SENG440 Embedded Systems

– Lesson 105: Huffman Decoding –

Mihai SIMA

msima@ece.uvic.ca

Academic Course

Copyright © 2019 Mihai SIMA

Disclaimer

The purpose of this course is to present general techniques and concepts for the analysis, design, and utilization of embedded systems. The requirements of any real embedded system can be intimately connected with the environment in which the embedded system is deployed. The presented design examples should not be used as the full design for any real embedded system.

Lesson 105: Huffman Decoding

Huffman (variable-length) encoding

- Optimal encoding with respect to transmission rate
- Based on the probability of each symbol
  - Uses a variable-length code table for encoding a source symbol
  - The code-length depends on the probability of occurrence
- Let us assume a 5-symbol alphabet having the following probability distribution: **A** / 0.4, **B** / 0.3, **C** / 0.15, **D** / 0.1, **E** / 0.05
- Encode in a way that minimizes the transmission rate:

A – 0
All the others – 1

B – 0, that is **B** is 10
All the others – 1

C – 0, that is **C** is 110
All the others – 1

...

Hufmann encoding I

- The coding table:

Symbol	Bit combination	Code-length
A	0	1
B	10	2
C	110	3
D	1110	4
E	1111	4

- 3 bits are needed to represent the alphabet symbols
  - Transmission rate: 3 bits/cycle
- Between 1 and 4 bits are needed to represent the code-words
  - Transmission rate: 2 bits/cycle
    $(0.4 \times 1 + 0.3 \times 2 + 0.15 \times 3 + 0.1 \times 4 + 0.05 \times 4 \approx 2)$
- Penalty: sequential (slow) decoding process

Hufmann encoding II

- Coding algorithm can rely on a reasonable small Look-Up Table (LUT)
  - For a 5-symbol alphabet: 3-input LUT with 4 outputs
    - This is a 32-bit memory
  - For a 128-symbol alphabet: 7-input LUT with 127 outputs
    - This is a 2KB memory
- A memory of 2KB should not be a problem even for an embedded system
- If the coding LUT is still too large for the considered embedded system
  - Subdivide the coding LUT into smaller LUTs and perform the coding process in several steps
  - Penalty: larger coding time
- What would a Huffman encoder implementation look like?
  - Huffman encoding does not pose difficult technical problems
  - Huffman decoding is a far more difficult task!

Possible Huffman encoder implementation strategies

- A single large LUT
  - The main code just access the LUT in order to retrieve the codeword
  - The LUT's word-width is equal to the longest codeword
- Several smaller LUTs
  - The LUT's word-width is smaller
  - The coding process is performed in several steps
- These strategies can be implemented both in:
  - Hardware: the LUT(s) are implemented within the functional unit
  - Software: the LUT(s) are stored into memory (ideally in cache)

All-software implementation of the Huffman encoder

```
#include <stdio.h>
char *HE_LUT[5] = { "0", "10", "110", "1110", "1111"};

int main( void) {
  char symbol_to_encode = 0;

  do {
    scanf( "%i", &symbol_to_encode);
    printf( "%s\n", HE_LUT[symbol_to_encode - 0x40]);
  } while ( (symbol_to_encode > 0x40) & (symbol_to_encode < 0x46));
  printf( "%s\n", "Not a valid symbol.");
  exit( 0);
}
```

- ASCII code of character 'A' is 0x41
- ASCII code of character 'E' is 0x45

Hufmann decoding I

- A Hufmann-encoded string: `1101001110111010`

```
110  10  0  1110  1111  0  10
  C   B  A     D     E  A   B
```

- To achieve maximum compression, the coded data does not contain specific guard bits separating consecutive codewords
- The decoding process must:
  - Determine the symbol itself
  - Determine the code-length of the symbol
  - Shift the incoming string in order to discard the decoded bits
- Before initiating a new decoding iteration, the input string has to be shifted by a number of bits equal to the decoded code-length
  - A new symbol cannot be decoded before the current one has been decoded
- There are a lot of recursive operations that generate true-dependencies

