SHIM: A Deterministic Concurrent Language

Languages for Embedded Systems

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SHIM

Definition

shim \'shim\ *n*

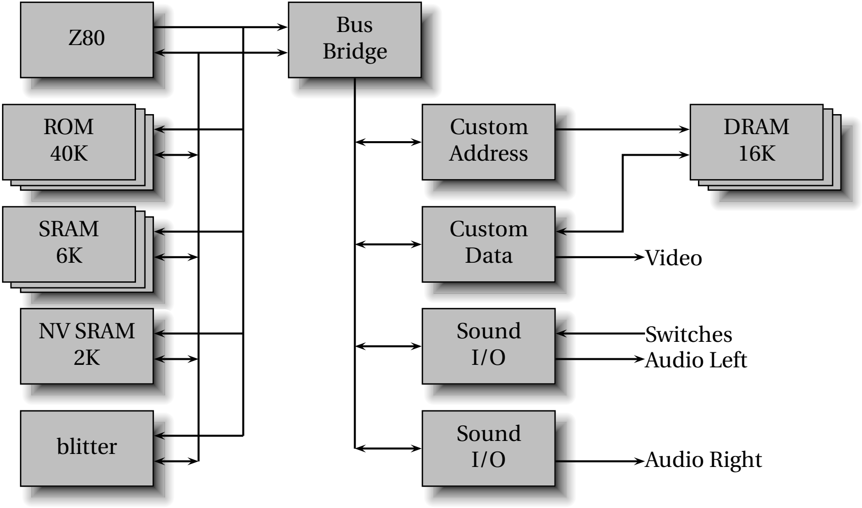
1 : a thin often tapered piece of material (as wood, metal, or stone) used to fill in space between things (as for support, leveling, or adjustment of fit).

2 : *Software/Hardware Integration Medium*, a model for describing hardware/software systems

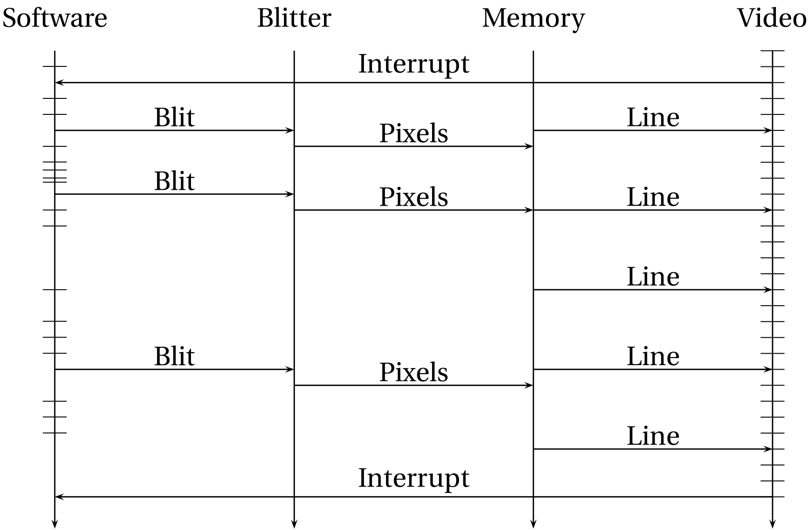
Robby Roto

(Bally/Midway 1981)

Robby Roto Block Diagram



HW/SW Interaction



SHIM Wishlist

- *Concurrent*
  Hardware always concurrent
- *Mixes synchronous and asynchronous styles*
  Need multi-rate for hardware/software systems
- *Only requires bounded resources*
  Hardware resources fundamentally bounded
- *Formal semantics*
  Do not want arguments about what something means
- *Scheduling-independent*
  Want the functionality of a program to be definitive
  Always want simulated behavior to reflect reality
  Verify functionality and performance separately

Basic SHIM

An imperative language with familiar C/Java-like syntax

```
int32 gcd(int32 a, int32 b)
{
  while (a != b) {
    if (a > b)
      a -= b;
    else
      b -= a;
  }
  return a;
}
```

```
struct foo { // Composite types
  int x;
  bool y;
  uint15 z; // Explicit-width integers
  int<-3,5> w; // Explicit-range integers
  int8 p[10]; // Arrays
  bar q; // Recursive types
};
```

