# EECS 221: System-on-Chip Software Synthesis Lecture 2

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## Lecture 2: Overview

- Assignment 1
- System-on-Chip Design with SpecC
  - Abstraction Levels
  - Design Methodology
  - The SpecC Model
  - The SpecC Language

## Assignment 1

- Introduction to Software Synthesis using SpecC
  - Reference Example
    - Anti-lock brake system
      - ARM7TDMI core
      - AMBA AHB system bus
      - CAN controller
  - Read Technical Report CECS_TR_06_06
    - "Modeling, Simulation and Synthesis in an Embedded Software Design Flow for an ARM Processor"
      - by G. Schirner, G. Sachdeva, A. Gerstlauer, R. Doemer
    - http://www.ics.uci.edu/~doemer/publications/CECS_TR_06_06.pdf

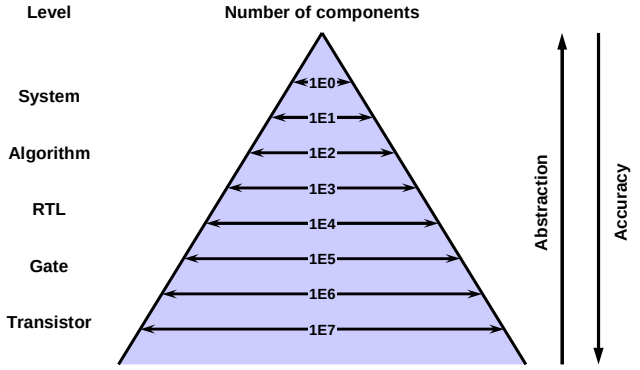


## System-on-Chip Design with SpecC

- Abstraction Levels
- Design Methodology
- The SpecC Model
- The SpecC Language

# Abstraction Levels

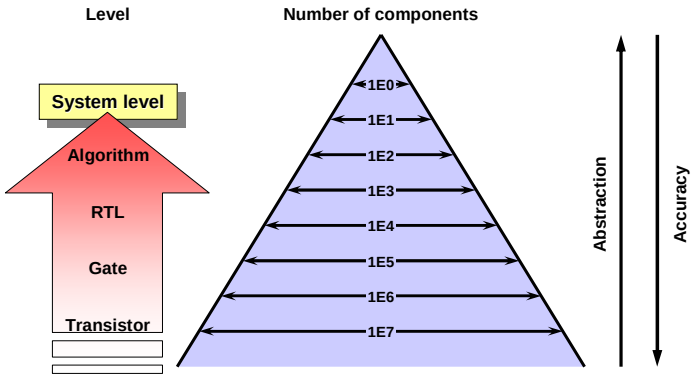
- Embedded system design faces tremendous increase of design complexity

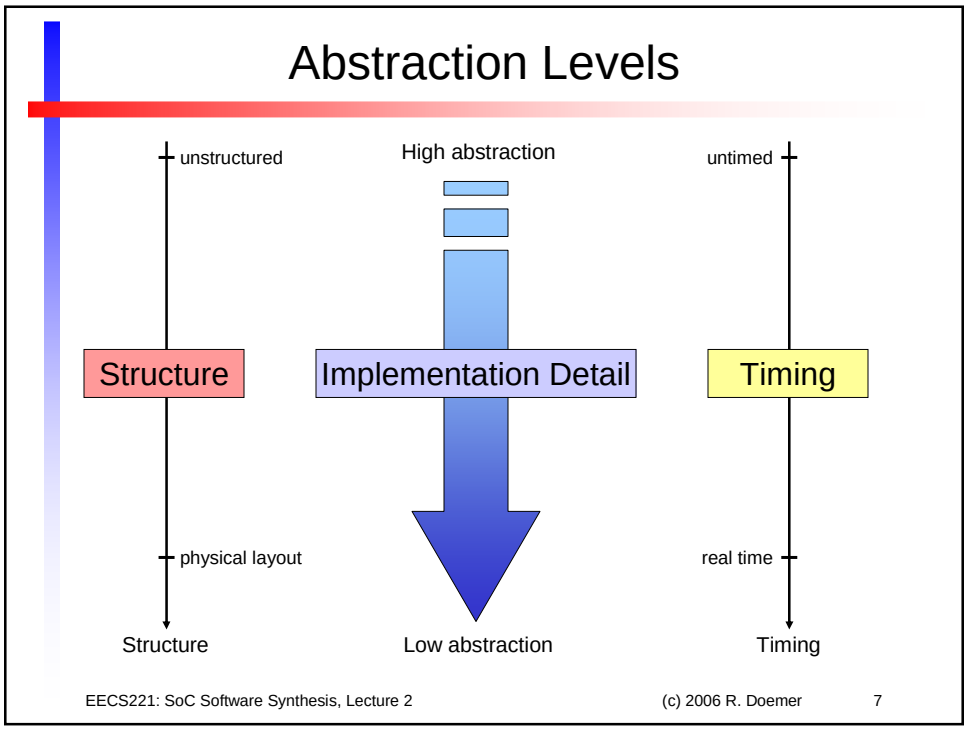





# Abstraction Levels

- Embedded system design faces tremendous increase of design complexity
- Move to higher levels of abstraction!