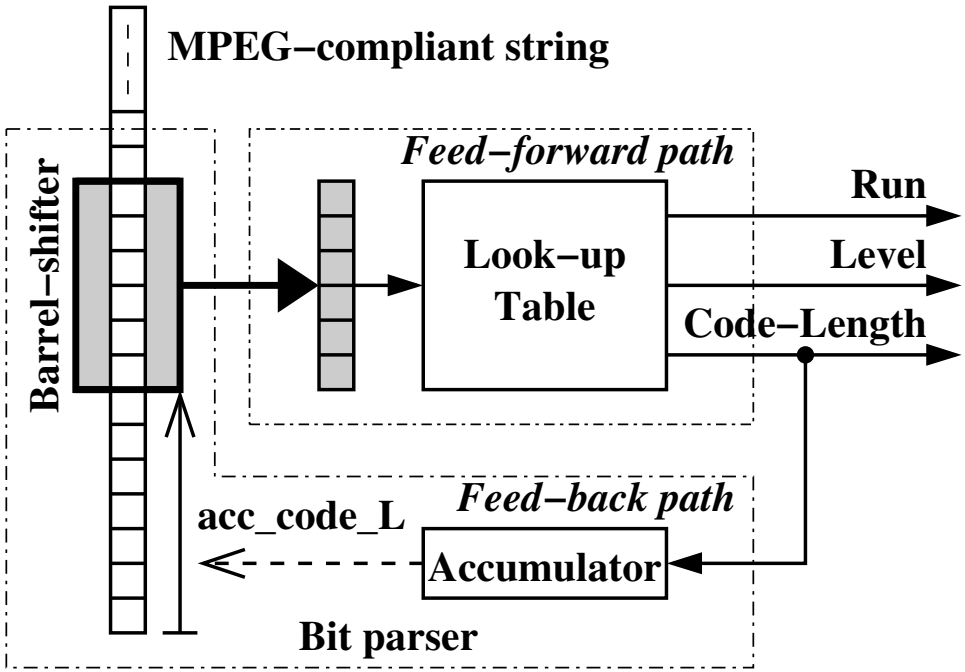
Hufmann decoding II

- Hufmann decoding is intrinsically a sequential process
- Parallel processing capabilities are not likely to improve the decoding rate
  - Pipelined engine
  - Horizontal engine
- Providing Huffman decoding hardware support is worth to be considered
- Will the processor be idle while the Huffman unit decodes the input string?
- Combine Huffman decoding with other tasks, for example:
  - Run-Length Decoding (RLD)
  - Inverse Discrete Cosine Transform (IDCT)

Hufmann decoding – the brute force approach

- Select a chunck of the incoming string that has a number of bits equal to the largest code-length
- Look-up into a Huffman decoding table with the selected chunck as address
- The LUT returns:
  - The bit combination of the decoded symbol
  - The code-length of the decoded symbol
- Discard *code-length* bits from the incoming string
- This approach is good for very small code-lengths since the LUT is small
- For large code-lengths the LUT size becomes very large!
  - MPEG: the longest codeword (excluding Escape!) is 17 bits $\longrightarrow$ the LUT size reaches $2^{17} = 128$ K words for a direct mapping of all possible codewords
  - MPEG: the symbol is a combination of a *run* code and a *length* code

Huffman (variable-length) decoding principle I



- VLD performance: the throughput is bounded by the inverse to the loop latency

Huffman (variable-length) decoding principle II

- VLD is a system with feedback, whose loop typically contains:
  - Look-Up Table on the feed-forward path
  - Bit parser on the feedback path
- LUT receives the variable-length code itself as an address and outputs:
  - the decoded symbol (*run-level* pair or *end_of_block*)
  - the codeword length
- To determine the starting position of the next codeword, the *code_length* is fed back to an accumulator and added to the previous sum of codeword lengths,
- The bit parsing operation is completed by the barrel-shifter (or funnel-shifter) which shifts out the decoded bits.

Huffman (variable-length) decoding performance

- The throughput is bounded by the inverse of the loop latency
- Major goal: reduce the loop latency!
  - Reduce the operation budget
    - Look-up operation
    - Accumulation
    - Barrel-shifting
  - Reduce the latency of each operation
- Hardware issues regarding VLD parts
  - Barrel-shifter is essentially a DEMUX – implemented within the standard instruction set (that is, in software)
  - Adder that performs the accumulation should be high-performance (carry look-ahead, carry select, etc.)
  - LUT: low latency is more important than silicon area

