Mapping High-Level Language Applications to SystemC

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Design of Embedded Systems

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Overview

- Many projects begin with a working HLL application.
  - Particularly common in multimedia and communications
- Goals
  - Maintain conformance with original application software throughout development
    - The HLL implementation serves as the gold model.
  - Profiling data and architecture considerations drive process
  - Support incremental mapping of modules
    - One accelerator at a time…
  - SystemC is well suited for use with C/C++ HLL apps.

Standards-Based Applications

- Predominant in some important domains
  - Wireless Communications
  - Networking
  - Audio, Video
- Standards are often developed using a community-developed HLL application.
  - The application embodies the standard.
- Such *reference* applications are seldom well structured or optimized.
- Full conformance to standard is crucial to success.

Steps in Moving from Reference Code to an Embedded Implementation

- Algorithm study and analysis
- Setting target performance requirements
- Understanding reference code structure
- Profiling, identification of bottlenecks
  - What functions must be accelerated to meet performance targets?
- Developing a Hardware Abstraction Layer (HAL)
- Modifying code to make it suitable for hardware
- Mapping the application onto the hardware
- Readying the application for production

From Reference Code to Embedded Implementation

- Conformance maintained at all phases of design
- Reference application used to generate module-level test vectors
- Hardware/Software co-design a natural by-product
- Hardware abstraction layer (HAL) defines the interface between application software and any special-purpose hardware
- Need a development environment supporting hardware models and application software execution
  - SystemC (informal software support)

SystemC

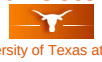
- Class library extension to C++
- Extended to support verification-specific constructs
- C++ can be intimidating to HW designers trained in Verilog or VHDL
- Software developers find it easier to integrate their programs and tools than with other ESL languages.
- Open standard effort through the Open SystemC Initiative (OSCI)
- Synthesis tools emerging in the marketplace (e.g., Forte, Mentor Graphics)

SystemC Architecture

Methodology-Specific Libraries *Master/Slave, etc.*	Layered Libraries *Verification, TLM, etc.*
Primitive Channels *Signals, FIFOs, mutexes, semaphores, etc.*	
Structure Elements *Modules* *Ports* *Interfaces* *Channels*	Data Types *4-value Logic* *Bits, Bit Vectors* *Arbitrary-Precision Integers* *Fixed-Point Types*
Event-Driven Simulation Engine *Events, Processes*	
C++ Language Standard	

Considerations in Selecting Modules for Realization as Accelerators

- Software profile data can help filter candidate modules.
- HLL function boundaries not always appropriate module boundaries
  - Some code refactoring may be necessary
- Input/output requirements also a factor
  - Transfer overhead can swamp advantage of acceleration
- Look for opportunities for module-level parallelism
  - Identify synchronization requirements
- Global variables must be eliminated from module
  - Map to arguments
- Data transfer alternatives (e.g., DMA, processor-directed)



The Hardware Abstraction Layer (HAL)

- Provides an efficient interface to hardware while maintaining application code structure.
  - From application, HW accelerator looks like a function call
  - From HW accelerator, application looks like HW/buffer
- Define functions for each HW/SW interaction, isolating hardware detail from application software.
- Provide synchronization primitives required for flow control, management of parallel activity.
- Enables mixture of hardware and software models
  - Selective use of hardware modules supports debug in emulation environment
  - Expanded verification challenge

Formalizing the HAL Interfaces

- A formal, standardized representation would be helpful.
  - Support tool-based interface generation and error-checking
  - Ease IP re-use
  - Capture constraints
  - Bridge the gap between software and hardware constraints
- The Architecture and Analysis and Design Language (AADL)
  - Originally the “Avionics Architecture Description Language”
  - Safety-critical and mission-critical applications were initial focus
  - Separates *types* (interfaces) and *implementations*
  - http://www.sei.cmu.edu/pub/documents/06.reports/pdf/06tn011.pdf

