JPEG Compression/Decompression using SystemC

COE838: Systems-on-Chip Design
http://www.ecb.torontomu.ca/~courses/coe838/

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Overview

- Introduction to JPEG Coding and Decoding
- Hardware-Software Partitioning
- FDCT and IDCT HW module for 8 x 8 Block
- JPEG Implementation

Introductory Articles on JPEG Compression and Lab-2b manual documents available at the course webpage. Digital Image Processing by Gonzolez and Wood Chapter 6

JPEG-based Encoding

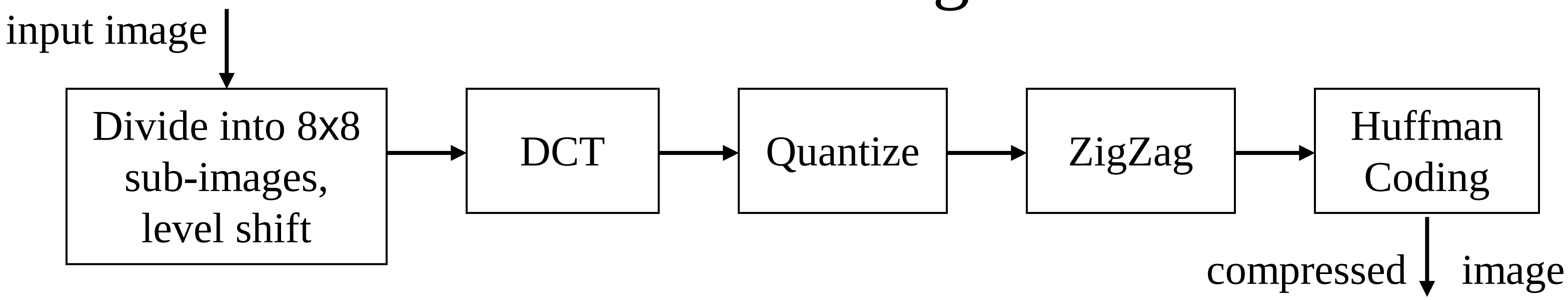
Four Stages of JPEG Compression

- Preprocessing and dividing an image into 8 x 8 blocks

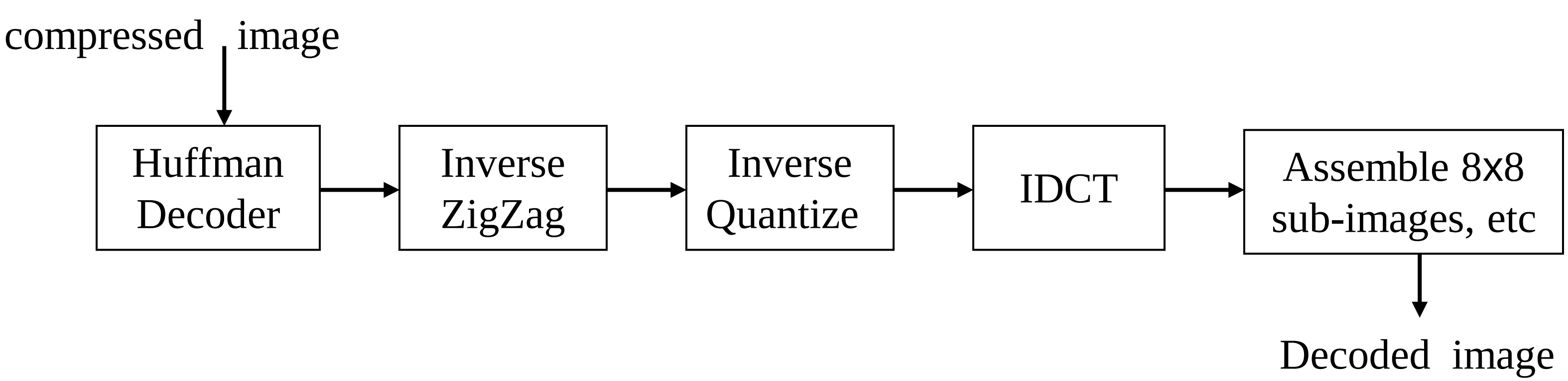
  Level-shift, for 8-bit gray scale images, subtract 128 from each pixel i.e.   pixel[i] = pixel[i] – 128 ;
- DCT (Discrete Cosine Transform) of 8 x 8 image blocks.
- Quantization
- ZigZag
- Entropy Encoding either of:
  - Huffman coding
  - Variable Length Coding

JPEG Encoding and Decoding

Encoding



Decoding



DCT: Discrete Cosine Transform

Mathematical definitions of 8 x 8 DCT and 8 x 8 IDCT respectively.