Three Additional Constructs

$stmt_1$ `par` $stmt_2$	Run $stmt_1$ and $stmt_2$ concurrently
`send` *var* `recv` *var* `next` *var*	Communicate on channel *var*
`try {`	Define the scope of an exception
⋮	
`throw` *exc*	Raise an exception
⋮	
`} catch(` *exc* `)` *stmt*	

Concurrency & *par*

Par statements run concurrently and asynchronously

Terminate when all terminate

Each thread gets private copies of variables; no sharing

Writing thread sets the variable's final value

```
void main() {
  int a = 3, b = 7, c = 1;
  {
    a = a + c; // a ← 4, b = 7, c = 1
    a = a + b; // a ← 11, b = 7, c = 1
  } par {
    b = b - c; // a = 3, b ← 6, c = 1
    b = b + a; // a = 3, b ← 9, c = 1
  }
             // a ← 11, b ← 9, c = 1
}
```

Restrictions

Both pass-by-reference and pass-by-value arguments

Simple syntactic rules avoid races

```
void f(int &x) { x = 1; } // x passed by reference
void g(int x) { x = 2; } // x passed by value

void main() {
  int a = 0, b = 0;

  a = 1; par b = a; // OK: a and b modified separately
  a = 1; par a = 2; // Error: a modified by both

  f(a); par f(b); // OK: a and b modified separately
  f(a); par g(a); // OK: a modified by f only
  g(a); par g(a); // OK: a not modified
  f(a); par f(a); // Error: a passed by reference twice
}
```

Communication

Blocking: thread waits for all processes that know about *a*

```
void f(chan int a) { // a is a copy of c
  a = 3; // change local copy
  recv a; // receive (wait for g)
          // a now 5
}

void g(chan int &b) { // b is an alias of c
  next b = 5; // sets c and send (wait for f)
              // b now 5
}

void main() {
  chan int c = 0;
  f(c); par g(c);
}
```

Synchronization, Deadlocks

Blocking communication makes for potential deadlock

{ ***next*** a; ***next*** b; } ***par*** { ***next*** b; ***next*** a; } // deadlocks

Only threads responsible for a variable must synchronize

{ ***next*** a; ***next*** b; } ***par next*** b; ***par next*** a; // OK

When a thread terminates, it is no longer responsible

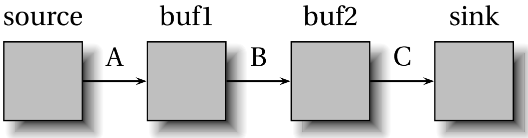
{ ***next*** a; ***next*** a; } ***par next*** a; // OK

Philosophy: deadlocks easy to detect; races are too subtle

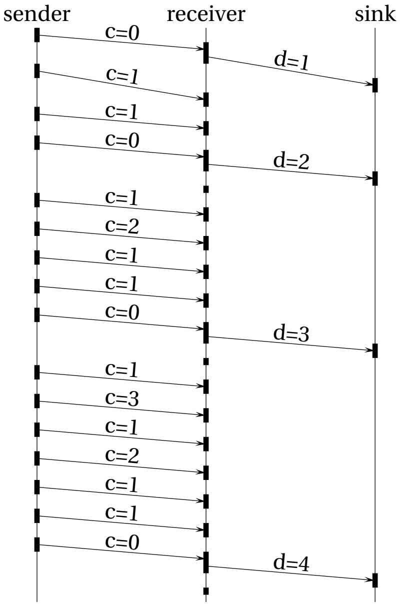
SHIM prefers deadlocks to races (always reproducible)

An Example

```
void main() {
  chan uint8 A, B, C;
  { // source: generate four values
    next A = 17;
    next A = 42;
    next A = 157;
    next A = 8;
  } par { // buf1: copy from input to output
    for (;;)
      next B = next A;
  } par { // buf2: copy, add 1 alternately
    for (;;) {
      next C = next B;
      next C = next B + 1;
    }
  } par { // sink
    for (;;)
      recv C;
  }
}
```



Message Sequence Chart

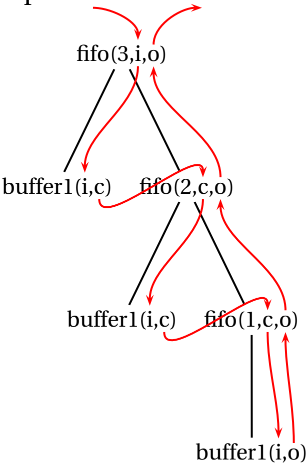



```
int a, b; chan int c, d;
{
  d = 0;
  for (;;) {
    e = d;
    while (e > 0) {
      next c = 1;
      next c = e;
      e = e - 1;
    }
    next c = 0;
    next d = d + 1;
  }
} par {
  a = b = 0;
  for (;;) {
    do {
      if (next c != 0)
        a = a + next c;
    } while (c);
    b = b + 1;
  }
} par {
  for (;;) recv d;
}
```