HAL Application Interface Layer

- Application Layer
  - Maps HLL function call to lower layer of HAL

```
void appFunction1(int * data, int dataSize)
{
#if HAL_ENABLED
    int i ;

    HAL_checkReadyFunction1(TRUE) ;

    for (i=0; i < dataSize ; i++)
    {
        HAL_enqueueToFunction1(data[i]) ;
    }

    HAL_startFunction1() ;
#else

    //  … Existing HLL application function code …

#endif
}
```

HAL Hardware Interface Layer

- Hardware Layer
  - Interacts with HW for synchronization, data transfers, and status queries

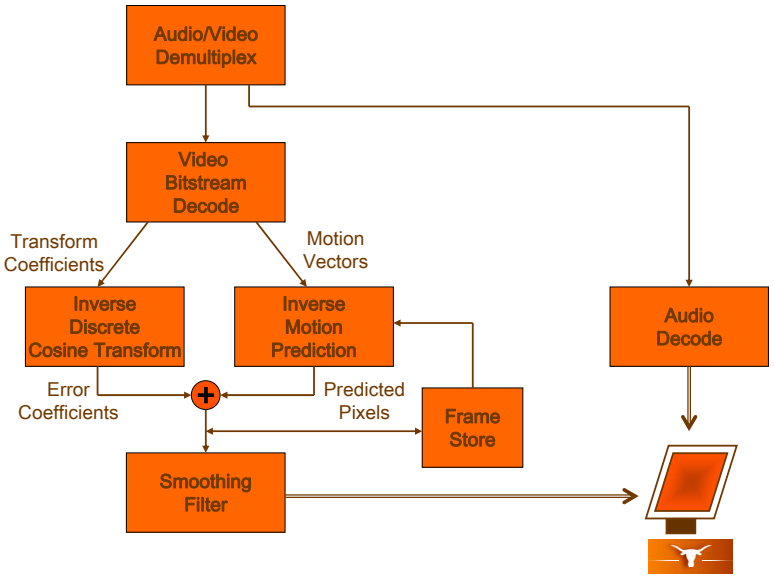
```
int HAL_waitReadyFunction1(int waitTillReady)
{
    int result ;
    do {
        result = HAL_ADR_Function1Status() ;
    } while (!result && waitTillReady) ;
    return result ;
}
```

HAL Layers

- Hardware Layer with Instrumentation
  - Can be used to capture stimuli

```
int HAL_enqueueToFunction1(int data)
{
#if HAL_GEN_VERILOG
    fprintf(pfVStim,"halFunction1InputData = %d ;\n", data) ;
#endif

    halFunction1InputQueue = data ;
}
```


Example - MPEG-2 Video Decode



Inverse Discrete Cosine Transform

- Fundamental process in most image compression algorithms
  - JPEG, MJPEG, MPEG
- Image data tends to show correlation in frequency domain.
- Forward discrete cosine transform (DCT) used during encoding
  - Intra (I) frames: coefficients are frequency-domain pixel values
  - Prediction (P) frames: coefficients are prediction errors
- Inverse discrete cosine transform (iDCT) used during decoding to recover image
- Color components processed separately

Inverse Discrete Cosine Transform

- Processing iDCTs becomes time critical for video decoding.
- Consider the case of 1080i HD video
  - Pixels per frame: 1088[1] * 1920 = 2,088,960
  - Frame rate: 30 frames per second[2]
  - Required two-dimensional 8x8 iDCTs per second: (2088960 * 30) / (8 * 8) = 244,800 iDCTs/second for luminance data alone
  - Time budget for each luminance iDCT: 4.08 uSecs (2.7 uSecs with chroma data added)

[1] Height padded to 1088 to be multiple of 16.
[2] Actually 60 interlaced fields per second

MPEG-2 iDCT Reference Software

```
#define BLSIZE 8
void dct_two_d(short int  **in, short int **coeff)
{
    register int      j1, i, j,offset;
    float    b[BLSIZE],c[BLSIZE];
    float    d[BLSIZE][BLSIZE];

    for(i=offset=0;i<8;i++,offset+=8){
       for(j=0;j<8;j++)
              b[j] = (float) in[i][j];

              /* Horizontal transform */
              for (j= 0;j<4;j++){
                     j1    = 7 - j;
                     c[j]  = b[j] + b[j1];
                     c[j1] = b[j] - b[j1];
              }

              b[0]    = c[0] + c[3];
              b[1]    = c[1] + c[2];
              b[2]    = c[1] - c[2];
              b[3]    = c[0] - c[3];
              b[4]    = c[4];
```