Abstraction Levels
unstructured
High abstraction
untimed
Structure
Implementation Detail
Timing
physical layout
real time
Structure
Low abstraction
Timing
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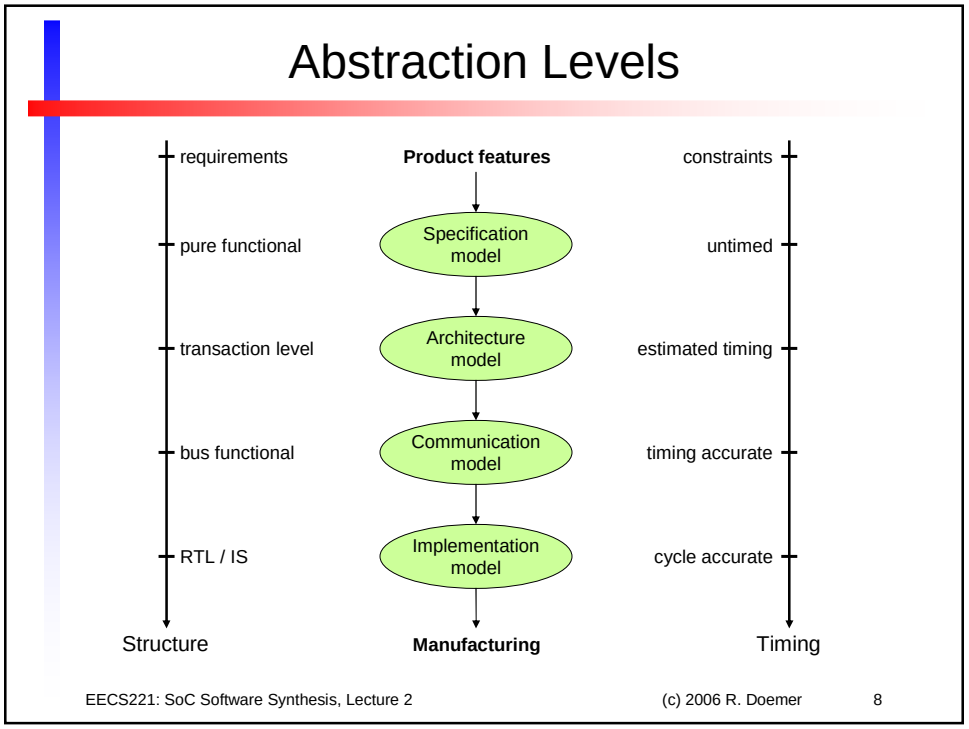
Abstraction Levels
requirements
Product features
constraints
pure functional
Specification model
untimed
transaction level
Architecture model
estimated timing
bus functional
Communication model
timing accurate
RTL / IS
Implementation model
cycle accurate
Structure
Manufacturing
Timing
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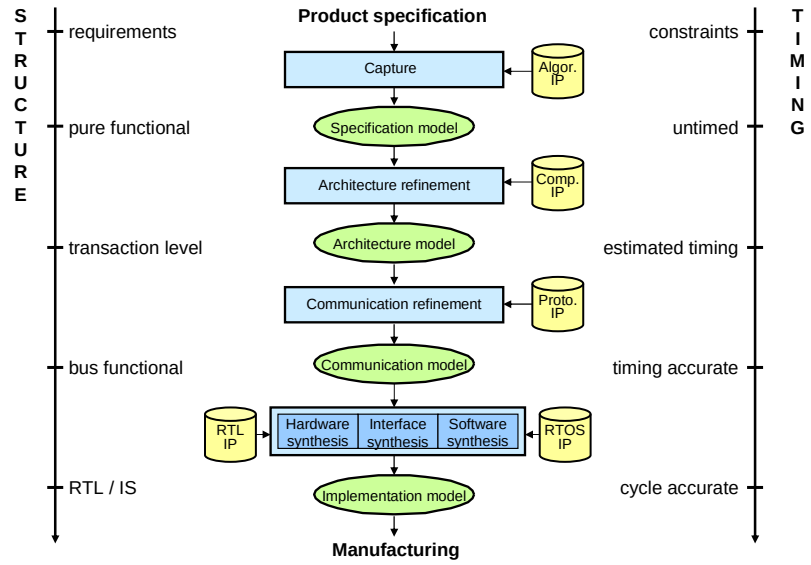
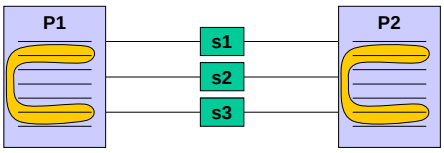
# Design Methodology






# The SpecC Model

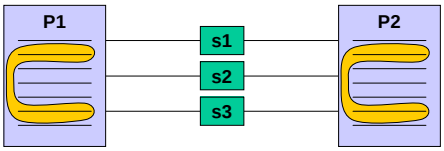
- Traditional model




  - Processes and signals
  - Mixture of computation and communication
  - Automatic replacement impossible

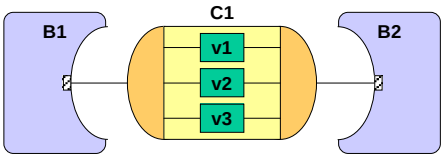
# The SpecC Model

- Traditional model




  - Processes and signals
  - Mixture of computation and communication
  - Automatic replacement impossible

