Data Compression in Solid State Storage

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Disclaimers

The opinions expressed herein are those of the author and do not necessarily represent those of any other organization or individual unless specifically cited.

A thorough attempt to acknowledge all sources has been made. That said, we're all human…

Learning Objectives

At the conclusion of this tutorial the audience will have been exposed to:

- The different types of Data Compression
- Common Data Compression Algorithms
- The Deflate/Inflate (GZIP/GUNZIP) algorithms in detail
- Implementation Options (Software/Hardware)
- Impacts of design parameters in Performance
- SSD benefits and challenges
- Resources for Further Study

Agenda

- Background, Definitions, & Context
- Data Compression Overview
- Data Compression Algorithm Survey
- Deflate/Inflate (GZIP/GUNZIP) in depth
- Software Implementations
- HW Implementations
- Tradeoffs & Advanced Topics
- SSD Benefits and Challenges
- Conclusions

Definitions

Item	Description	Comments
Open System	A system which will compress data for use by other entities. I.E. the compressed data will exit the system	Must strictly adhere to standards on compress / decompress algorithms Interoperability among vendors mandated for Open Systems
Closed System	A system which utilizes compressed data internally but does not expose compressed data to the outside world	Can support a limited, optimized subset of standard. Also allows custom algorithms No Interoperability req'd.
Symmetric System	Compress and Decompress throughputs are similar	Example – 40 Gb/s Ethernet Connection.
Asymmetric System	Compress and Decompress throughputs are dissimilar	Asymmetric can be workload balance or throughput differences

Definitions

Item	Description	Comments
Structured Data	Data which can be grouped into records of similar type and organized into a database (typically in Row & Column format)	Can included metadata about unstructured data
Unstructured Data	Data which does not fit into the structured classification	You know it when you see it…
Corpra	Example Datasets used to verify and compare algorithms and their implementations	Examples: Calgary Corpus, Canterbury Corpus, etc. Note: Other datasets also exist that are used for this purpose (TPC-H and TPC-R for example

Definitions

Item	Description	er
Literal	Within the context of LZ77 compression – a byte of data not part of a matched string	Substitutes 8 bits with 9 i.e. “a” becomes 0,a
Length, Distance	Within the context of LZ77 compression , the representation of a string 3 – 258 bytes long which matches a previous string in the history	Replaces the string with 24 bits of Offset and Distance back into the history i.e.: 1,L,D
Algorithm	A strictly defined procedure (well in a perfect world…) to implement a particular function.	Different methods of implementing algorithms possible for different use cases
Alphabet	The total set of possible members of a group	A-Z = alphabet of 26 “Literals = alphabet of 256

Compression Approaches

Compression is the elimination of redundancy in data in a reversible manner, increasing entropy and reducing the size of the data.

Compression can be lossless or lossy:

- Lossy - In some applications, it is acceptable to “lose” a small amount of input information during compression / decompression in exchange for higher compression ratios
  - Examples are Video or Audio, where eyes or ears will seldom detect some reasonable loss of detail
- Lossless – In many application, no data loss is acceptable, and in general this means lossless algorithms compress less than lossy algorithms.
  - Examples are financial data, medical records, user databases, etc.; where any data loss means data corruption and cannot be tolerated.

Lossless Compression Techniques

- Run Length Encoding – Replaces long strings of identical data with two symbols representing a symbol and length. Works well for long runs of repeating data:
  - i.e. 000000011111111 replaced with 0,7;1,8
- Dictionary Coder – Substitutes matched strings with references to a “dictionary”. The dictionary can be fixed or variable. A file can serve as its own dictionary.
  - Can Emulate Run Length Encoding (LZ77 for example)
- Huffman Encoding – Creating variable length symbols based on frequency of usage that replace a fixed length alphabet.

Lempel-Ziv Algorithm Family

LZ1(LZ77) & LZ2 (LZ78): Algorithms first described in papers published by Abraham Lempel and Jacob Ziv in 1977 and 1978. Named an IEEE Milestone in 1984

Algorithm	Description / Comments
LZ1 (LZ77) LZ2 (LZ78)	Initial algorithms published in Lempel-Ziv's classic 1977 & 1978 papers: LZ77: Sliding Window Dictionary up to 32K LZ78: Explicit Dictionary
LZS: Lempel-Ziv Stac	Sliding Window of fixed 2K Size + Static Huffman Encoder. Simple fast, popular
LZW: Lempel-Ziv Welch	Improvement on LZ78
LZMA: Lempel-Ziv Markhov Algorithm	Used in 7 Zip
Plus: LZO, LZRW, LZJB, LZWL, LZX, LZ4…..	

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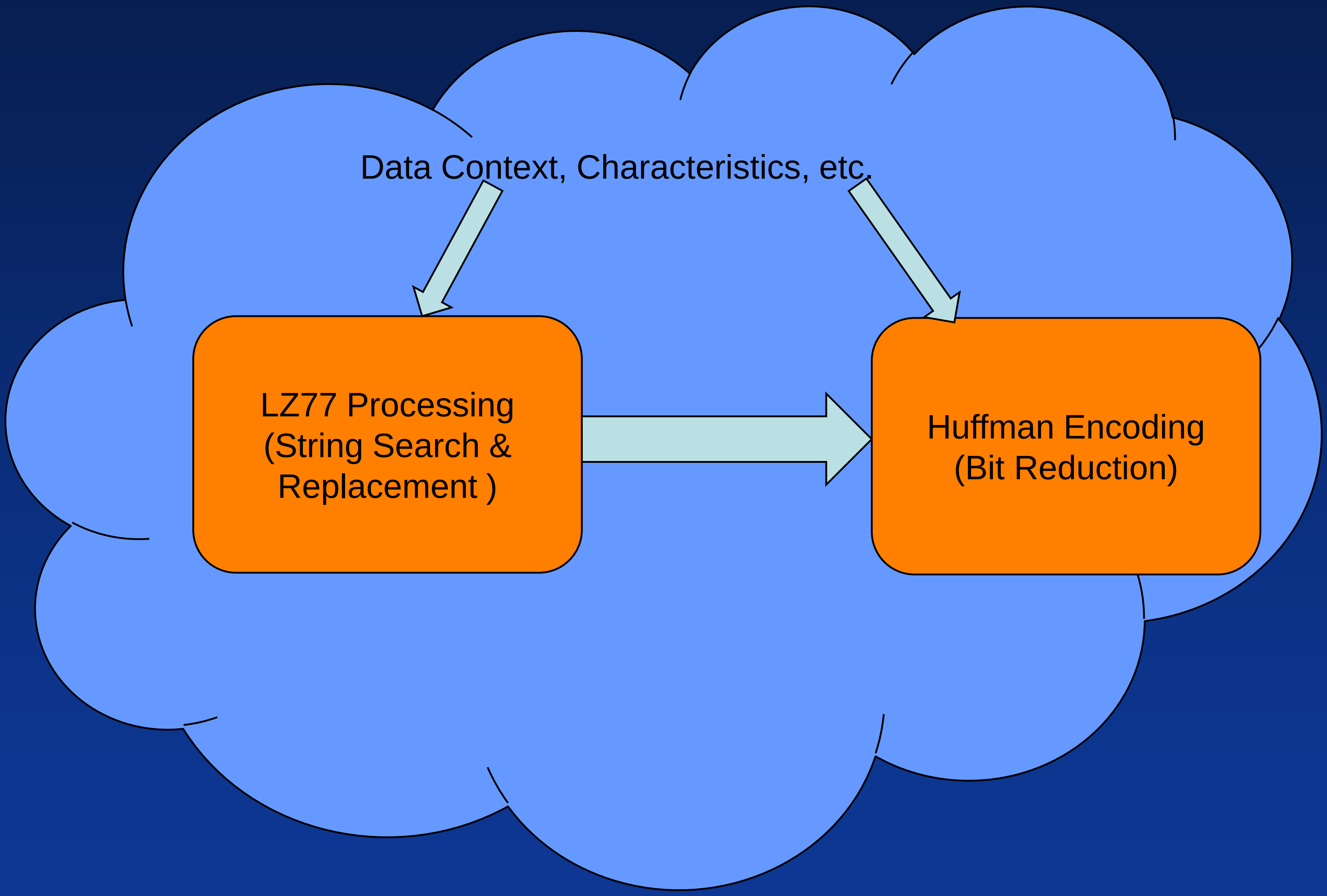
Deflate Algorithm:

The Deflate Algorithm combines LZ77 & Huffman Encoding into a popular lossless data compression algorithm.

- LZ77: Duplicate String Search and Replacement
  - Up to 32KB History Window
  - Minimum 3 byte string, max 258 byte
- Huffman: Bit Decimation
  - Static Huffman: Default code table presumed by encoder and decoder
  - Dynamic Huffman: Optimized code table constructed and stored/transmitted within Deflate Block
- Deflate is the algorithm that is used in the popular GZIP and Zlib formats.

Deflate Processing



Deflate/Zlib/GZIP Decoder Ring:

GZIP, Zlib, and Deflate are interrelated but separate standards and often used interchangeably in the vernacular. This is inaccurate, and can cause issues…

Name	Standard	Description
Deflate / Inflate	RFC-1951	The fundamental compression / decompression algorithm. Can be used without GZIP / Zlib.
GZIP	RFC-1950	File format which supports multiple algorithms – although only Deflate has been used to date: Wraps deflate output with header / trailer Optional flags allow detailed metadata to be inserted if so desired.
ZLIB	RFC-1952	Streaming format which supports multiple algorithms – although only Deflate has been specified and used to date: Wraps Deflate output with lightweight header/trailer

Deflate Characteristics

- Non Recursive - Cannot compress already compressed data for additional Compression Ratio: Data will typically expand after first pass.