MPEG-2 iDCT Reference Software (2)

```
              b[5]    = (c[6] - c[5]) * f0;
              b[6]    = (c[6] + c[5]) * f0;
              b[7]    = c[7];
              d[i][0] = (b[0] + b[1]) * f4;
              d[i][4] = (b[0] - b[1]) * f4;
              d[i][2] = b[2] * f6 + b[3] * f2;
              d[i][6] = b[3] * f6 - b[2] * f2;
              c[4]    = b[4] + b[5];
              c[7]    = b[7] + b[6];
              c[5]    = b[4] - b[5];
              c[6]    = b[7] - b[6];
              d[i][1] = c[4] * f7 + c[7] * f1;
              d[i][5] = c[5] * f3 + c[6] * f5;
              d[i][7] = c[7] * f7 - c[4] * f1;
              d[i][3] = c[6] * f3 - c[5] * f5;
       }

    /* Vertical transform */
    for (i=0;i<8;i++){
       for (j=0;j<4;j++){
              j1    = 7 - j;
              c[j]  = d[j][i] + d[j1][i];
              c[j1] = d[j][i] - d[j1][i];
              }
```

MPEG-2 iDCT Reference Software (3)

```
        b[0]    = c[0] + c[3];
        b[1]    = c[1] + c[2];
        b[2]    = c[1] - c[2];
        b[3]    = c[0] - c[3];
        b[4]    = c[4];
        b[5]    = (c[6] - c[5]) * f0;
        b[6]    = (c[6] + c[5]) * f0;
        b[7]    = c[7];

        d[0][i] = (b[0] + b[1]) * f4;
        d[4][i] = (b[0] - b[1]) * f4;
        d[2][i] = b[2] * f6 + b[3] * f2;
        d[6][i] = b[3] * f6 - b[2] * f2;

        c[4]    = b[4] + b[5];
        c[7]    = b[7] + b[6];
        c[5]    = b[4] - b[5];
        c[6]    = b[7] - b[6];
        d[1][i] = c[4] * f7 + c[7] * f1;
        d[5][i] = c[5] * f3 + c[6] * f5;
        d[7][i] = c[7] * f7 - c[4] * f1;
        d[3][i] = c[6] * f3 - c[5] * f5;
}
```

MPEG-2 iDCT Reference Software (4)

```
//  Do rounding instead of just truncating.
//  Decided in 38.MPEG-meeting in Sevilla
//    Note: rounding is for accurate reference
//          If for speed encoding, you may go without this.
//          There is no discernible effect in image quality.
for (i=0;i<8;i++){
       for (j=0;j<8;j++){
              if(d[i][j] >=0) {
                     coeff[i][j] = (short int)(d[i][j] +
                                   0.499999999999);
              }
              else {
                     coeff[i][j] = (short int)(d[i][j] –
                                   0.499999999999);
              }

              // clipping range
              if(coeff[i][j] < -2048) coeff[i][j] = -2048;
              if(coeff[i][j] >  2047) coeff[i][j] =  2047;
       }
}
}
```

Observations on the Reference Code

- Floating point is expensive in hardware
- Highly sequential computation as structured
  - Two-dimensional control loop doesn't take advantage of observation that the vertical and horizontal operation sequences are identical
  - Opportunity to re-use hardware and/or software for both directions
- Final rounding operation and clipping pass over data is time-consuming
- Rounding and clipping pass highly sequential in general-purpose hardware

Conversion of Floating Point Arithmetic Operations to Integer Arithmetic

- Determine dynamic range of floating point calculations, including all intermediate values
  - Analytical approach superior when possible
  - Random and directed test vectors with range accumulation on each variable where direct analysis is not practical
- If range is too large
  - Consider pre-scaling data to narrower range.
    - Must determine if error introduced is acceptable
  - Re-scale the results at end of computation
  - Restructure/reorder arithmetic operations to reduce dynamic range for intermediate calculations.