- SpecC model

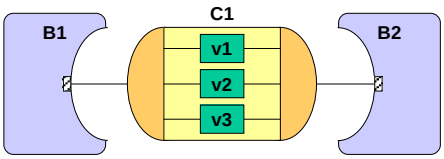



  - Behaviors and channels
  - Separation of computation and communication
  - Plug-and-play



# The SpecC Model

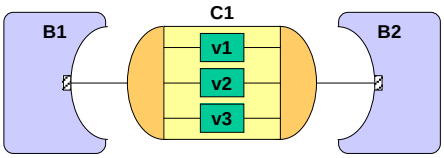
- Protocol Inlining
  - Specification model
  - Exploration model



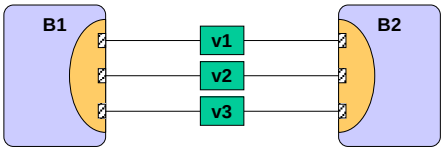

    - Computation in behaviors
    - Communication in channels

# The SpecC Model

- Protocol Inlining
  - Specification model
  - Exploration model




    - Computation in behaviors
    - Communication in channels
  - Implementation model




    - Channel disappears
    - Communication inlined into behaviors
    - Wires exposed



# The SpecC Language

- Overview
  - Foundation
  - Types
  - Structural and behavioral hierarchy
  - Concurrency
  - State transitions
  - Exception handling
  - Communication
  - Synchronization
  - Timing
  - (RTL)

## The SpecC Language

- Foundation: ANSI-C
  - Software requirements are fully covered
  - SpecC is a true superset of ANSI-C
  - Every C program is a SpecC program
  - Leverage of large set of existing programs
  - Well-known
  - Well-established



## The SpecC Language

- Foundation: ANSI-C
  - Software requirements are fully covered
  - SpecC is a true superset of ANSI-C
  - Every C program is a SpecC program
  - Leverage of large set of existing programs
  - Well-known
  - Well-established
- SpecC has extensions needed for hardware
  - Minimal, orthogonal set of concepts
  - Minimal, orthogonal set of constructs
- SpecC is a real language
  - Not just a class library

# The SpecC Language

- ANSI-C
  - Program is set of functions
  - Execution starts from function `main()`

```
/* HelloWorld.c */

#include <stdio.h>

void main(void)
{
  printf("Hello World!\n");
}
```



# The SpecC Language

- ANSI-C
  - Program is set of functions
  - Execution starts from function `main()`

```
/* HelloWorld.c */

#include <stdio.h>

void main(void)
{
  printf("Hello World!\n");
}
```

- SpecC
  - Program is set of behaviors, channels, and interfaces
  - Execution starts from behavior `Main.main()`

```
// HelloWorld.sc

#include <stdio.h>

behavior Main
{
  void main(void)
  {
    printf("Hello World!\n");
  }
};
```

# The SpecC Language

- SpecC types
  - Support for all ANSI-C types
    - predefined types (**`int`**, **`float`**, **`double`**, …)
    - composite types (arrays, pointers)
    - user-defined types (**`struct`**, **`union`**, **`enum`**)
  - Boolean type: Explicit support of truth values
    - **`bool`** `b1 =` **`true;`**
    - **`bool`** `b2 =` **`false;`**
  - Bit vector type: Explicit support of bit vectors of arbitrary length
    - **`bit`**`[15:0] bv = 1111000011110000b;`
  - Event type: Support of synchronization
    - **`event`** `e;`
  - Buffered and signal types: Explicit support of RTL concepts
    - **`buffered`**`[clk]` **`bit`**`[32] reg;`
    - **`signal bit`**`[16] address;`



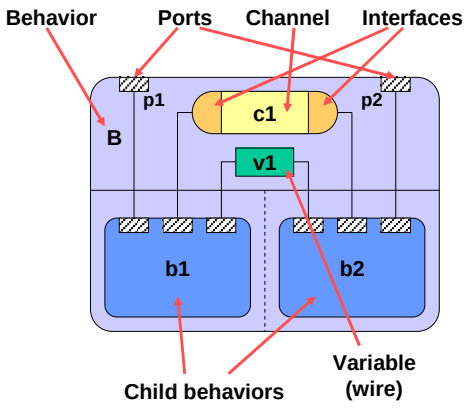
# The SpecC Language

- Bit vector type
  - signed or unsigned
  - arbitrary length
  - standard operators
    - logical operations
    - arithmetic operations
    - comparison operations
    - type conversion
    - type promotion
  - concatenation operator
    - `a @ b`
  - slice operator
    - `a[l:r]`

```
typedef bit[7:0] byte;  // type definition
byte             a;
unsigned bit[16] b;

bit[31:0] BitMagic(bit[4] c, bit[32] d)
{
 bit[31:0] r;

 a = 11001100b;          // constant
 b = 1111000011110000ub; // assignment

 b[7:0] = a;             // sliced access
 b = d[31:16];

 if (b[15])              // single bit
    b[15] = 0b;          // access

 r = a @ d[11:0] @ c     // concatenation
     @ 11110000b;

 a = ~(a & 11110000);    // logical op.
 r += 42 + 3*a;          // arithmetic op.

 return r;
}
```