$$F(u,v) = \frac{1}{4} C(u)\, C(v) \left[\sum_{x=0}^{7} \sum_{y=0}^{7} f(x,y) * cos((2x+1)u\pi)/16 * cos((2y+1)v\pi/16 \right]$$

$$f(x,y) = \frac{1}{4} \left[\sum_{u=0}^{7} \sum_{v=0}^{7} C(u)\, C(v) F(u,v) * cos((2x+1)u\pi)/16 * cos((2y+1)v\pi/16 \right]$$

where $C(u), C(v) = 1/\sqrt{2}$ for $u,v = 0$

$C(u), C(v) = 1$ otherwise

$F(u,v)$ is the Discrete Cosine Transform of 8 x 8 block

$f(x,y)$ is the Inverse Discrete Cosine Transform

Why DCT instead of DFT

DCT is close to DFT (Discrete Fourier Transform) with many advantages

- DCT coefficients are purely real.
- Near-optimal for energy compaction.
- DCT computation is efficient due to the existence of fast algorithms
- Hardware solutions available that do not need multipliers

DCT is extensively used in image compression standards such as JPEG, MPEG-1, MPEG-2, MPEG-4, etc.

$$
\begin{pmatrix}
52 & 55 & 61 & 66 & 70 & 61 & 64 & 73 \\
63 & 59 & 66 & 90 & 109 & 85 & 69 & 72 \\
62 & 59 & 68 & 113 & 144 & 104 & 66 & 73 \\
63 & 58 & 71 & 122 & 154 & 106 & 70 & 69 \\
67 & 61 & 68 & 104 & 126 & 88 & 68 & 70 \\
79 & 65 & 60 & 70 & 77 & 68 & 58 & 75 \\
85 & 71 & 64 & 59 & 55 & 58 & 65 & 83 \\
87 & 79 & 69 & 68 & 65 & 65 & 78 & 94
\end{pmatrix}
\quad \text{DCT} \Rightarrow \quad
\begin{pmatrix}
-415 & -29 & -62 & 25 & 55 & -20 & -1 & 3 \\
7 & -21 & -62 & 9 & 11 & -7 & -6 & 6 \\
-46 & 8 & 77 & -25 & -30 & 10 & 7 & -5 \\
-50 & 13 & 35 & -15 & -9 & 6 & 0 & 3 \\
11 & -8 & -13 & -2 & -1 & 1 & -4 & 1 \\
-10 & 1 & 3 & -3 & -1 & 0 & 2 & -1 \\
-4 & -1 & 2 & -1 & 0 & -3 & 1 & -2 \\
-1 & -1 & -1 & -2 & -3 & -1 & 0 & -1
\end{pmatrix}
$$

Quantization

The 8x8 block of DCT transformed values is divided by a quantization value for each block entry.

$$F_{quantized}(u,v) = F(u,v) / Quantization\_Table(x,y)$$

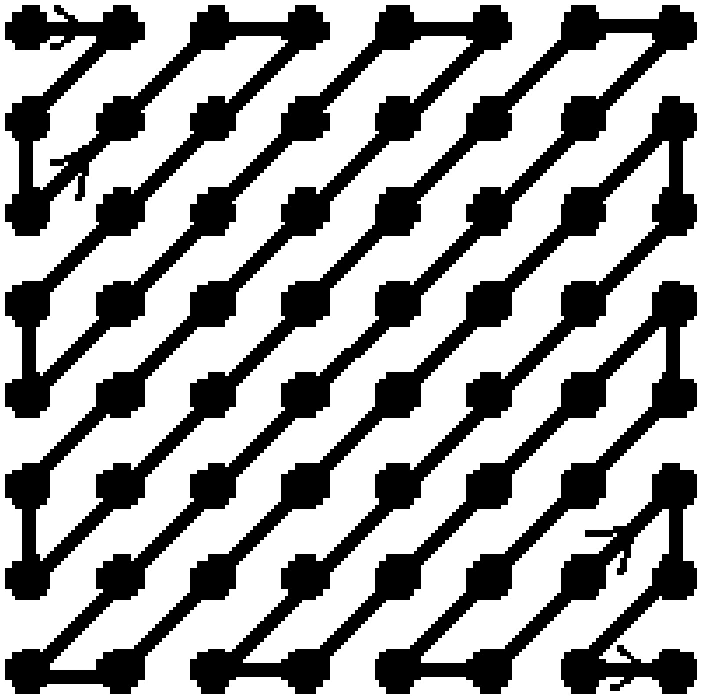
Quantization table :

16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	99

Zig-Zag

It takes the quantized 8x8 block and orders it in a 'Zig-Zag' sequence, resulting in a 1-D array of 64 entries,

- This process place low-frequency coefficients (larger values) before the high-frequency ones (nearly zero).
- One can ignore any continuous zeros at the end of block
- Insert a (EOB) End of Block at the end of each 8x8 block encoding.