Modifying the iDCT Code for Hardware

- Integer-only computation needed
- Mapping the reference code directly into an integer representation
  - Dynamic range of data within 32-bit integer capacity
  - Only barely
- Can the algorithm be modified to reduce the dynamic range required?
  - Can 16-bit intermediate values suffice?
- What loss of accuracy will occur?

MPEG-2 Integer iDCT Software

```
#define W1 2841 /* 2048*sqrt(2)*cos(1*pi/16) */
#define W2 2676 /* 2048*sqrt(2)*cos(2*pi/16) */
#define W3 2408 /* 2048*sqrt(2)*cos(3*pi/16) */
#define W5 1609 /* 2048*sqrt(2)*cos(5*pi/16) */
#define W6 1108 /* 2048*sqrt(2)*cos(6*pi/16) */
#define W7 565  /* 2048*sqrt(2)*cos(7*pi/16) */

/* row (horizontal) IDCT
 *           7                       pi         1
 * dst[k] = sum c[l] * src[l] * cos( -- * ( k + - ) * l )
 *          l=0                      8          2
 * where: c[0]    = 128
 *        c[1..7] = 128*sqrt(2)
 */

static void idctrow(short *blk)
{
  int x0, x1, x2, x3, x4, x5, x6, x7, x8;

  if (!((x1 = blk[4]<<11) | (x2 = blk[6]) | (x3 = blk[2]) |
       (x4 = blk[1]) | (x5 = blk[7]) | (x6 = blk[5]) | (x7 = blk[3])))
  {
    blk[0]=blk[1]=blk[2]=blk[3]=blk[4]=blk[5]=blk[6]=blk[7]=blk[0]<<3;
    return;
  }
```

MPEG-2 Integer iDCT Software (2)

```
x0 = (blk[0]<<11) + 128; /* for proper rounding in the fourth stage */

/* first stage */
x8 = W7*(x4+x5);
x4 = x8 + (W1-W7)*x4;
x5 = x8 - (W1+W7)*x5;
x8 = W3*(x6+x7);
x6 = x8 - (W3-W5)*x6;
x7 = x8 - (W3+W5)*x7;

/* second stage */
x8 = x0 + x1;
x0 -= x1;
x1 = W6*(x3+x2);
x2 = x1 - (W2+W6)*x2;
x3 = x1 + (W2-W6)*x3;
x1 = x4 + x6;
x4 -= x6;
x6 = x5 + x7;
x5 -= x7;
```

MPEG-2 Integer iDCT Software (3)

```
/* third stage */
x7 = x8 + x3;
x8 -= x3;
x3 = x0 + x2;
x0 -= x2;
x2 = (181*(x4+x5)+128)>>8;
x4 = (181*(x4-x5)+128)>>8;

/* fourth stage */
blk[0] = (x7+x1)>>8;
blk[1] = (x3+x2)>>8;
blk[2] = (x0+x4)>>8;
blk[3] = (x8+x6)>>8;
blk[4] = (x8-x6)>>8;
blk[5] = (x0-x4)>>8;
blk[6] = (x3-x2)>>8;
blk[7] = (x7-x1)>>8;
}
```

MPEG-2 Integer iDCT Software (4)

```
/* column (vertical) IDCT
 *             7                         pi         1
 * dst[8*k] = sum c[l] * src[8*l] * cos( -- * ( k + - ) * l )
 *            l=0                        8          2
 *
 * where: c[0]    = 1/1024
 *        c[1..7] = (1/1024)*sqrt(2)
 */
static void idctcol(short *blk)
{
  int x0, x1, x2, x3, x4, x5, x6, x7, x8;
  /* shortcut */
  if (!((x1 = (blk[8*4]<<8)) | (x2 = blk[8*6]) | (x3 = blk[8*2]) |
      (x4 = blk[8*1]) | (x5 = blk[8*7]) | (x6 = blk[8*5]) |
      (x7 = blk[8*3])))
  {
      blk[8*0]=blk[8*1]=blk[8*2]=blk[8*3]=
               blk[8*4]=blk[8*5]=blk[8*6]=blk[8*7]=
          gVideoData->iclp[(blk[8*0]+32)>>6];
    return;
  }

  x0 = (blk[8*0]<<8) + 8192;
```