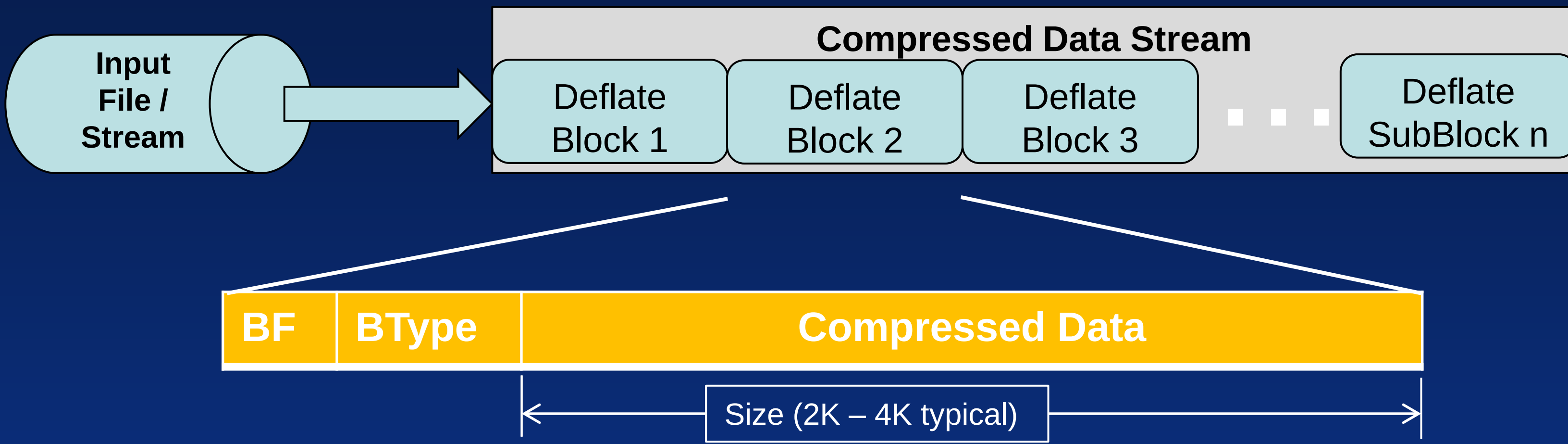
- Tremendous flexibility in Compressing Data
  - Window Size
  - Output Block Size
  - Maximum Max Length
  - Implementation options for LZ77 Search Engine
    - Hash Based (HW and SW)
    - Systolic Array Based (HW Only)
  - Huffman Encoding
    - Static or Dynamic

Deflate in Closed Systems

Tremendous Additional Flexibility in Closed Systems (Typical of Flash Use Cases) Note: No longer standards based Deflate – proceed with care!

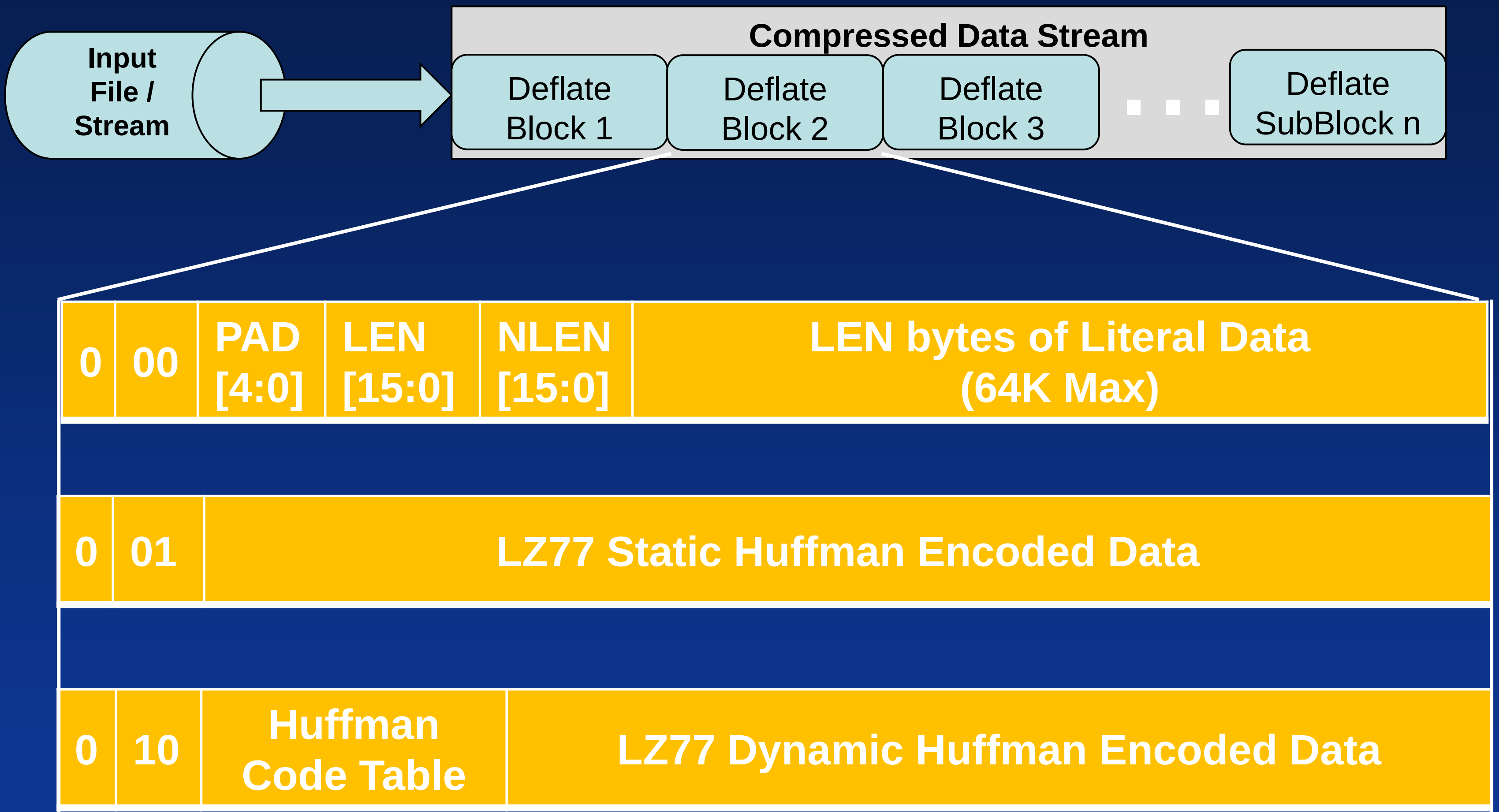
- Custom Optimized Static Huffman Trees (Based on optimizations of known data characteristics)
- Metadata Additions for housekeeping / error detection/correction
  - CRC's, Hashes, etc.
- Custom Fixed Dictionaries ()
  - Extreme Example: Calgary Corpus = 14 files:
  - Could be represented as a 4 bit dictionary (with 2 spare bits …)

RFC 1950 – Deflate Header Format

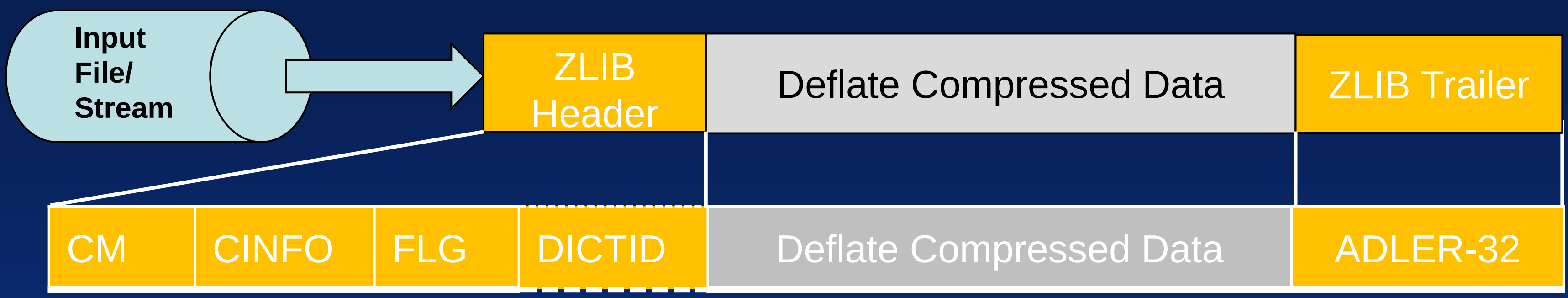


Field	Description	Decoder
BF	Block Final	0 – More Blocks Follow
		1 – Last Block of Data Stream
Btype	Block Type	00 – Raw/Stored Mode
		01 – Static Huffman Coding
		10 – Dynamic Huffman Coding
		11 – Reserved, Not Used