# The SpecC Language

- Basic structure
  - Top behavior
  - Child behaviors
  - Channels
  - Interfaces
  - Variables (wires)
  - Ports

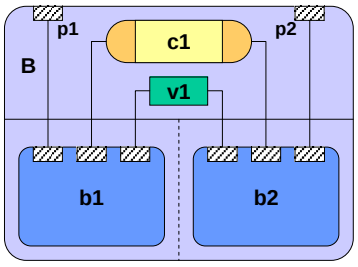





# The SpecC Language

- Basic structure

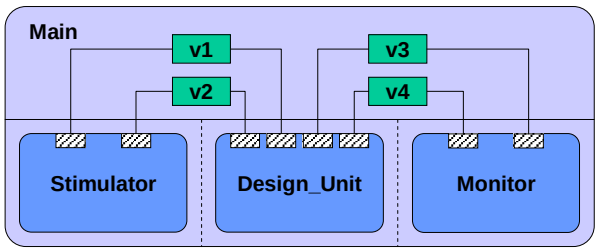
```
interface I1
{
  bit[63:0] Read(void);
  void Write(bit[63:0]);
};

channel C1 implements I1;

behavior B1(in int, I1, out int);

behavior B(in int p1, out int p2)
{
  int v1;
  C1  c1;
  B1  b1(p1, c1, v1),
      b2(v1, c1, p2);

  void main(void)
  { par {
      b1;
      b2;
    }
  }
};
```




SpecC 2.0:
if `b` is a behavior instance,
`b;` is equivalent to `b.main();`

# The SpecC Language

- Typical test bench
  - Top-level behavior: `Main`
  - Stimulator provides test vectors
  - Design unit under test
  - Monitor observes and checks outputs

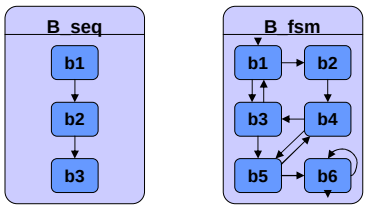





# The SpecC Language

- Behavioral hierarchy

**Sequential execution** | **FSM execution** | **Concurrent execution** | **Pipelined execution**

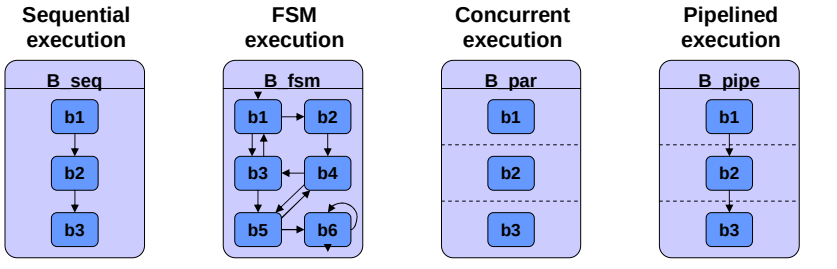



```
behavior B_seq
{
 B b1, b2, b3;

 void main(void)
 {  b1;
    b2;
    b3;
  }
};
```

```
behavior B_fsm
{
 B b1, b2, b3,
   b4, b5, b6;
 void main(void)
 { fsm { b1:{…}
         b2:{…}
         …}
  }
};
```

# The SpecC Language

- Behavioral hierarchy




```
behavior B_seq
{
 B b1, b2, b3;

 void main(void)
 {  b1;
    b2;
    b3;
  }
};
```

```
behavior B_fsm
{
 B b1, b2, b3,
   b4, b5, b6;
 void main(void)
 { fsm { b1:{…}
         b2:{…}
         …}
  }
};
```

```
behavior B_par
{
 B b1, b2, b3;

 void main(void)
 { par{ b1;
        b2;
        b3; }
  }
};
```

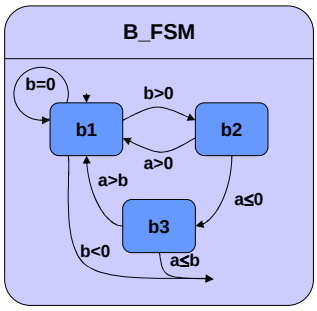
```
behavior B_pipe
{
 B b1, b2, b3;

 void main(void)
 { pipe{ b1;
         b2;
         b3; }
  }
};
```



# The SpecC Language

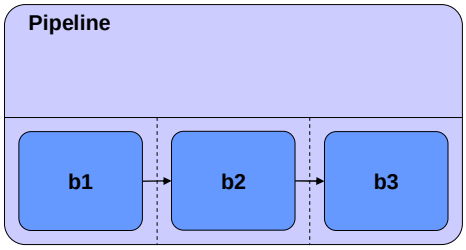
- Finite State Machine (FSM)
  - Explicit state transitions
    - triple < *current_state, condition, next_state* >
    - **fsm** { <*current_state*> : { **if** <*condition*> **goto** <*next_state*> } … }
  - Moore-type FSM
  - Mealy-type FSM

```
behavior B_FSM(in int a, in int b)
{
 B b1, b2, b3;

 void main(void)
 { fsm { b1:{ if (b<0) break;
              if (b==0) goto b1;
              if (b>0) goto b2; }
         b2:{ if (a>0) goto b1; }
         b3:{ if (a>b) goto b1; }
       }
 }
};
```