MPEG-2 Integer iDCT Software (5)

```
  /* first stage */
  x8 = W7*(x4+x5) + 4;
  x4 = (x8+(W1-W7)*x4)>>3;
  x5 = (x8-(W1+W7)*x5)>>3;
  x8 = W3*(x6+x7) + 4;
  x6 = (x8-(W3-W5)*x6)>>3;
  x7 = (x8-(W3+W5)*x7)>>3;

  /* second stage */
  x8 = x0 + x1;
  x0 -= x1;
  x1 = W6*(x3+x2) + 4;
  x2 = (x1-(W2+W6)*x2)>>3;
  x3 = (x1+(W2-W6)*x3)>>3;
  x1 = x4 + x6;
  x4 -= x6;
  x6 = x5 + x7;
  x5 -= x7;
```

MPEG-2 Integer iDCT Software (6)

```
  /* third stage */
  x7 = x8 + x3;
  x8 -= x3;
  x3 = x0 + x2;
  x0 -= x2;
  x2 = (181*(x4+x5)+128)>>8;
  x4 = (181*(x4-x5)+128)>>8;

  /* fourth stage */
  blk[8*0] = gVideoData->iclp[(x7+x1)>>14];
  blk[8*1] = gVideoData->iclp[(x3+x2)>>14];
  blk[8*2] = gVideoData->iclp[(x0+x4)>>14];
  blk[8*3] = gVideoData->iclp[(x8+x6)>>14];
  blk[8*4] = gVideoData->iclp[(x8-x6)>>14];
  blk[8*5] = gVideoData->iclp[(x0-x4)>>14];
  blk[8*6] = gVideoData->iclp[(x3-x2)>>14];
  blk[8*7] = gVideoData->iclp[(x7-x1)>>14];
}
```

MPEG-2 Integer iDCT Software (7)

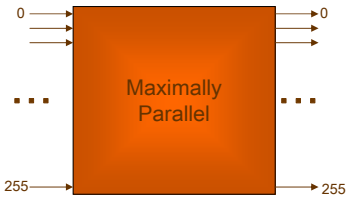
```
/* two dimensional inverse discrete cosine transform */
void Fast_IDCT(short **inblock, short** outblock)
{
  short *block =  *inblock;

  int i;

  for (i=0; i<8; i++)
    idctrow(block+8*i);

  for (i=0; i<8; i++)
    idctcol(block+i);
}
```

Comments on the Integer iDCT Variant

- Only slight loss of accuracy (>40 dB pSNR for iDCT)
  - Anything > ~30 dB pSNR is usually deemed okay for video
- Use of 16-bit integers allows efficient mapping to MMX instructions for faster execution on a general-purpose machine.
- Shifts are efficiently implemented in hardware.
- Opportunity for early cut-off in software
- Note similarity of horizontal and vertical processing

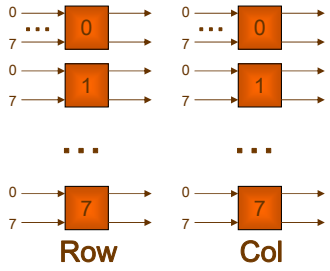
Options for Accelerating the iDCT

- Simplest: use existing MMX instructions on PC
- Highest performance: map into 256-input, 256-output maximally parallel logic
  - Fast, but very large
  - No flexibility



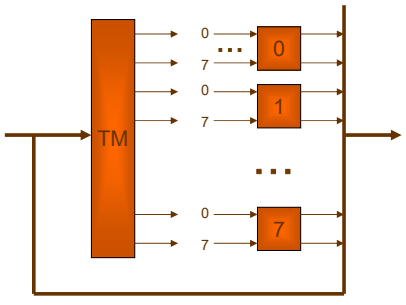
Options for Accelerating the iDCT

- High performance: translate the simple C to Verilog, synthesize one-dimensional vector iDCT, replicate the module 8 times for each dimension
  - Simpler than maximally parallel concept
  - Still no flexibility