RFC 1950 – Deflate Header Format

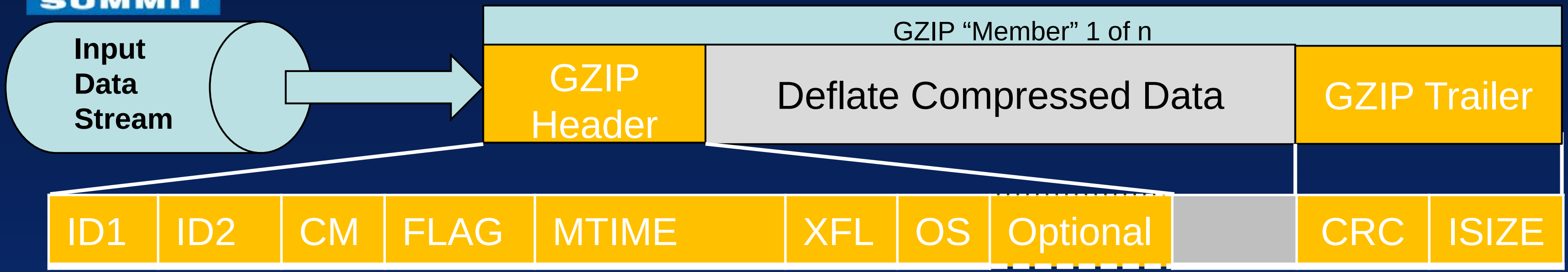


RFC 1950 – ZLIB Header Format



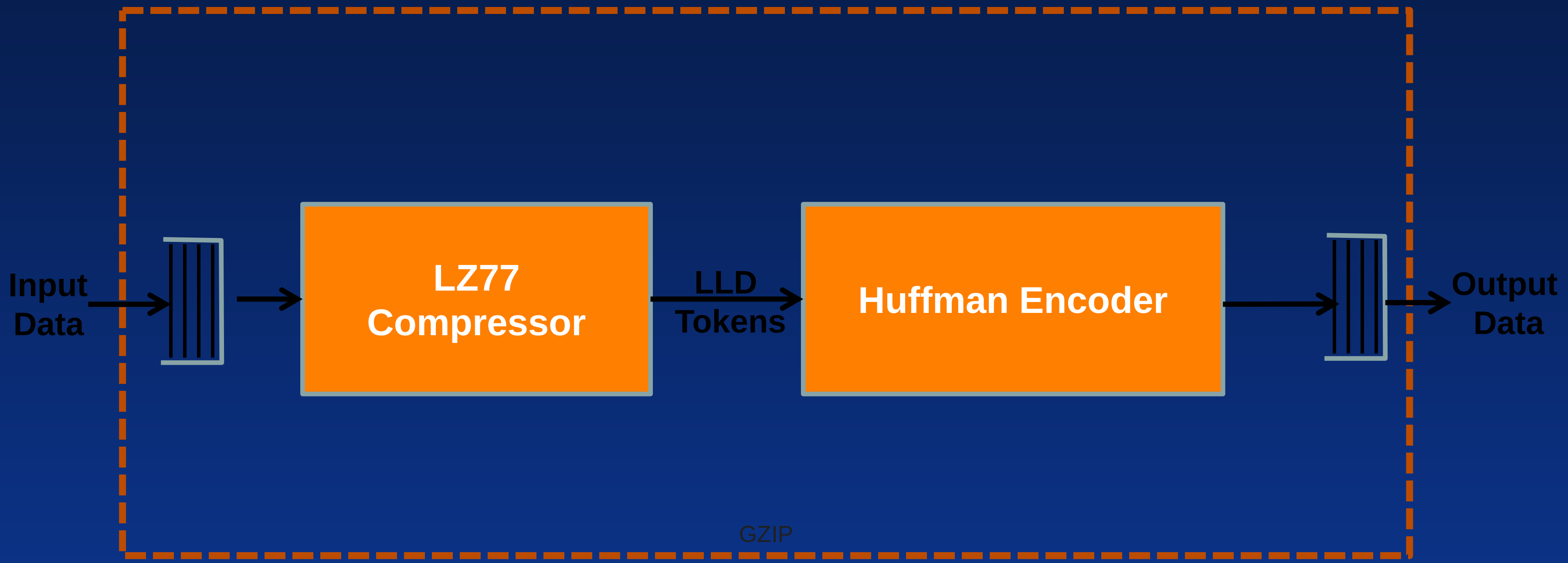
Field	Description	Decoder
CM	Compression Method	x8 = Deflate; xff = Reserved; Others – Not Assigned
CINFO	Compression Information	For CM = 0x8: 0x8 – xFF: Not Allowed 0x7: - x0: 32K – 256B History Window For CM Not = x8: Not Defined
FLG	Flags	FLG [4:0] Check Bits; FLG[5] = 1: Dictionary ID Present FLG [7:6] = Compression Level
DICTID	Dictionary ID	Identification for optional pre-defined Dictionary. See RFC-1950 for Details
ADLR-32	Checksum	ALDER-32 Checksum over uncompressed data (Before Deflate Processing)

RFC 1952 – GZIP Header Format



Field	Description	Decoder
ID1 & ID2	ID Flags	ID1 = 0x1F; ID2 = 0x8B: GZIP; All others undefined
CM	Compression Method	CM = 0x8; Deflate: CM = 0x7- 0x0; Reserved
FLG	Flags If FLG [n] = 1:	FLG [0] FTEXT ("Probably" Compressed ASCII Text) FLG [1] FHCRC (Optional CRC-16 for Header Present) FLG [2] FEXTRA (Optional Extra Fields Present) FLG [3] FNAME (Filename Present) FLG [4] FCOMMENT (Comments Present) FLG [7:5] Reserved
MTIME	Modification Time	Creation / Modification time in Unix Format
XFL	Extra Flags: For CM = 0x8	XFL =2; Max Compression; XFL = 4: Fastest Compression
OS	Operating System	OS [8:0] (See RFC 1952 for list)
CRC	CRC-32	CRC-32 of Uncompressed Data (Before Deflate Processing)
ISIZE	Input Size	Size of original input data modulo 2^32

GZIP Functional Block Diagram



Applies to HW or SW Implementation

LZ77 Compression - Overview

- LZ77 is a data compression method first described by Lempel & Ziv in 1977
- It uses a moving “window” of the last N bytes of the data that has been processed, and for the subsequent bytes it then searches for the longest match it can make in that earlier history.
- The minimum match length is 3, so even if there is no current match a sequence of 3 new bytes is typically the minimum being searched for.

LZ77 Compression - operation

- If no match >=3 characters is found, the 1st byte of the string is output as a literal byte, the window start and end are adjusted by one, and the next input byte is appended to the end of the 2 remaining bytes and a new search commences.
- If a 3 byte match IS found, new bytes are one-at-a-time added to the end of the match string, and searches are made to determine if the new longer string also has at least one match in the window.
- If a byte is added and there is no new match for the longer string, the previous matched string is emitted as a windows offset, length pair instead of the literal bytes.

LZ77 Compression – Compression Rates

- In the Gzip/ZLIB variant of LZ77, an output literal byte occupies 9 bits, and a matched string up to 258 bytes occupies 24 bits.
- Thus the worst-case result for just the LZ77 in this case is 1/8 = 12% growth, vs. a best case of 24/258*8 = 98.8% reduction in size.

LZ77 Compression – Example

	Input String Index																							
Step	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Output	
1	a																						wait	
2	a	a																					wait	
3	a	a	c																				0,a	
4	a	a	c	a																			0,a	Literals
5	a	a	c	a	a																		0,c	
6	a	a	c	a	a	c																	wait	
7	a	a	c	a	a	c	a																wait	
8	a	a	c	a	a	c	a	b															1,0,4	Length, Distance
9	a	a	c	a	a	c	a	b	c														wait	
10	a	a	c	a	a	c	a	b	c	a													0,b	
11	a	a	c	a	a	c	a	b	c	a	b												wait	
12	a	a	c	a	a	c	a	b	c	a	b	a											1,5,3	
13	a	a	c	a	a	c	a	b	c	a	b	a	a										wait	
14	a	a	c	a	a	c	a	b	c	a	b	a	a	a									0,a	
15	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c								wait	
16	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a							wait	
17	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a	a						wait	
18	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a	a	b					1,0,5	
19	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a	a	b					0,b	
																							126	144

Lazy Match

- Usually when a match string is broken LZ77 will immediately output a L,D pair and begin a new string. This is a Greedy Match
- Often a better Compression Ratio will occur if the search engine waits to see if a better match will occur later. This is a Lazy Match
- Lazy Match waits can repeat for more than one byte.

Greedy vs. Lazy Match

	Input String Index																						
Step										10	11	12	13	14	15	16	17	18	19	20	21	Output	
1	a																					wait	
2	a	b																				wait	
3	a	b	c																			0,a	
4	a	b	c	d																		0,b	
5	a	b	c	d	b																	0,c	
6	a	b	c	d	b	c																0,d	
7	a	b	c	d	b	c	d															wait	
8	a	b	c	d	b	c	d	e														1,1,3	
9	a	b	c	d	b	c	d	e	b													wait	
10	a	b	c	d	b	c	d	e	b	a												0,e	
11	a	b	c	d	b	c	d	e	b	a	a											0,b	
12	a	b	c	d	b	c	d	e	b	a	a	b										0,a	
13	a	b	c	d	b	c	d	e	b	a	a	b	c									wait	
14	a	b	c	d	b	c	d	e	b	a	a	b	c	d								wait	
15	a	b	c	d	b	c	d	e	b	a	a	b	c	d	e							1,1,4	
16	a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b						wait	
17	a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a					wait	
18	a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a				wait	
19	a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a	a			1,7,4	
20	a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a	a	d		0,a	
21	a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a	a	d		0,d	
																						153	160
																							4.38%

Greedy vs. Lazy Match Example

Input String Index																							
									10	11	12	13	14	15	16	17	18	19	20	#		Output	
a																						wait	
a	b																					wait	
a	b	c																				0,a	
a	b	c	d																			0,b	
a	b	c	d	b																		0,c	
a	b	c	d	b	c																	0,d	
a	b	c	d	b	c	d																wait	
a	b	c	d	b	c	d	e															Lwait	
a	b	c	d	b	c	d	e	b														1,1,3	
a	b	c	d	b	c	d	e	b	a													0,e	
a	b	c	d	b	c	d	e	b	a	a												0,b	
a	b	c	d	b	c	d	e	b	a	a	b											0,a	
a	b	c	d	b	c	d	e	b	a	a	b	c										wait	
a	b	c	d	b	c	d	e	b	a	a	b	c	d									wait	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e								Lwait	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b							0,a	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a						wait	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a					wait	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a	a				Lwait	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a	a	d			1,2,7	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a	a	d			0,a	
a	b	c	d	b	c	d	e	b	a	a	b	c	d	e	b	a	a	a	d			0,d	160
																						138	13.75%

Huffman Encoding

- Huffman encoding was invented by a MIT student in 1951, as part of a class assignment (David A Huffman).
- It uses uniquely-encoded binary bit strings to encode data.
- It encodes the most-frequently occurring characters to the shortest strings, and less-frequent characters in longer strings.
- It is only required to instantiate as many bit strings as you have characters, so if the characters to be encoded are "sparse", the number of bits used will be minimal.
- The bit strings are constructed in such a manner that it is guaranteed when you decode the resulting string, it is always lossless and can be reconstructed from the tree .