Quantization and ZigZag

-415	-29	-62	25	55	-20	-1	3
7	-21	-62	9	11	-7	-6	6
-46	8	77	-25	-30	10	7	-5
-50	13	35	-15	-9	6	0	3
11	-8	-13	-2	-1	1	-4	1
-10	1	3	-3	-1	0	2	-1
-4	-1	2	-1	0	-3	1	-2
-1	-1	-1	-2	-3	-1	0	-1

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16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	99

-26	-3	-6	2	2	0	0	0
1	-2	-4	0	0	0	0	0
-3	1	5	-1	-1	0	0	0
-4	1	2	-1	0	0	0	0
1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Zig-Zag

[-26 -3 1 -3 -2 -6 2 – 4 1 -4 1 1 5 0 2
0 0 -1 2 0 0 0 0 0 -1 -1 EOB]

FDCT SC_Module

```
// fdct.h
struct fdct : sc_module {
  sc_out<double> out64[8][8]; // the dc transformed 8x8 block
  sc_in<double> fcosine[8][8]; // cosine table input
  sc_in<FILE *> sc_input; // input file pointer port
  sc_in<bool> clk; // clock signal
  char input_data[8][8]; // the data read from the input file
  void read_data( void ); // read the 8x8 block
  void calculate_dct( void ); // perform direct cosine transform
  // define fdct as a constructor
  SC_CTOR( fdct ) {
  // read_data method sensitive to +ve & calculate_dct sensitive to
  // -ve clock edge, entire read and dct will take one clock cycle
       SC_METHOD( read_data ); // define read_data as a method
       dont_initialize();
       sensitive << clk.pos;
       SC_METHOD( calculate_dct ); // define calc. DCT as a method
       dont_initialize();
       sensitive << clk.neg;
  }
};
```

DCT Module

```
#include "fdct.h"
void fdct :: calculate_dct( void ) {
unsigned char  u, v, x, y;
double           temp;
   for (u = 0; u < 8; u++) // do forward discrete cosine transform
     for (v = 0; v < 8; v++) {  temp = 0.0;
        for (x = 0; x < 8; x++)
        for (y = 0; y < 8; y++)
          temp += input_data[x][y] * fcosine[x][u].read() *
               fcosine[y][v].read();
        if ((u == 0) && (v == 0)) temp /= 8.0;
        else if (((u == 0) && (v != 0)) || ((u != 0) && (v == 0)))
          temp /= (4.0*sqrt(2.0)); else temp /= 4.0;
        out64[u][v].write(temp);
}   }
void fdct :: read_data( void ) { // read the 8*8 block
   fread(input_data, 1, 64, sc_input.read());
   // shift from range [0, 255] to [-128, 127]
   for (unsigned char uv = 0; uv < 64; uv++)
        input_data[uv/8][uv%8] -= (char) (pow(2,8-1));
}
```

DCT Module Structures

```
#define PI 3.1415926535897932384626433832795 // the value of PI
unsigned char quant[8][8] =             // quantization table
       {{16,11,10,16,24,40,51,61},
        {12,12,14,19,26,58,60,55},
        {14,13,16,24,40,57,69,56},
        {14,17,22,29,51,87,80,62},
        {18,22,37,56,68,109,103,77},
        {24,35,55,64,81,104,113,92},
        {49,64,78,87,103,121,120,101},
        {72,92,95,98,112,100,103,99}};
unsigned char zigzag_tbl[64]={          // zigzag table
       0,1,5,6,14,15,27,28,
       2,4,7,13,16,26,29,42,
       3,8,12,17,25,30,41,43,
       9,11,18,24,31,40,44,53,
       10,19,23,32,39,45,52,54,
       20,22,33,38,46,51,55,60,
       21,34,37,47,50,56,59,61,
       35,36,48,49,57,58,62,63};
signed char MARKER = 127; // end of block marker
```

Functions: Read File Header

```
#define rnd(x) (((x)>=0)? ((signed char)((signed char)((x)+1.5)-
  1)):((signed char)((signed char)((x)-1.5)+1))) // round 8-bit
#define rnd2(x) (((x)>=0)? ((short int)((short int)((x)+1.5)-
  1)):((short int)((short int)((x)-1.5)+1))) // round 16-bit

// read the header of the bitmap and write it to the output file

void write_read_header(FILE *in, FILE *out) {
  unsigned char temp[60]; // temporary array of 60 characters,
         // which is enough for the bitmap header: 54 bytes
  printf("\nInput Header read and written to the output file");
  fread(temp, 1, 54, in); // read 54 bytes and store them in temp
  fwrite(temp, 1, 54, out); // write 54 bytes to the output file
  printf("......Done\n");
  printf("Image is %d bit Image. Enter to Continue\n>", temp[28]);
  getchar();
}
```