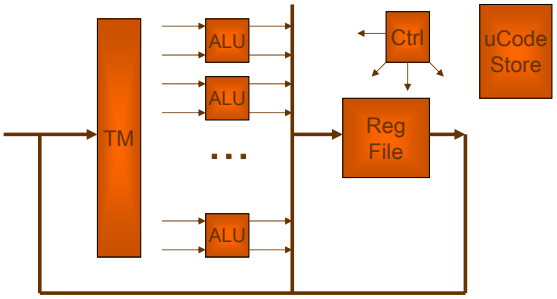
Options for Accelerating the iDCT

- High performance but smaller: reuse one-dimensional slices for row and column
  - "Transpose memory" serves as buffer
  - Still no flexibility



Options for Accelerating the iDCT

- High performance with increased flexibility: microcode engine with SIMD
  - "Transpose memory" serves as buffer
  - Works on 8x8 (or smaller) blocks for iDCT, DCT, forward and inverse integer transform (H.264)



Integer iDCT for Microcode Engine

```
static void idct_x2(int i0, int i1, int i2, int i3,   /* input values */
                    int i4, int i5, int i6, int i7,
                    int j0, int j1, int j2, int j3,
                    int j4, int j5, int j6, int j7,
                    char isRow, /* non-zero if row */
                    int * o0, int * o1, int * o2, int * o3,  /* outputs */
                    int * o4, int * o5, int * o6, int * o7,
                    int * p0, int * p1, int * p2, int * p3,
                    int * p4, int * p5, int * p6, int * p7)

{
        int r0, r1, r2, r3, r4, r5, r6, r7 ;
        /* 1 */
        r0  = i1 * C7 ;
        /* 2 */
        r1  = i7 * C1 ;
        /* 3 */
        r2  = i5 * C3 ;
        /* 4 */
        r3  = i3 * C5 ;
        r0  = (r0 - r1) >> (isRow ? 0 : 8) ;  /* e */
        /* 5 */
        r1  = i7 * C7 ;
```

Integer iDCT for Microcode Engine (2)

```
/* 6 */
r3   = i1 * C1 ;
r2  = (r2 - r3) >> (isRow ? 0 : 8) ; /* f */
/* 7 */
r7  = i3 * C3 ;
/* 8 */
r3  = i5 * C5 ;
r1  = (r1 + r3) >> (isRow ? 0 : 8) ; /* h */
/* 9 */
r4  = i6 * C6 ;
r0  = r0 + r2 ;          /* b[4] */
r2  = (r0 - r2) >> 3 ;/* b1[5] */
/* 10 */
r5  = i2 * C2 ;
r3  = (r7 + r3) >> (isRow ? 0 : 8) ; /* g */
/* 11 */
r7  = i6 * C2 ;
r1  = (r1 - r3) >> 3 ;               /* b1[6] */
r3  = r1 + r3 ;                             /* b[7] */
/* 12 */
r6  = i2 * C6 ;
r4  = (r4 + r5) >> (isRow ? 0 : 8) ; /* b1[3] */
r1  = r1 - r2 ;
```

Integer iDCT for Microcode Engine (3)

```
/* 13 */
r6  = (r6 - r7) >> (isRow ? 0 : 8) ; /* b1[2] */
r7  = i0 + i4 ;
/* 14 */
r7  = (r7 * C4) >> (isRow ? 0 : 8) ; /* b1[0] */
r2  = r1 + r2 ;
r5  = i0 - i4 ;
/* 15 */
r5  = (r5 * C4) >> (isRow ? 0 : 8) ; /* b1[1] */
r7  = r7 + r4 ;                             /* b[0] */
r4  = r7 - r4 ;                             /* b[3] */
/* 16 */
r1  = (r1 * C0) >> 8 ;               /* b[5] */
r5  = r5 + r6 ;                             /* b[1] */
r6  = r5 - r6 ;                             /* b[2] */
/* 17 */
r2  = (r2 * C0) >> 8 ;               /* b[6] */
```