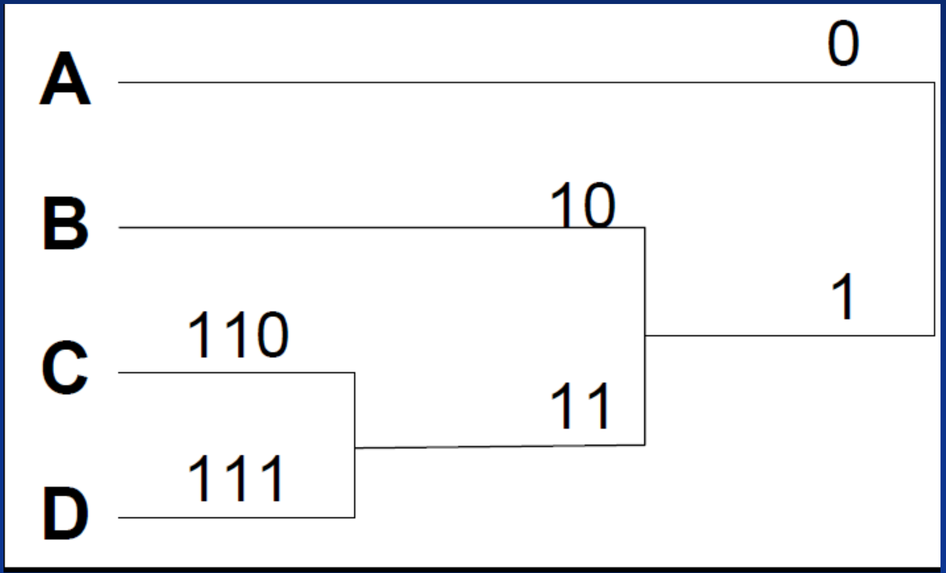
Huffman Encoding (1)

Example:

Initial String: ACBCABAADB

Frequency Table: A(4); B(3); C(2); D(1)

Huffman Binary Tree



19 Bits w/ Huffman vs. 80 Bits ASCII

Encoded String: 0 110 10 110 0 10 0 0 111 10

Deflate Huffman Encoding

- Complex and Efficient
- Three Alphabets
  - Literals (256 possible values of a byte)
  - Match Length (3-258)
  - Distance (1 – 32,768)
- Encodes 288 +32 (320 Total) Symbols
  - 288 Literals, Match Lengths, Overhead
  - 32 Distance Codes (Separate Tree)
- NOTE: RFC1951 is 15 pages.
  - Boilerplate, References, etc. Several Pages
  - Hashing – a couple of paragraphs
  - Huffman Encoding – over 7 pages…

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Implementation Approaches:

Software: Dedicated Programs

- Intel Architecture Processors
- RISC Processors (ARM, PPC, MIPS)
- Others (GPUs, DSP, etc.)

Hardware:

- Dedicated Accelerators
- Task Specific Custom CPUs

Hybrid:

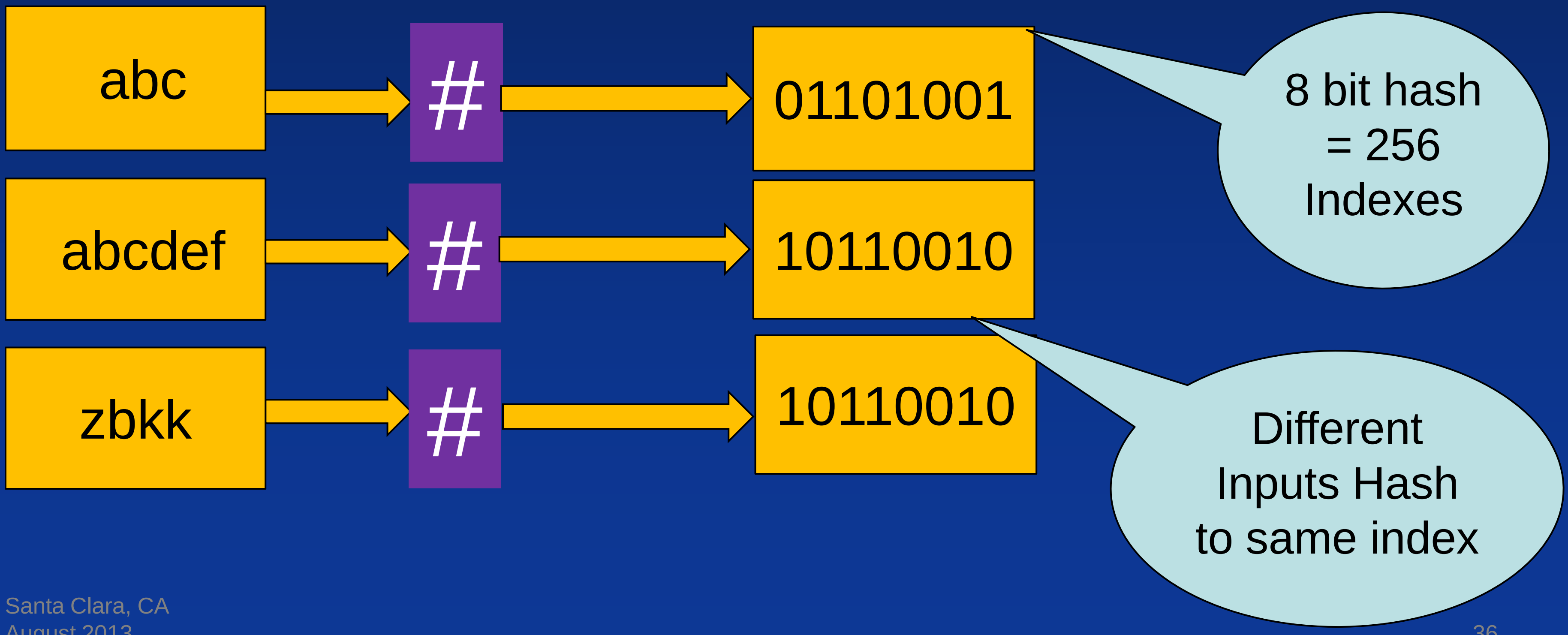
- ISA Enhancements: (e.g. HUFF $temp)
- Algorithm Partitioning (SW + Accelerators)

Implantation Tradeoffs:

Metric	Description	Comments
Throughput	Gb/s capability of a particular implementation. Aggregate – total throughput Thread – throughput of single Deflate Stream	Single Stream throughput is most challenging: I.E. – 12 Gb/s single stream is MUCH harder than 12 1 Gb/s streams.
Latency	Delay from start to finish of compression / decompression	Larger History Windows, Dynamic Huffman increase latency
Compression Ratio	Reduction in size of original file. E.g. a 3:1 ratio means the final result is 1/3 the size of the starting block or file	Larger History Windows, Dynamic Huffman increase compression ratio
Resource Utilization	Die Area, CPU Cores, Memory, Power are all resources utilized by H/W or SW implementations	Faster = more power & area Tighter CR = more power & area

Hashing

Hashing is the operation of applying an algorithm to a variable length string of data and generating a fixed length output:



Hashing Considerations

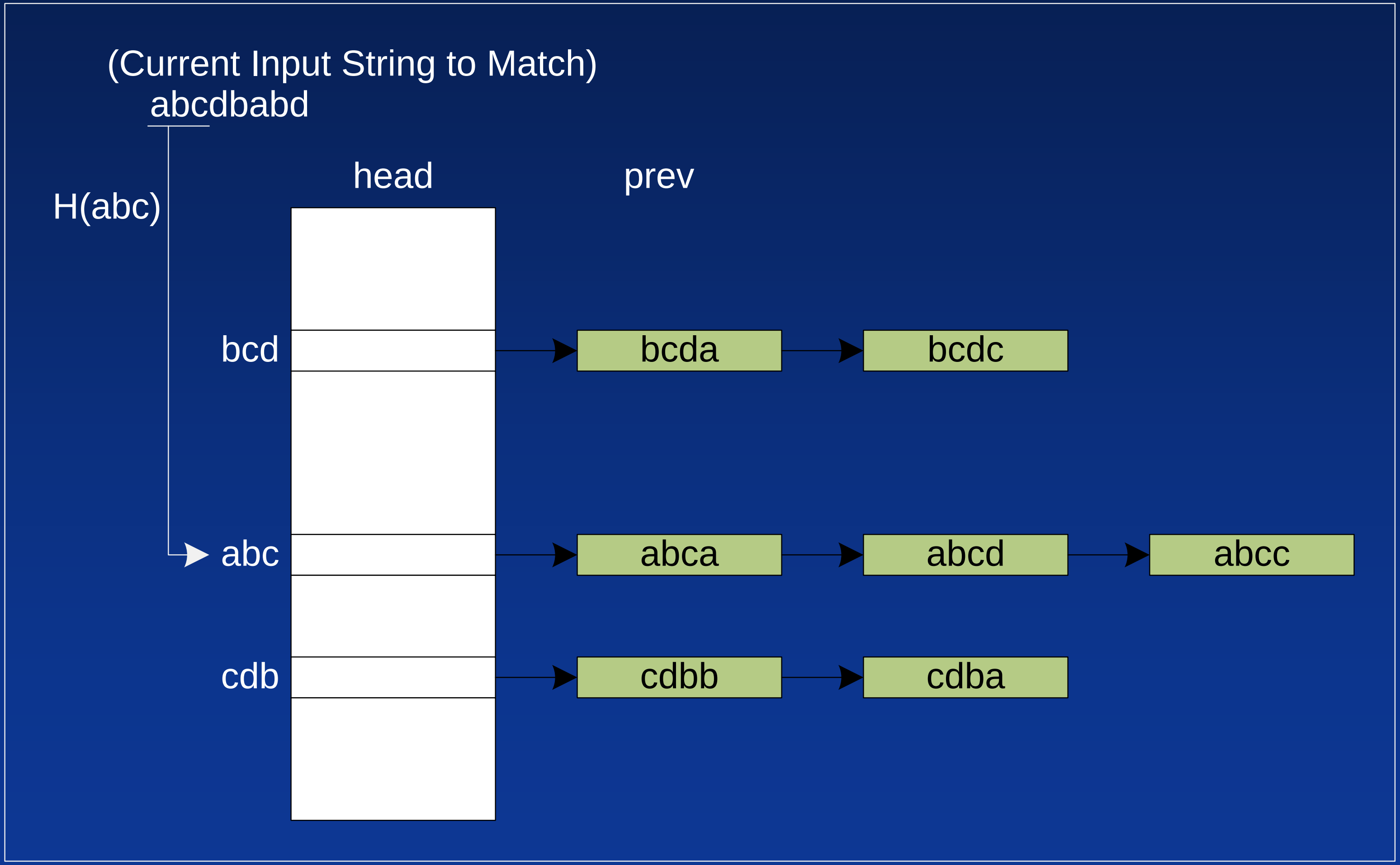
Hashing is a critical path function

- Must be Simple (Small Resource cost)
- Must be Fair" (equally distribute inputs into bins)
- Must be Fast (Throughput, Low Latency)

# of Indexes/Bins impacts CR & Performance

- More Bins = less matches per bin
- More Bins = more resources

SW GZIP Implementation



SW GZIP Implementation

- Hashing and Hash Chaining (1)
  - In SW, LZ77 longest-string matches are implemented with a Hash Table (Head) and a chaining table (Prev).
  - Head is indexed by the hash of all active 3-byte sequences in the window, and is basically the 3-byte "head" of all possible window strings.
  - Prev keeps track of all "suffixes" to the 3 bytes indexed by "head".
  - Head is $2^{HashLength}$ in size
  - Prev is $2^{WindowSize}$ in size
  - Hash of chars c_i, c_{i+1}, c_{i+2} is:
    - $((((C_i << 5) \wedge c_{i+1}) << 5) + c_{i+2})$ & WMASK where ^ = XOR, << = SHL

SW GZIP Implementation

- Hashing and Hash Chaining (2)
  - The hash tables fill as multiple string matches in the window are found
  - Because of hash collisions, hash table “hits” have to be verified by byte-comparisons in the window, although there are some shortcuts used to simplify this.
  - The “Prev” chain can become quite long if there are multiple matches concurrently in the window (think 32KB of all 0’s).
  - Four parameters are specified to limit the time spent creating / searching / maintaining the hash tables to an acceptable level

SW Parameter Tuning

GZIP SW defines the following parameters which are specified by a command line input

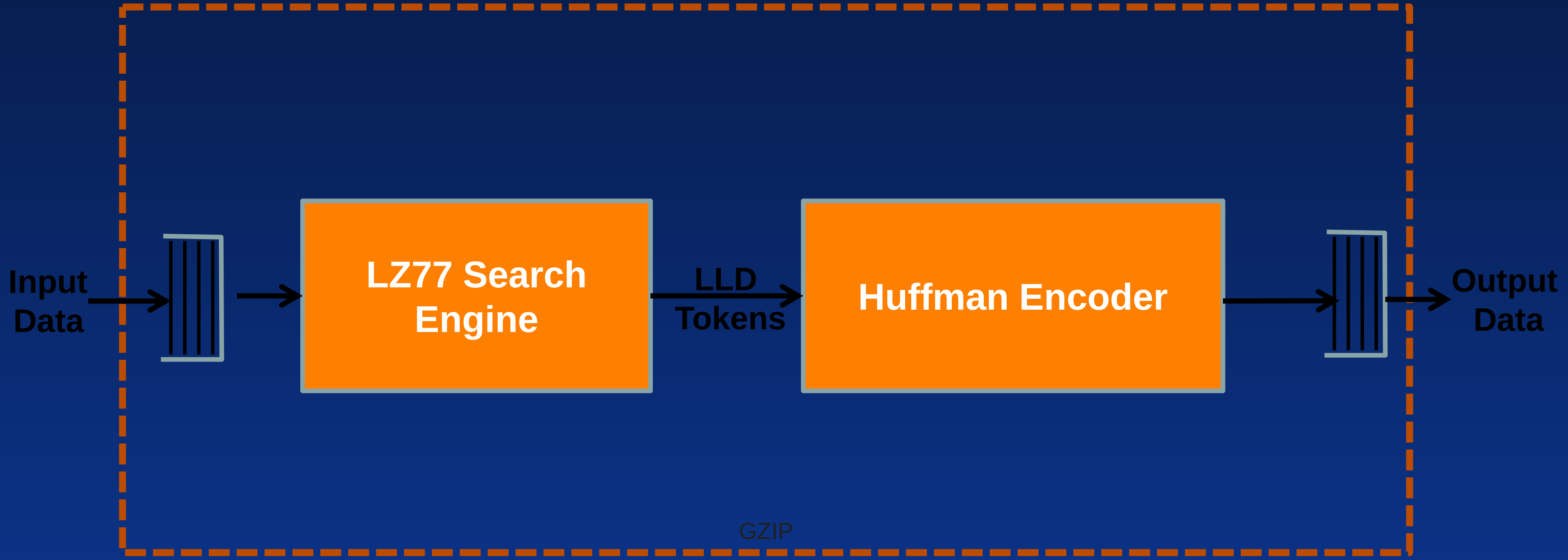
Parameter	Description
good_length	Reduce lazy search above this match length
max_lazy	Do not perform lazy search above this match length
nice_length	Quit search above this match length
max_chain	Maximum length of hash chain to follow

GZIP SW Compression "Levels"

- Default is Level 6

Level	Good Length	Max Lazy	Nice Length	Max Chain	Mode	Comments
0	0	0	0	0	Raw/Store	Apply Format
1	4	4	8	4	Static Huffman	No Lazy Matches
2	4	5	16	8		
3	4	6	32	32		
4	4	4	16	16	Dynamic Huffman	Lazy Matches
5	8	16	32	32		
6	8	16	128	128		
7	8	32	128	256		
8	32	128	258	1024		
9	32	258	258	4096		

GZIP Functional Block Diagram



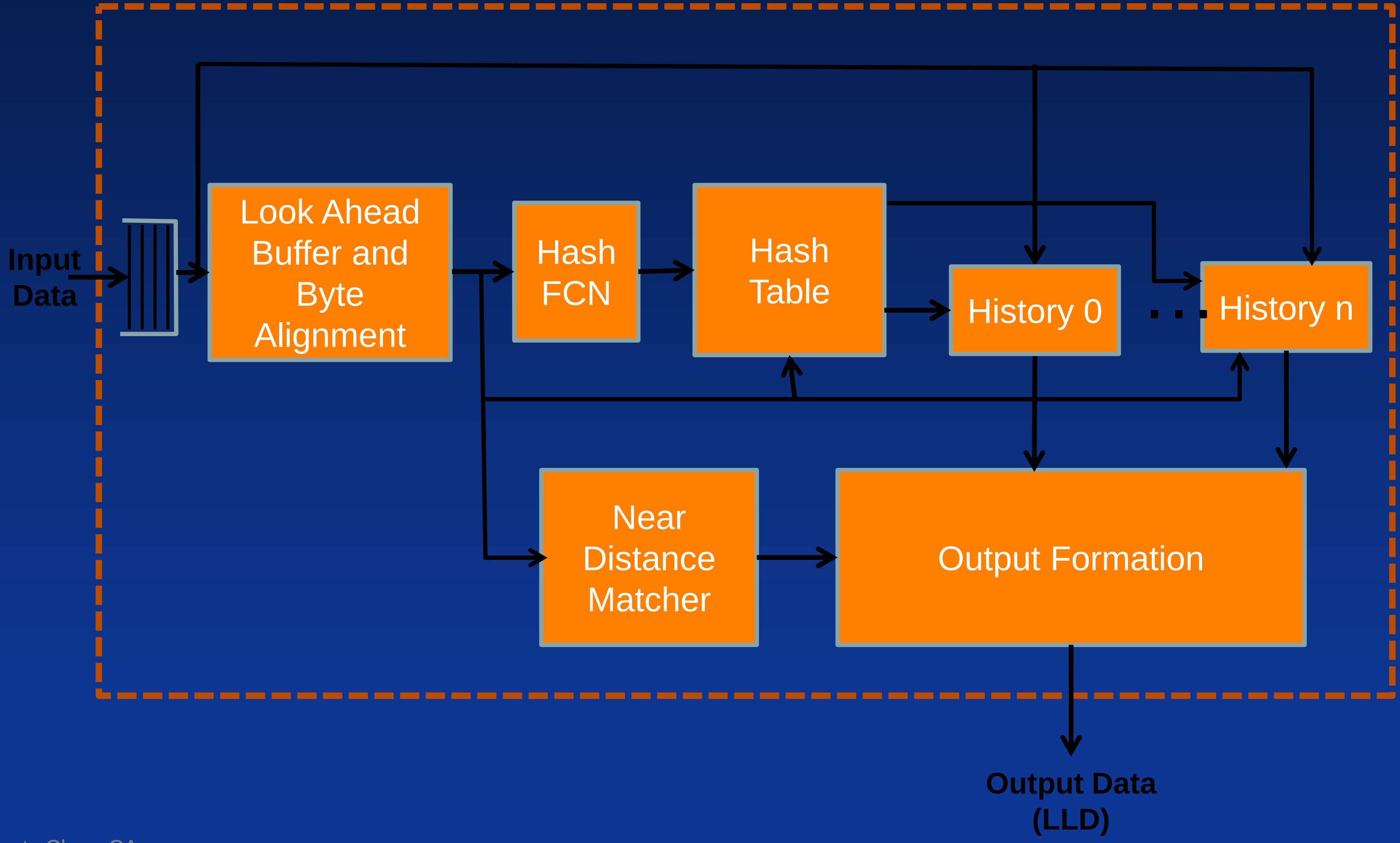
LZ77 HW Search Engines

Two common approaches:

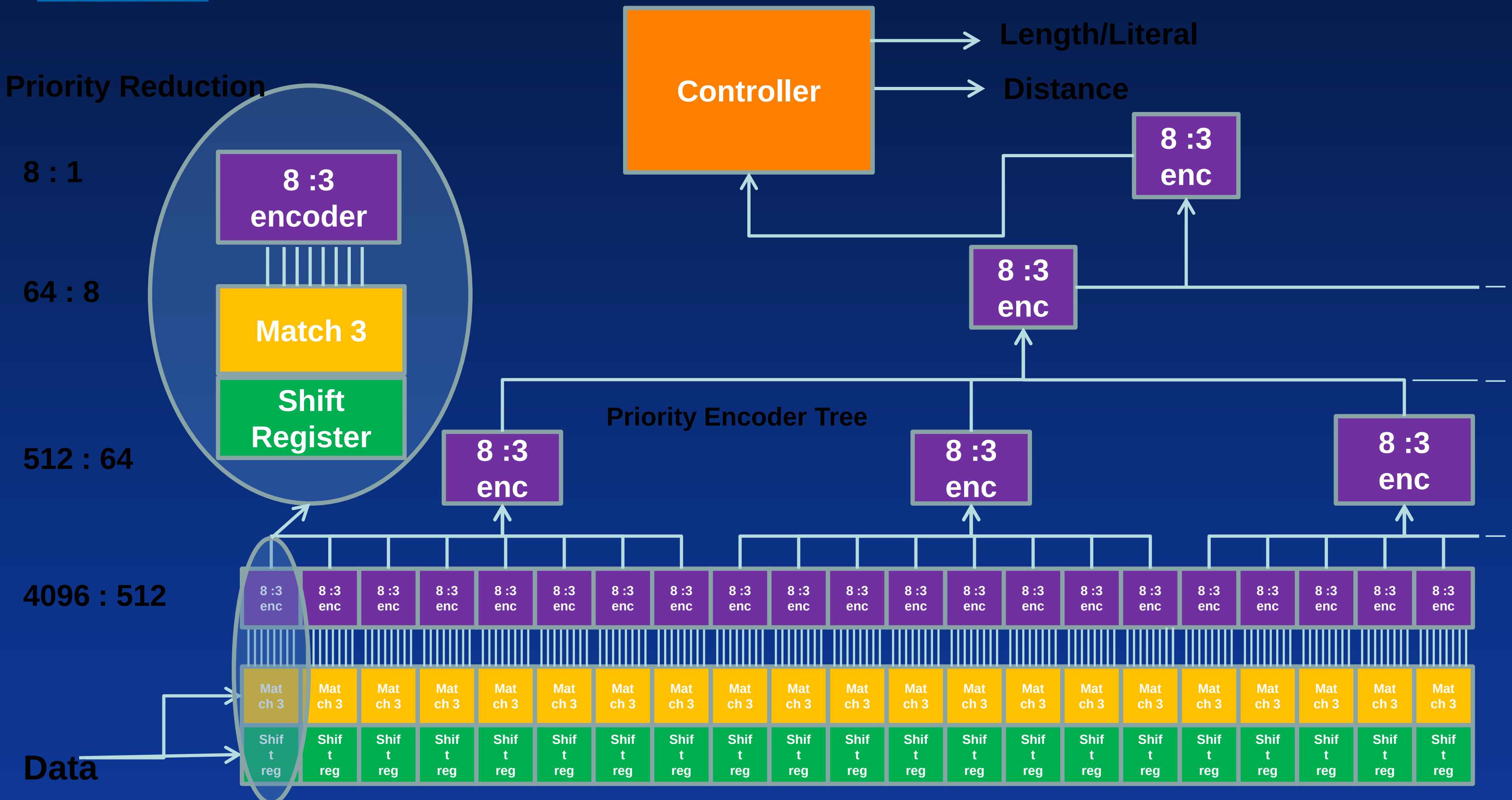
- Hash Based
  - Traditional Implementation – History stored in buffer(s)
  - Logic finds the longest match by stepping through a hash table
  - Limits on length of search within each history required
  - Multiple histories allow parallel searches

- Systolic Array Based
  - History stored in hardware registers
  - Hardware priority encoder locates longest match
  - Fast, deterministic operation (No Hashing / Hash Chains)