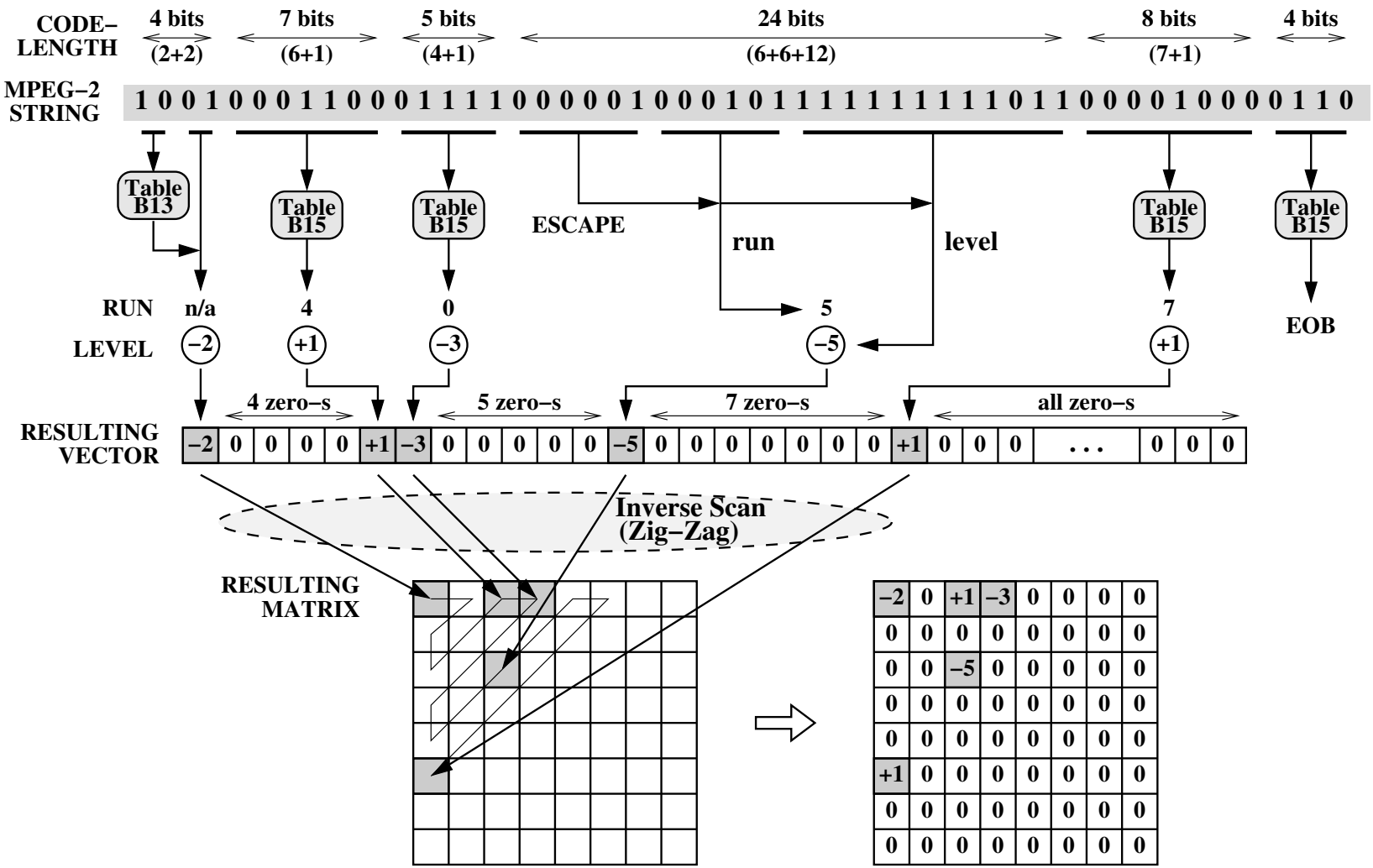
Huffman decoding: reducing the operation count

- Keep the accumulator out of the critical path:
  M.-T. Sun, VLSI architecture and Implementation of a High-Speed Entropy Decoder, Proceedings of the IEEE International Symposium on Circuits and Systems, 1991, pp. 200-203.
- Is multiple-symbol decoding possible?
  - What is really important is to detect the code-lengths to be able to initiate the next decoding iteration
  - What would be the LUT size in this case? Try multiple-symbol decoding for short codewords and single symbol decoding for long codewords.
- Try to split the accumulation operation is plain addition and storage

MPEG: Entropy decoding

- MPEG video coding standard:
  - DCT + Quantization: lossy compression
  - Entropy coding: lossless compression
- Entropy decoding consists of two distinct steps:
  - Variable-Length (Huffman) Decoding (VLD)
  - Run-Length Decoding (RLD)
- Both VLD and RLD are sequential tasks (due to data dependencies)
- Entropy decoding is an intricate function on parallel computing engines
- Entropy decoding is an ideal candidate to benefit from hardware support.

MPEG-2 entropy decoding



Hufmann decoding – project requirements I

- Define your own alphabet
- Assume a particular distribution for the probabilities of occurence
- Define the Huffman codes and calculate the average transmission rate with and without Huffman coding
- Build the testbench (= a file that contains alphabet symbols occuring with the assumed probabilities)
- Provide a pure-software solution for Huffman decoding
  - Try to reduce the cache misses (do not use very large LUTs)
  - Estimate the performance for the particular testbench
- Try also a firmware solution, but since Huffman decoding is a sequential process do not expect any improvement

Hufmann decoding – project requirements II

- Build a full-custom hardware unit for the Huffman decoder and estimate its performance against 32-bit addition
  - Reentrant or non-reentrant functional unit?
- Define a new instruction that will call the full-custom Huffman decoder
  - You must comply with the ARM architecture (you can have at most two arguments and one result per instruction call)
- Rewrite the high-level code and instantiate the new instruction
  - Use assembly inlining
- Estimate the performance of the ARM processor augmented with a Huffman decoding unit
- Estimate the speed-up (if any) and the penalty in terms of number of gates required to implement the Huffman decoder

Questions, feedback

Notes I

Notes II

Notes III

Notes IV

Project Specification Sheet

- **Student name:** .....
- **Student ID:** .....
- **Function to be implemented:** .....
- **Argument range:** .....
- **Wordlength:** .....