# The SpecC Language

- Pipeline
  - Explicit execution in pipeline fashion
    - **pipe** { <*instance_list*> };

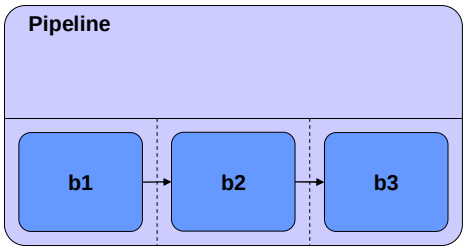



```
behavior Pipeline
{



 Stage1 b1;
 Stage2 b2;
 Stage3 b3;

 void main(void)
 {

   pipe
       { b1;
         b2;
         b3;
        }
  }
};
```



# The SpecC Language

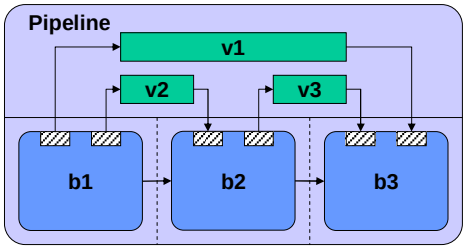
- Pipeline
  - Explicit execution in pipeline fashion
    - **pipe** { <*instance_list*> };
    - **pipe** (<*init*>; <*cond*>; <*incr*>) { … }




```
behavior Pipeline
{



 Stage1 b1;
 Stage2 b2;
 Stage3 b3;

 void main(void)
 {
   int i;
   pipe(i=0; i<10; i++)
       { b1;
         b2;
         b3;
        }
  }
};
```

# The SpecC Language

- Pipeline
  - Explicit execution in pipeline fashion
    - **pipe** { <*instance_list*> };
    - **pipe** (<*init*>; <*cond*>; <*incr*>) { … }
  - Support for automatic buffering

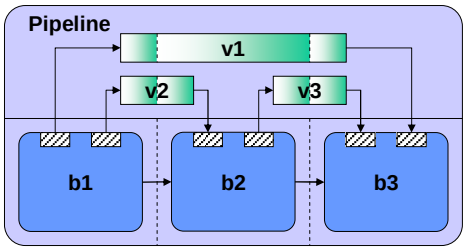



```
behavior Pipeline
{
 int v1;
 int v2;
 int v3;

 Stage1 b1(v1, v2);
 Stage2 b2(v2, v3);
 Stage3 b3(v3, v1);

 void main(void)
 {
   int i;
   pipe(i=0; i<10; i++)
        { b1;
          b2;
          b3;
        }
  }
};
```



# The SpecC Language

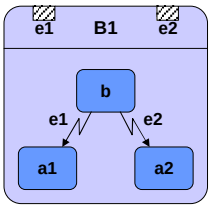
- Pipeline
  - Explicit execution in pipeline fashion
    - **pipe** { <*instance_list*> };
    - **pipe** (<*init*>; <*cond*>; <*incr*>) { … }
  - Support for automatic buffering
    - **piped** […] <*type*> <*variable_list*>;




```
behavior Pipeline
{
 piped piped int v1;
 piped int v2;
 piped int v3;

 Stage1 b1(v1, v2);
 Stage2 b2(v2, v3);
 Stage3 b3(v3, v1);

 void main(void)
 {
   int i;
   pipe(i=0; i<10; i++)
        { b1;
          b2;
          b3;
        }
  }
};
```

# The SpecC Language

- Exception handling
  - Abortion
  - Interrupt

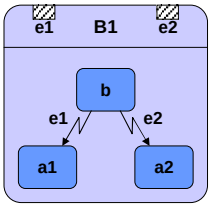


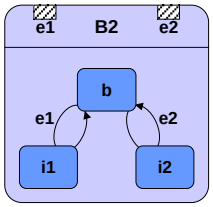

```
behavior B1(in event e1, in event e2)
{
 B b, a1, a2;

 void main(void)
 { try { b; }
   trap (e1) { a1; }
   trap (e2) { a2; }
  }
};
```



# The SpecC Language

- Exception handling
  - Abortion
  - Interrupt



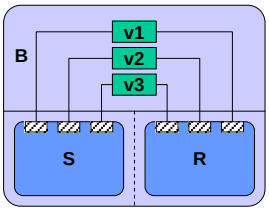




```
behavior B1(in event e1, in event e2)
{
 B b, a1, a2;

 void main(void)
 { try { b; }
   trap (e1) { a1; }
   trap (e2) { a2; }
  }
};
```

```
behavior B2(in event e1, in event e2)
{
 B b, i1, i2;

 void main(void)
 { try { b; }
   interrupt (e1) { i1; }
   interrupt (e2) { i2; }
  }
};
```

