source code for Vcodex available for anyone to use to transmit data via HTTP/1.1 Delta Encoding [10,11]. The source code and according license is accessible at the below URL:

http://www.research.att.com/sw/tools

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15. IANA Considerations

The Internet Assigned Numbers Authority (IANA) administers the number space for Secondary Compressor ID values. Values and their meaning must be documented in an RFC or other peer-reviewed, permanent, and readily available reference, in sufficient detail so that interoperability between independent implementations is possible. Subject to these constraints, name assignments are First Come, First Served - see RFC 2434 [13]. Legal ID values are in the range 1..255.

This document does not define any values in this number space.

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