Functions: Cosine-table

```
// make the cosine table
void make_cosine_tbl(double cosine[8][8]);
void make_cosine_tbl(double cosine[8][8]) {
  printf("Creating the cosine table to be used in FDCT and
  IDCT");
  // calculate the cosine table as defined in the formula
  for (unsigned char i = 0; i < 8; i++)
      for (unsigned char j = 0; j < 8; j++)
            cosine[i][j] = cos((((2*i)+1)*j*PI)/16);
  printf("......Done\n");
}
```

Functions: ZigZag

```
// zigzag the quantized input data
// end of block marker, which is unlikely to be found in a DCT-block
  signed char MARKER = 127;
void zigzag_quant(double data[8][8], FILE *output) {
  signed char to_write[8][8];
    // this is the rounded values, to be written to the file
  char last_non_zero_value = 0; // index to last non-zero in a block
   // zigzag data array & copy it to to_write, round the values
   // and find out the index to the last non-zero value in a block
  for (unsigned char i = 0; i < 64; i++) {
   to_write[zigzag_tbl[i]/8][zigzag_tbl[i]%8] =
       rnd(data[i/8][i%8] /   quant[i/8][i%8]);
       if (to_write[i/8][i%8] != 0) last_non_zero_value = i;
  }
  // write all values in the block including the last non-zero value
  for (unsigned char i = 0; i <= last_non_zero_value; i++)
      fwrite(&to_write[i/8][i%8], sizeof(signed char), 1, output);
        // write the end of block marker
  fwrite(&MARKER, sizeof(signed char), 1, output);
}
```

Functions: Main

```
#include "systemc.h"
#include "functions.h"
#include "fdct.h"
#include "idct.h"
#define NS *1e-9 // constant for clock signal i.e. in nanoseconds
int sc_main(int argc, char *argv[]) {
   char choice;
   sc_signal<FILE *> sc_input; // input file pointer signal
   sc_signal<FILE *> sc_output; // output file pointer signal
   sc_signal<double> dct_data[8][8]; // signal to the dc transformed
   sc_signal<double> cosine_tbl[8][8]; // signal for cos-table values
   sc_signal<bool> clk1, clk2; // clock signal for FDCT and IDCT
   FILE *input, *output; // input and output file pointers
   double cosine[8][8]; // cosine table
   double data[8][8]; // data read from signals to be zigzagged
   if (argc == 4) {
      if (!(input = fopen(argv[1], "rb")))
            // some error occurred while trying to open the input file
      printf("\nSystemC JPEG-LAB:\nCannot Open File '%s'\n",argv[1]),
                                                               exit(1);
```

Functions: Main

cont.1

```
write_read_header(input, output);
            // write the header got from the input file
make_cosine_tbl(cosine); // make the cosine table

// copy cosine and quantization tables onto corresponding signals
for (unsigned char i = 0; i < 8; i++)
     for (unsigned char j = 0; j < 8; j++)
            cosine_tbl[i][j].write(cosine[i][j]);

fdct FDCT("fdct"); // call the forward discrete transform module
// bind the ports
for (unsigned char i = 0; i < 8; i++)
     for (unsigned char j = 0; j < 8; j++) {
        FDCT.out64[i][j](dct_data[i][j]);
        FDCT.fcosine[i][j](cosine_tbl[i][j]);
     }
FDCT.clk(clk1);
FDCT.sc_input(sc_input);
```

Functions: Main

cont 2.

```
// we must use two different clocks. To make sure that when we
// want to compress, we will compress and don't decompress.
   sc_start(SC_ZERO_TIME);     // initialize the clock
   if ((choice == 'c') || (choice == 'C')) { // for compression
        while (!(feof(input))) { // create the FDCT clock signal
          clk1.write(1);          // convert the clock to high
          sc_start(10, SC_NS);  // cycle high for 10 nanoseconds
          clk1.write(0);         // start the clock as low
          sc_start(10, SC_NS); //cycle low for 10 nanoseconds
               // read all the signals into the data variable
               // to use these values in a software block
            for (unsigned char i = 0; i < 8; i++)
              for (unsigned char j = 0; j < 8; j++)
                       data[i][j] = dct_data[i][j].read();
          zigzag_quant(data, output);
               // zigzag and quantize the read data
        }
    }
}
```