# The SpecC Language

- Communication
  - via shared variable

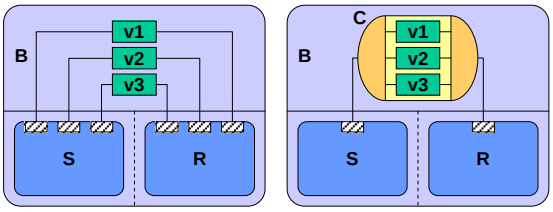



**Shared memory**



# The SpecC Language

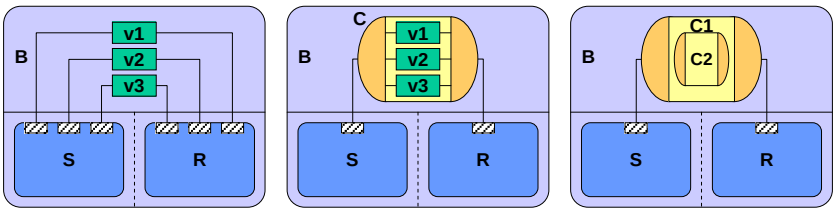
- Communication
  - via shared variable
  - via virtual channel




**Shared memory** **Message passing**

# The SpecC Language

- Communication
  - via shared variable
  - via virtual channel
  - via hierarchical channel

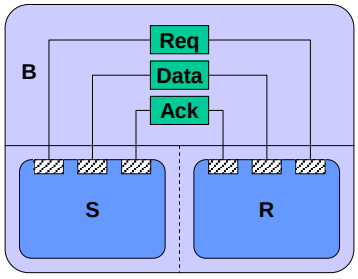



**Shared memory** **Message passing** **Protocol stack**



# The SpecC Language

- Synchronization
  - Event type
    - **event** <*event_List*>;
  - Synchronization primitives
    - **wait** <*event_list*>;
    - **notify** <*event_list*>;
    - **notifyone** <*event_list*>;

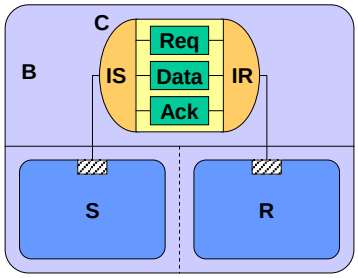



```
behavior S(out event Req,
           out float Data,
           in  event Ack)
{
 float X;
 void main(void)
 { ...
   Data = X;
   notify Req;
   wait Ack;
   ...
 }
};
```

```
behavior R(in  event Req,
           in  float Data,
           out event Ack)
{
 float Y;
 void main(void)
 { ...
   wait Req;
   Y = Data;
   notify Ack;
   ...
 }
};
```

# The SpecC Language

- Communication
  - Interface class
    - **interface** <*name*> { <*declarations*> };
  - Channel class
    - **channel** <*name*> **implements** <*interfaces*> { <*implementations*> };




```
interface IS
{
 void Send(float);
};
interface IR
{
 float Receive(void);
};
```

```
behavior S(IS Port)
{
 float X;
 void main(void)
 { ...
   Port.Send(X);
   ...
 }
};
```

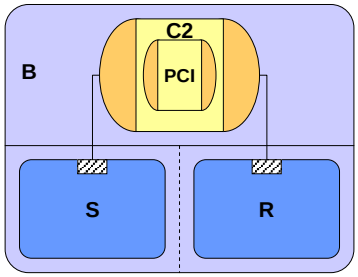
```
behavior R(IR Port)
{
 float Y;
 void main(void)
 {...
  Y=Port.Receive();
  ...
 }
};
```

```
channel C
    implements IS, IR
{
 event Req;
 float Data;
 event Ack;

 void Send(float X)
 { Data = X;
   notify Req;
   wait Ack;
 }
 float Receive(void)
 { float Y;
   wait Req;
   Y = Data;
   notify Ack;
   return Y;
 }
};
```



# The SpecC Language

- Hierarchical channel
  - Virtual channel implemented by standard bus protocol
    - example: PCI bus




```
interface PCI_IF
{
 void Transfer(
      enum Mode,
      int NumBytes,
      int Address);
};
```

```
interface IS
{
 void Send(float);
};
interface IR
{
 float Receive(void);
};
```

```
behavior S(IS Port)
{
 float X;
 void main(void)
 { ...
   Port.Send(X);
   ...
 }
};
```

```
channel PCI
   implements PCI_IF;

channel C2
   implements IS, IR
{
 PCI Bus;
 void Send(float X)
 { Bus.Transfer(
       PCI_WRITE,
       sizeof(X),&X);
 }
 float Receive(void)
 { float Y;
   Bus.Transfer(
       PCI_READ,
       sizeof(Y),&Y);
   return Y;
 }
};
```

```
behavior R(IR Port)
{
 float Y;
 void main(void)
 {...
  Y=Port.Receive();
  ...
 }
};
```

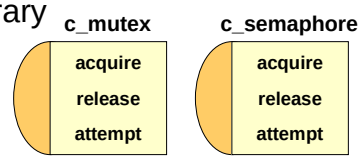
# The SpecC Language

- SpecC Standard Channel Library
  - introduced with SpecC Language Version 2.0
  - includes support for
    - mutex
    - semaphore
    - critical section
    - barrier
    - token
    - queue
    - handshake
    - double handshake
    - …



# The SpecC Language

- SpecC Standard Channel Library
  - mutex channel
  - semaphore channel



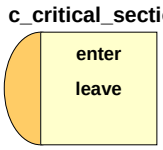

```
interface i_semaphore
{
  void acquire(void);
  void release(void);
  void attempt(void);
};
```

```
channel c_mutex
  implements i_semaphore;
```

```
channel c_semaphore(
    in const unsigned long c)
  implements i_semaphore;
```