Hash Based Search Engine – Functional Block Diagram



Systolic Array Search Engine – Functional Block Diagram



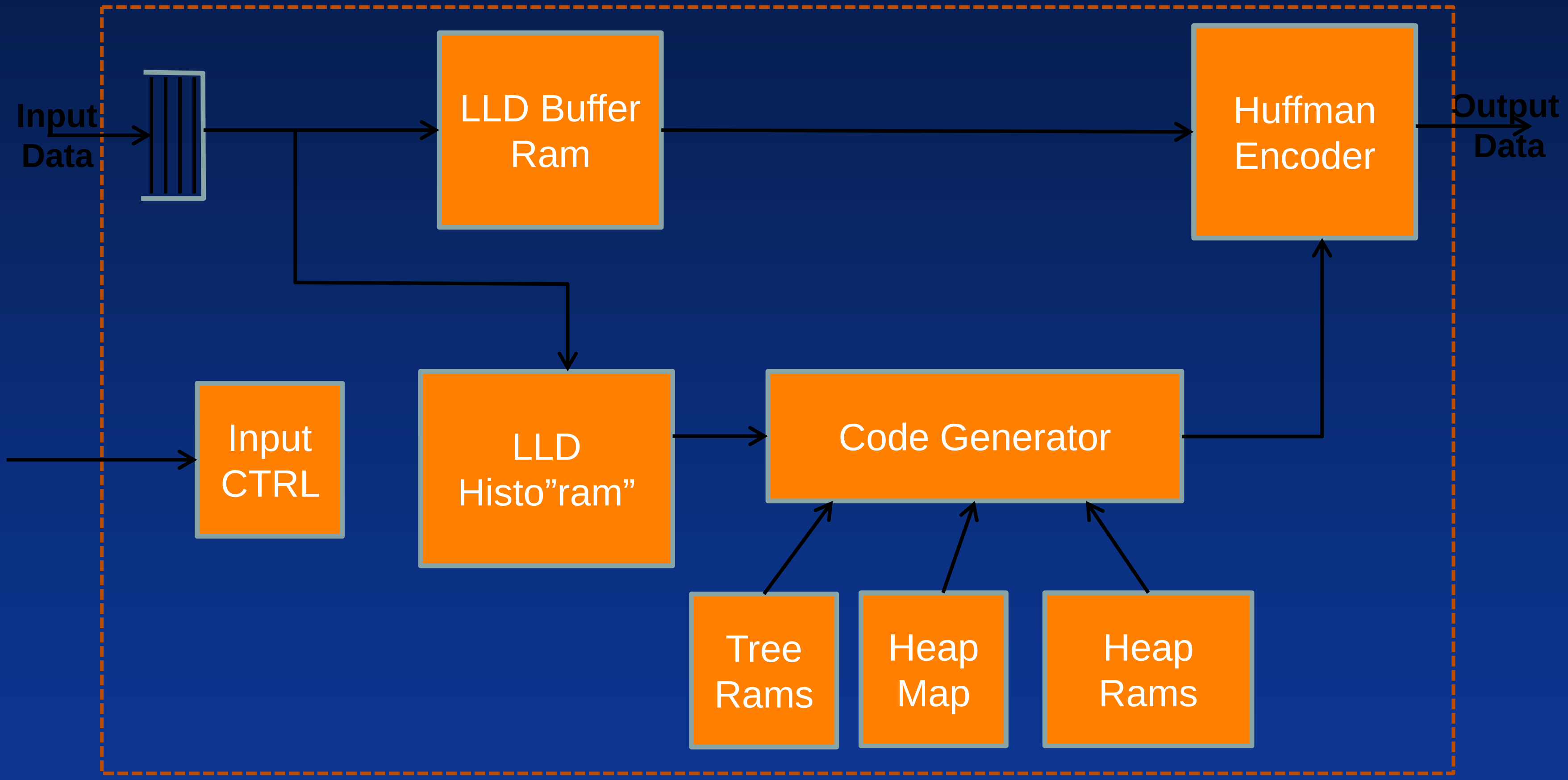
4096x8 shift register
4K History Window

HW Huffman Encoders

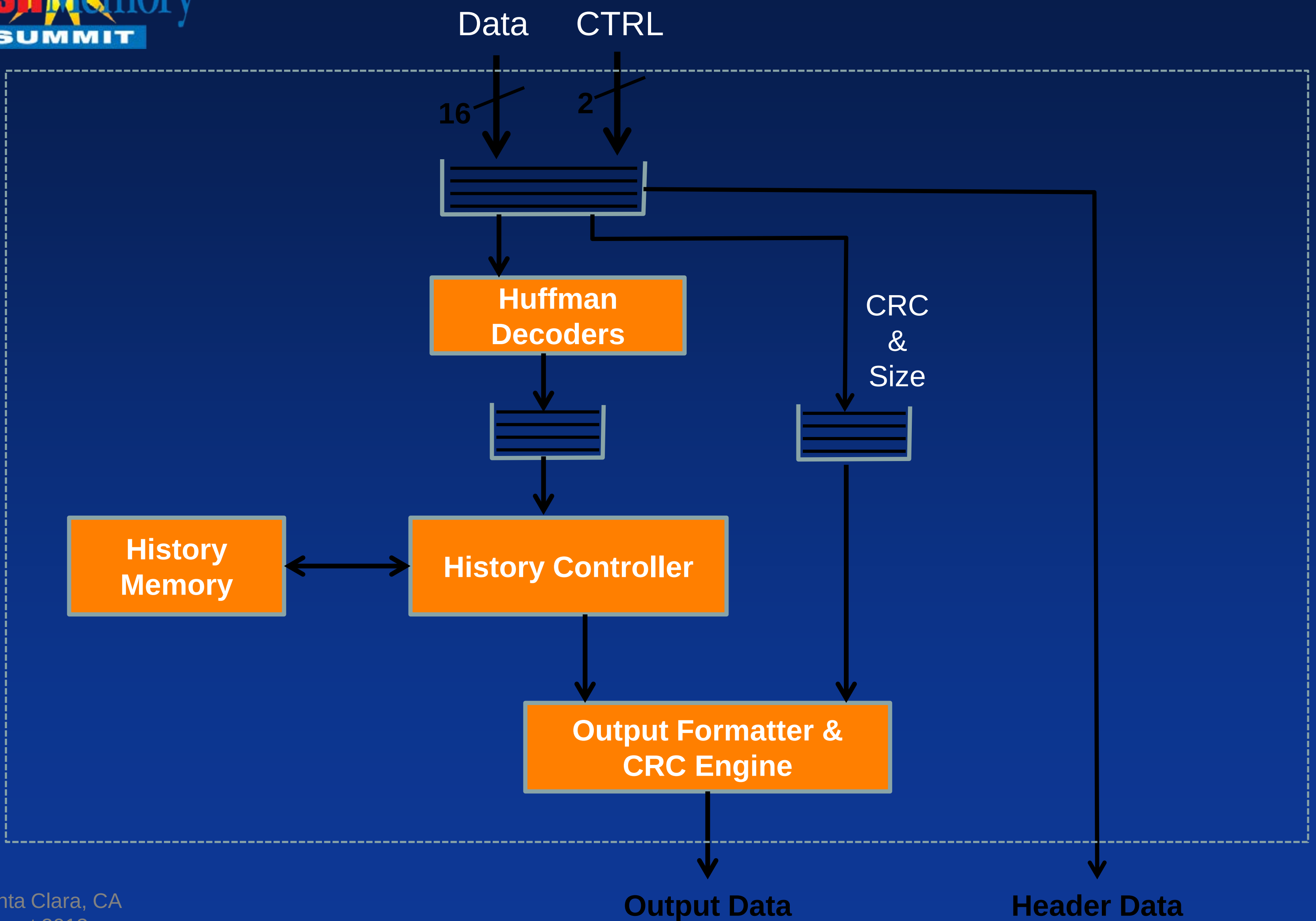
Two Huffman Encoder implementations for Deflate:

- Static Huffman only
  - Trivially small, simple, low latency
  - Encodes all blocks as "Static Huffman", so compression ratio is compromised
  - This is what existing industry players usually offer
- Dynamic Huffman (includes static encoding capability)
  - Derives optimum Huffman code, creates "Dynamic Huffman" blocks.
  - Options allow selection of smallest size between dynamic Huffman, static Huffman, or stored mode. *No compromises – always produces highest possible compression ratio output for a given search engine.*
  - Numerous run time options to help user logic:
    - Concatenate output blocks
    - Raw buffer management
    - Output byte alignment (ZFLUSH) capability
    - Various tuning capabilities – see user guide

Dynamic Huffman Encoding Engine – Functional Block Diagram (simplified)



GUNZIP Functional Block Diagram



Agenda

- Background, Definitions, & Context
- Data Compression Overview
- Data Compression Algorithm Survey
- Deflate/Inflate (GZIP/GUNZIP) in depth
- Software Implementations
- HW Implementations
- Tradeoffs & Advanced Topics
- SSD Benefits and Challenges
- Conclusions

Verification Datasets

Corpora are datasets used to benchmark compression implementations

- Classic corpora
  - Canterbury, Calgary, Large, Artificial, Miscellaneous
- Other corpora
  - Protein, Lukas, Silesia (see http://www.data-compression.info)
  - The “Govdocs1 Million Files Corpus” (see http://digitalcorpora.org)
    - Several CPU-months of simulation time, many hours of FPGA emulation time
- Locally generated
  - Special test cases which cannot be generated by GNU zip
  - Arbitrary files taken from various *nix, Windows systems, mobile phones
- WWW and other content
  - Video streams (e.g. youtube, news services), image and other near incompressible data
  - DVD files

Parallel Processing Options

Software

Standard Data Center Processors lack Symmetric Multi-Processing (SMP) Capabilities – Must pre-process somehow to take advantage of multi-core CPUs

Alternative Processor Architectures (ARM, PPC, MIPS) can be more capable…

PigZ is one alternative that attempts to utilize multiple processor cores to process a single stream of data

Hardware

Many more alternatives exist for Parallel Processing with HW Implementations of Deflate

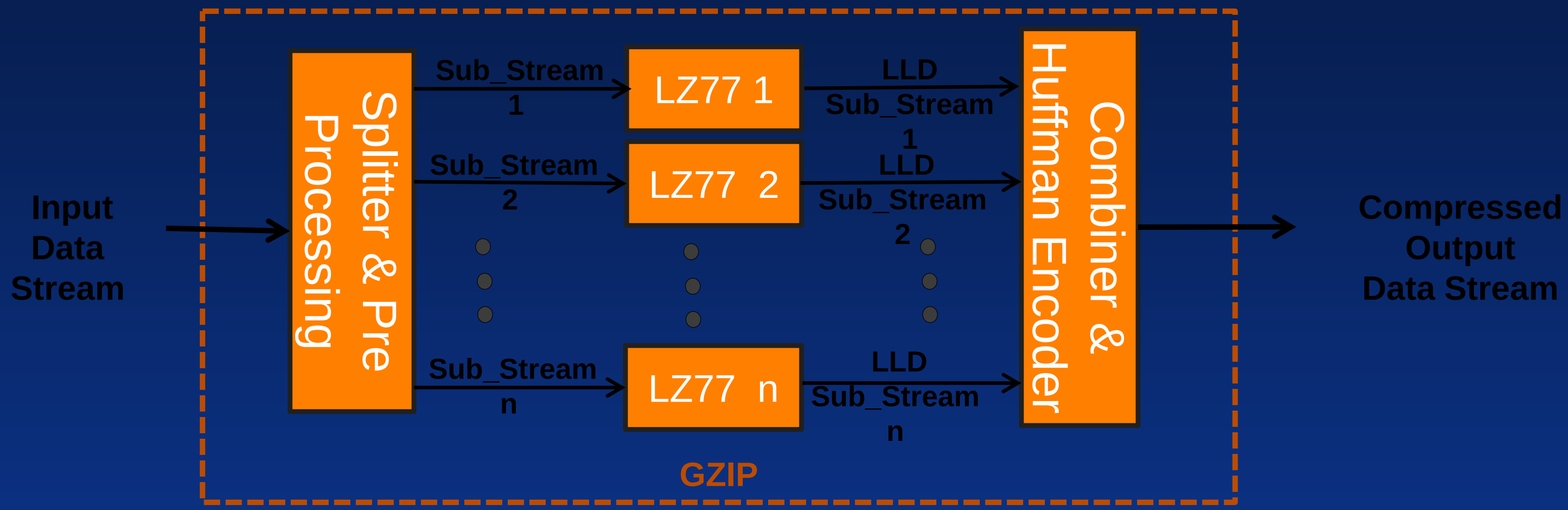
LZ77 and Huffman Encoders can be "Stacked" to process a stream in parallel

- Slight decrease in CR – dataset dependent but typically between 1% to 3%
- Linear scaling in Throughput
- Linear scaling in consumed resources (area, power, etc).