Integer iDCT for Microcode Engine (4)

```
/* 18 */
r0  = j1 * C7 ;
a0  = (r4 + r0) ;
*o3 = (int) (a0 + (isRow ? 0 :       /* d[3] */
                   ((a0 > 0) ? 1023 : 1024))) >> (isRow ? 3 : 11);
if (!isRow)
{
       if (*o3 > 255)
              *o3 = 255 ;
       else if (*o3 < -255)
              *o3 = -255 ;
}
a1  = (r4 - r0) ;
*o4 = (int) (a1 + (isRow ? 0 :      /* d[4] */
                   ((a1 > 0) ? 1023 : 1024))) >> (isRow ? 3 : 11);
if (!isRow)
{
       if (*o4 > 255)
              *o4 = 255 ;
       else if (*o4 < -255)
              *o4 = -255 ;
}
...
```

Mapping the Hardware Functions to SystemC Models

- HAL separates application software from SystemC “collars” (application-layer HAL) on functions to be implemented in hardware
- Initially, SystemC model is nothing more than functional HLL code with ports.
- Follow-on with successive refinements to model reflecting hardware structural decomposition.
  - Useful for simulation-based debugging of microcode engines
- Alternatively, refine model to synthesizable form
- All models verified against reference software

SystemC HAL Interface for Integer iDCT

```
#include "systemc.h"
SC_MODULE(idct)                       // declare iDCT sc_module
{
  sc_in_clk ck ;
  sc_in<sc_bv<32>>  indata ;          // input signal ports
  sc_in<sc_bv<8>>   addr ;
  sc_in<sc_bit>     wr, sel, go ;
  sc_out<sc_bv<32>> outdata ;

  unsigned int tm[BLSIZE][BLSIZE] ;  // transpose memory

  // Interface to the bus
  if (sel)
  {
    if (wr)
    {
      tm[addr>>4][addr&0xF] = indata ;
    }
    else if (!go)
    {
      outdata = tm[addr>>4][addr&0xF] ;
    }
```


SystemC HAL Interface for Integer iDCT (2)

```
    else
    {
      int i ;
      for (i=0; i < 8 ; i++)
      {
        // Call behavioral function for rows
        idct_x2(tm[i][0], tm[i][1], tm[i][2], tm[i][3],
                tm[i][4], tm[i][5], tm[i][6], tm[i][7],
                1,
                &tm[0][i], &tm[1][i], &tm[2][i], &tm[3][i],
                &tm[4][i], &tm[5][i], &tm[6][i], &tm[7][i]) ;
      }

      for (i=0; i < 8 ; i++)
      {
        // Call behavioral function for columns
        idct_x2(tm[0][i], tm[1][i], tm[2][i], tm[3][i],
                tm[4][i], tm[5][i], tm[6][i], tm[7][i],
                0,
                &tm[i][0], &tm[i][1], &tm[i][2], &tm[i][3],
                &tm[i][4], &tm[i][5], &tm[i][6], &tm[i][7]) ;
      }
    }
}
```

Things to Consider

- Application profiling with SystemC models presents a challenge.
  - "Back out" profile data and overhead for hardware models
  - Determine cycle counts of the hardware models
  - Build spreadsheet to compute adjusted profile results with clock cycle as parameter
- An instrumented HAL can be useful in assessing system performance.
  - Track bus activity, memory reference patterns, bandwidth requirements.

Conclusions

- For target applications based on reference software, or for any project that begins with "gold" application software, SystemC can provide a smooth path from software to embedded system.
  - Select candidate models based on profile data or by known performance requirements (e.g., frame rates for video decode)
  - Convert floating point operations to integer to reduce HW complexity and processing time
  - Consider interface issues
    - Polling or interrupt for control events
    - DMA or processor-directed transfers

Conclusions (continued)

- Map functions to hardware by first “collaring” them with port interfaces around the pure behavior.
- Increase detail and accuracy of SystemC model as design progresses.
- Use reference application as test bench throughout.
- Use HAL to hide hardware detail from application and to instrument the model.

- Maintain a working model that matches the gold model throughout the entire design.