# The SpecC Language

- SpecC Standard Channel Library
  - mutex channel
  - semaphore channel
  - critical section



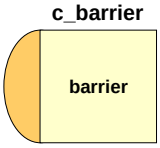

```
interface i_critical_section
{
  void enter(void);
  void leave(void);
};
```

```
channel c_critical_section
  implements i_critical_section;
```



# The SpecC Language

- SpecC Standard Channel Library
  - mutex channel
  - semaphore channel
  - critical section
  - barrier

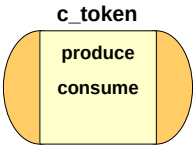



```
interface i_barrier
{
  void barrier(void);
};
```

```
channel c_barrier(
     in unsigned long n)
  implements i_barrier;
```

# The SpecC Language

- SpecC Standard Channel Library
  - mutex channel
  - semaphore channel
  - critical section
  - barrier
  - token




```
interface i_token
{
  void consume(unsigned long n);
  void produce(unsigned long n);
};
```

```
interface i_consumer
{
  void consume(unsigned long n);
};
```

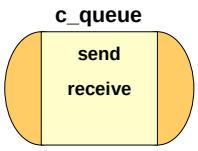
```
interface i_producer
{
  void produce(unsigned long n);
};
```

```
channel c_token
  implements i_consumer,
             i_producer,
             i_token;
```



# The SpecC Language

- SpecC Standard Channel Library
  - mutex channel
  - semaphore channel
  - critical section
  - barrier
  - token
  - queue




```
interface i_tranceiver
{
  void receive(void *d, unsigned long l);
  void send(void *d, unsigned long l);
};
```

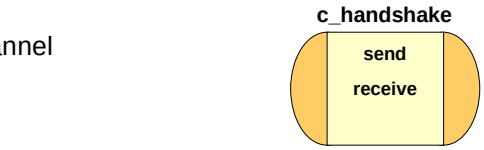
```
interface i_receiver
{
  void receive(void         *d,
               unsigned long l);
};
```

```
interface i_sender
{
  void send(void         *d,
            unsigned long l);
};
```

```
channel c_queue(
     in const unsigned long s)
  implements i_receiver,
             i_sender,
             i_tranceiver;
```

# The SpecC Language

- SpecC Standard Channel Library
  - mutex channel
  - semaphore channel
  - critical section
  - barrier
  - token
  - queue
  - handshake




```
interface i_receive
{
  void receive(void);
};
```

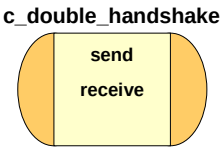
```
interface i_send
{
  void send(void);
};
```

```
channel c_handshake
  implements i_receive,
             i_send;
```



# The SpecC Language

- SpecC Standard Channel Library
  - mutex channel
  - semaphore channel
  - critical section
  - barrier
  - token
  - queue
  - handshake
  - double handshake
  - …




```
interface i_tranceiver
{
  void receive(void *d, unsigned long l);
  void send(void *d, unsigned long l);
};
```

```
interface i_receiver
{
  void receive(void          *d,
               unsigned long l);
};
```

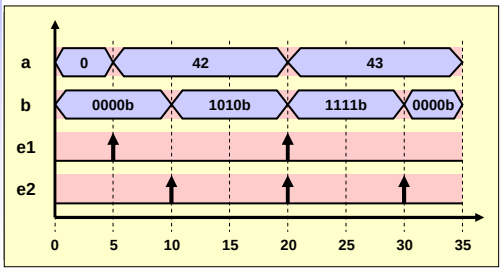
```
interface i_sender
{
  void send(void          *d,
            unsigned long l);
};
```

```
channel c_double_handshake
  implements i_receiver,
             i_sender;
```

# The SpecC Language

- Timing
  - Exact timing
    - **waitfor** <*delay*>;

**Example: stimulator for a test bench**



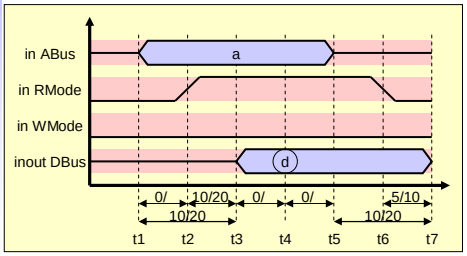

```
behavior Testbench_Driver
         (inout int a,
          inout int b,
          out event e1,
          out event e2)
{
  void main(void)
  {
   waitfor 5;
   a = 42;
   notify e1;

   waitfor 5;
   b = 1010b;
   notify e2;

   waitfor 10;
   a++;
   b |= 0101b;
   notify e1, e2;

   waitfor 10;
   b = 0;
   notify e2;
  }
};
```



# The SpecC Language

- Timing
  - Exact timing
    - **waitfor** <*delay*>;
  - Timing constraints
    - **do** { <*actions*> }
      **timing** {<*constraints*>}