GZIP Instance Stacking

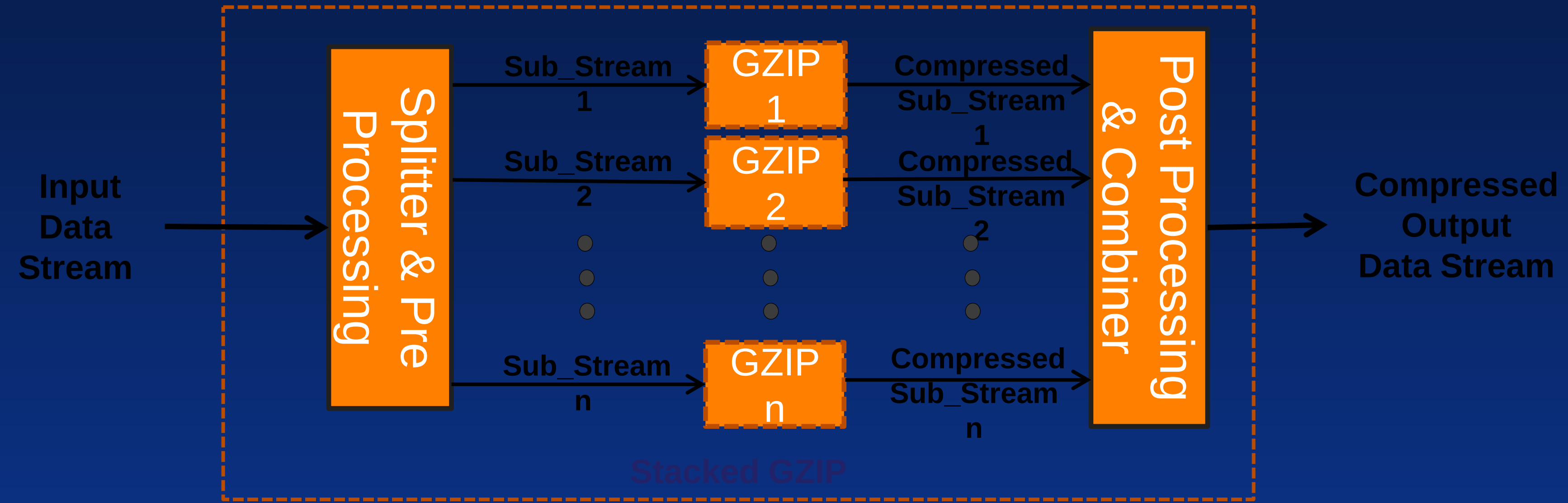
Item	Notes
Objectives:	Provide order of magnitude higher per stream throughput than achievable via traditional techniques applied to individual instances (clock rate enhancement, data bus widening, etc.) Maximize Utilization of Huffman Encoding Engine
Throughput Enhancement	Effectively n * x – i.e. 4 instances yield a ~ 4x throughput improvement
Compression Ratio Impacts	Negligible – Current benchmarking shows ~ 0.33% to ~ 1.3 % C/R degradation (depending upon configuration options) between 1 instance and 2 stacked instances. No further C/R degradation observed for additional stacked GZIP instances (beyond 2nd).
Resource (Gates, Memory) Impacts	Scales Linearly – very little overhead for splitter and combiner logic. Potential interconnect impact, depending on configuration options, number of instances used, etc.
Standards Compatibility	RFC Compliant – can decompress using standard GUNZIP IP or Software

Search Engine Instance Stacking - Typical Application



Search Engine Instance stacking maximizes throughput of Huffman Encoder
Can also stack GZIP Instances containing stacked Search Engines

GZIP Instance Stacking
- Typical Application



GZIP Instance stacking achieves order of magnitude throughput improvements !

Examples – a GZIP Block with:

8 stacked instances @ 4 Gb/s = 4 GB/s (32 Gb/s)

10 stacked instances @ 6.4 Gb/s = 8 GB/s (64 Gb/s)

An FPGA proof of concept which compresses at 124 Gb/s has been simulated…

Parallel Processing Challenges

- Decompression: Equivalent of parallel processing / stacking for Inflate/GUNZIP not possible for standards compatible files
- PigZ SW pre & post processing, but core inflate processing CPU bound.
  - Maybe OK for asymmetric systems
- HW Inflate engines optimized by design but ….
- Solution is addition of small amount of meta-data to deflate blocks – but problematic for open systems

State of Industry - Accelerators

- Under the hood in many flash subsystems
- Most current MIPS CPUs offer acceleration of deflate/inflate. ARM & PPC?
- A Recent Intel Server Chipset platform supports GZIP acceleration in HW.
- PCIe Cards (ComTech, Exar)
- Semiconductor IP also available to “roll your own”
- Real time compression “appliances” available
  - HW & SW approaches

Implementation Challenges in SSDs

- 8 Bit Algorithms vs. 32/64 Bit Processors
- Processor Architectures:
  - Lack of Symmetric Multi-Processing capability in some CPUs limits single thread performance (ARM, PPC MIPS excluded)
  - Errors in Data Compression Process (Soft errors)
- Lack of Deterministic Outcome on Compression - One byte change in a block can promulgate large change in compressed block size.
- Mismatch between standard formats and fixed sectors for SSDs / HDDs
- Uncompressible Data can Grow in size
- Mismatch in output between HW & SW implementations

Solutions to Challenges

Challenge	Solution
Soft Errors	Error Corrected Memories
Lack of Determinism in block size	Force Deflate Block Generation on desired boundaries
Lack of Determinism in throughput / latency	Choose small windows, Static Huffman, or Systolic Array LZ77 implementation
Data Expansion (Attempting to compress encrypted or pre-compressed data)	Select best of available Deflate Block formats on a block by block basis
Lack of Equivalency between HW and SW Implementations	SW Model that exactly matches HW implementation

Conclusions

- There is no perfect Data Compression Solution – all are subject to tradeoffs
- To the extent possible – know your data and tune the Data Compression Solution accordingly
- H/W and SW solutions optimize performance for different parameters
- Using both HW and SW solutions in the same system requires careful thought & planning

Resources & References

- www.sandgate.com
- http://www.ics.uci.edu/~dan/pubs/DataCompression.html
- http://mattmahoney.net/dc/dce.html
- http://www.zlib.net/feldspar.html
- http://en.wikipedia.org/wiki/DEFLATE
- http://www.gzip.org/algorithm.txt

Thank You!

Supplemental Materials

LZ77 Compression – Example

	Input String Index																							
Step	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Output	
1	a																						wait	
2	a	a																					wait	
3	a	a	c																				0,a	
4	a	a	c	a																			0,a	
5	a	a	c	a	a																		0,c	
6	a	a	c	a	a	c																	wait	
7	a	a	c	a	a	c	a																wait	
8	a	a	c	a	a	c	a	b															1,0,4	
9	a	a	c	a	a	c	a	b	c														wait	
10	a	a	c	a	a	c	a	b	c	a													0,b	
11	a	a	c	a	a	c	a	b	c	a	b												wait	
12	a	a	c	a	a	c	a	b	c	a	b	a											1,5,3	
13	a	a	c	a	a	c	a	b	c	a	b	a	a										wait	
14	a	a	c	a	a	c	a	b	c	a	b	a	a	a									0,a	
15	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c								wait	
16	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a							wait	
17	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a	a						wait	
18	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a	a	b					1,0,5	
19	a	a	c	a	a	c	a	b	c	a	b	a	a	a	c	a	a	b					0,b	
																							126	144

LZ77 Compression – Example

- Steps 1-2: wait for 3 bytes to search for.
- Steps 3-5: Have 3 bytes, but no 3 byte match, so emit 1 char and try next input char.
- Step 6-7: Have 3B match, then 4
- Step 8: no 5B match on next char, so output 4B match and restart search with 1 new byte (#8)
- Steps 9-10: wait for 3 bytes to search for; no 3B match, so emit 'b' and continue with next byte
- Step 11: Have 3B match, wait to see if it gets bigger
- Step 12: Match ends, emit 3B, start w/1 new byte
- Step 13-14: Get 3 bytes, but no 3 byte match, so emit 1 char and try next input char.
- Step 15-17: Have 3,4,5B match
- Step 18: New byte breaks string match, emit 5B string & restart
- Step 19: End of input file, output remaining bytes as literal
- Results: input=18*8=144 bits, Out=6*9+3*24=126b, 12.5% smaller

Lazy Match

- When scanning new input data to continue a match string, normally at the first character that breaks the string match, the search terminates and the whole match string is output and a new search commences. This is called Greedy Match.
- What if there was a match starting @ N+m in the above case, which continues and includes the newly added last byte, and in fact would be a longer match than the one emitted?
- Lazy Match delays committing to output when a match breaks for one or more additional characters, looking to see if a longer match is possible. If a longer match is found, the longer match is used and the initial character of the smaller match is emitted as a literal.

Greedy vs Lazy Match – Example

- Steps 1-14: roughly same for both cases, except “lazy wait” in step 8 that doesn't pan out.
- Step 15, greedy match: Have 4 byte match, end of match, emit 4B match..
- Step 15, lazy match: Don't commit to 4B match, add one more byte and see if we may have another 4B match – and we do.
- Step 16, lazy match: Search using next byte, find we now have a 5B match, better than original 4B match, so emit 1st char as literal and continue search.
- Steps 17-18, lazy match: extend match to 6 then 7 bytes
- Step 19, lazy match: match ends, but hold off committing to output until we see if still no match on next byte (lazy wait).
- Step 20, lazy match: no new 7B match, output original 7B match
- Step 21, lazy match: output 1B literal
- Step 22, lazy match: End of file, output remaining chars as literals
- Results: Greedy match=4.38% smaller vs . Lazy Match=13.75%

Huffman Encoding (1)

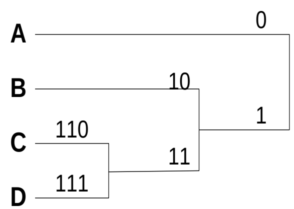
Example:

Huffman Encode the string: ACBCABAADB

Frequency Table:

A 4
B 3
C 2
D 1

Build the Binary Tree:



Huffman Encode the original String:

0 110 10 110 0 10 0 0 111 10

ASCII Size = 10*8 = 80 Bits

Huffman Size = 19 Bits

Note the receiver needs BOTH the Huffman String AND the encoding binary tree. This is “Dynamic” Huffman. It adapts to and minimally encodes the given dataset.

“Static Huffman” uses a pre-defined binary tree with “typically good” encodings; this eliminates the need to construct, send, and reconstruct the tree with the encoded data, as both sides can have a pre-provisioned static tree, but it is not an optimal encoding.

GZIP Implementation

- Hashing and Hash Chaining – Implications
  - SW implementations require RAM to implement the HASH tables. This has a cost in die size for on-chip applications.
  - Since the hash tables vary in length and search depth based on the input data, the time to search varies greatly based on the input data. This means the search time is non-deterministic within limits set by the compression level.
  - Systolic-Array (HW) based LZ77 implementations can deliver a search result in a fixed-time per new character, regardless of the input data and window, and it can be much less than the worst-case hash-based approach.