**Example: SRAM read protocol**



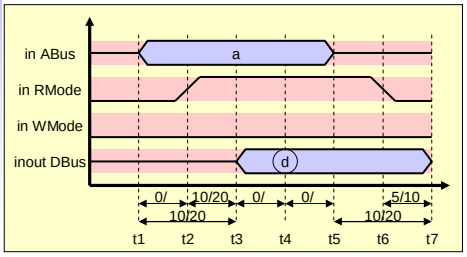

**Specification**

```
bit[7:0] Read_SRAM(bit[15:0] a)
{
 bit[7:0] d;

 do { t1: {ABus = a;  }
      t2: {RMode = 1;
           WMode = 0; }
      t3: {           }
      t4: {d = Dbus;  }
      t5: {ABus = 0;  }
      t6: {RMode = 0;
           WMode = 0; }
      t7: { }
    }
  timing { range(t1; t2;  0;   );
           range(t1; t3; 10; 20);
           range(t2; t3; 10; 20);
           range(t3; t4;  0;   );
           range(t4; t5;  0;   );
           range(t5; t7; 10; 20);
           range(t6; t7;  5; 10);
         }
  return(d);
}
```

# The SpecC Language

- Timing
  - Exact timing
    - **waitfor** <*delay*>;
  - Timing constraints
    - **do** { <*actions*> }
      **timing** {<*constraints*>}

**Example: SRAM read protocol**




**Implementation 1**

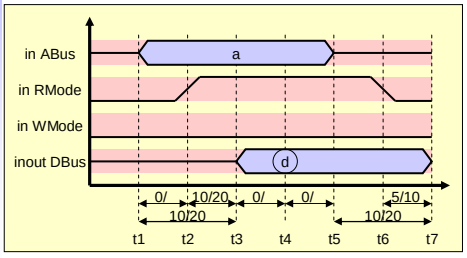
```
bit[7:0] Read_SRAM(bit[15:0] a)
{
 bit[7:0] d;

 do { t1: {ABus = a;  waitfor( 2);}
      t2: {RMode = 1;
           WMode = 0; waitfor(12);}
      t3: {           waitfor( 5);}
      t4: {d = Dbus;  waitfor( 5);}
      t5: {ABus = 0;  waitfor( 2);}
      t6: {RMode = 0;
           WMode = 0; waitfor(10);}
      t7: { }
     }
  timing { range(t1; t2;  0;   );
           range(t1; t3; 10; 20);
           range(t2; t3; 10; 20);
           range(t3; t4;  0;   );
           range(t4; t5;  0;   );
           range(t5; t7; 10; 20);
           range(t6; t7;  5; 10);
          }
  return(d);
}
```



# The SpecC Language

- Timing
  - Exact timing
    - **waitfor** <*delay*>;
  - Timing constraints
    - **do** { <*actions*> }
      **timing** {<*constraints*>}

**Example: SRAM read protocol**




**Implementation 2**

```
bit[7:0] Read_SRAM(bit[15:0] a)
{
 bit[7:0] d;       // ASAP Schedule

 do { t1: {ABus = a;  }
      t2: {RMode = 1;
           WMode = 0; waitfor(10);}
      t3: {           }
      t4: {d = Dbus;  }
      t5: {ABus = 0;  }
      t6: {RMode = 0;
           WMode = 0; waitfor(10);}
      t7: { }
     }
  timing { range(t1; t2;  0;   );
           range(t1; t3; 10; 20);
           range(t2; t3; 10; 20);
           range(t3; t4;  0;   );
           range(t4; t5;  0;   );
           range(t5; t7; 10; 20);
           range(t6; t7;  5; 10);
          }
  return(d);
}
```

# The SpecC Language

- Library support
  - Import of precompiled SpecC code
    - **import** <*component_name*>;
  - Automatic handling of multiple inclusion
    - no need to use **`#ifdef`** - **`#endif`** around included files
  - Visible to the compiler/synthesizer
    - not inline-expanded by preprocessor
    - simplifies reuse of IP components

```
// MyDesign.sc

#include <stdio.h>
#include <stdlib.h>

import "Interfaces/I1";
import "Channels/PCI_Bus";
import "Components/MPEG-2";

...
```



# The SpecC Language

- Persistent annotation
  - Attachment of a key-value pair
    - globally to the design, i.e. **note** <*key*> = <*value*>;
    - locally to any symbol, i.e. **note** <*symbol*>.<*key*> = <*value*>;
  - Visible to the compiler/synthesizer
    - eliminates need for pragmas
    - allows easy data exchange among tools

# The SpecC Language

- Persistent annotation
  - Attachment of a key-value pair
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  - Visible to the compiler/synthesizer
    - eliminates need for pragmas
    - allows easy data exchange among tools

SpecC 2.0: <*value*> can be a composite constant (just like complex variable initializers)

```
/* comment, not persistent */

// global annotations
note Author = "Rainer Doemer";
note Date   = "Fri Feb 23 23:59:59 PST 2001";

behavior CPU(in event CLK, in event RST, ...)
{
  // local annotations
  note MinMaxClockFreq = {750*1e6, 800*1e6 };
  note CLK.IsSystemClock = true;
  note RST.IsSystemReset = true;
  ...
};
```



# SpecC Summary

- SpecC model
  - Hierarchical network of behaviors and channels
  - Separation of communication and computation
- SpecC language
  - True superset of ANSI-C
    - ANSI-C plus extensions for HW-design
  - Support of all concepts needed in system design
    - Structural and behavioral hierarchy
    - Concurrency
    - State transitions
    - Communication
    - Synchronization
    - Exception handling
    - Timing
    - RTL