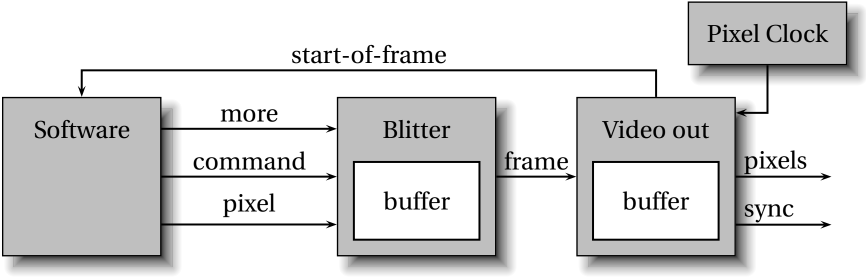
Recursion & Concurrency

A bounded FIFO: compiler will analyze & expand

```
void buffer1(chan int in, chan int &out) {
  for (;;) next out = next in;
}

void fifo(int n, chan int in, chan int &out) {
  if (n == 1)
    buffer1(in, out);
  else {
    chan int channel;
      buffer1(in, channel);
    par
      fifo(n-1, channel, out);
  }
}
```



Robby Roto in SHIM




```
while (player is alive) {
  next start-of-frame;
  ...game logic...
  next more = true;
  next command = ...;
  ...game logic...
  next more = false;
}
```

```
for (;;) {
  while (next more) {
    next command;
    Write to buffer
  }
  next frame = buffer;
}
```

```
for (;;) {
  next start-of-frame;
  for each line {
    next sync = ...;
    for each pixel {
      next clock;
      Read pixel
      next pixel = ...;
    }
  }
  buffer = next frame;
```

Exceptions

Sequential semantics are classical

```
void main() {
  int i = 1;
  try {
    throw T;
    i = i * 2; // Not executed
  } catch (T) {
     i = i * 3; // Executed by throw T
  }
                 // i = 3 on exit
}
```

Exceptions & Concurrency

```
void main() {
  chan int i = 0, j = 0;
  try {
    while (i < 5)
      next i = i + 1;
    throw T;
  } par {
    for (;;) {
      next j =
        next i + 1;
    }
  } par {
    for (;;)
      recv j;
  } catch (T) {}
}
```

Exceptions propagate through communication actions to preserve determinism

Idea: “transitive poisoning”

Raising an exception “poisons” a process

Any process attempting to communicate with a poisoned process is itself poisoned (within exception scope)

“Best effort preemption”

Another Example

Five functions that call each other and communicate through channel *A*

```
void main() {
  try {
    chan int A;
    f(A); par g(A);
  } catch (Done) {}
}
```

```
void f(chan int &A) throws Done {
  h(A); par j(A);
}
```

```
void g(chan int A) {
  recv A;
  recv A;
}
```

```
void h(chan int &A) {
  A = 4; send A;
  A = 2; send A;
}
```

```
void j(chan int A) throws Done {
  recv A;
  throw Done;
}
```

Another Example

Parents call children

```
void main() {
  try {
    chan int A;
    f(A); par g(A);
  } catch (Done) {}
}
```

```
void f(chan int &A) throws Done {
  h(A); par j(A);
}
```

```
void g(chan int A) {
  recv A;
  recv A;
}
```

```
void h(chan int &A) {
  A = 4; send A;
  A = 2; send A;
}
```

```
void j(chan int A) throws Done {
  recv A;
  throw Done;
}
```

Another Example

h sends 4 on *A*,
g and *j* rendezvous

```
void main() {
  try {
    chan int A;
    f(A); par g(A);
  } catch (Done) {}
}
```

```
void f(chan int &A) throws Done {
  h(A); par j(A);
}
```

```
void g(chan int A) {
  recv A;
  recv A;
}
```

```
void h(chan int &A) {
  A = 4; send A;
  A = 2; send A;
}
```

```
void j(chan int A) throws Done {
  recv A;
  throw Done;
}
```

Another Example

j throws an exception. *g* and *h* poisoned by attempting communication

```
void main() {
  try {
    chan int A;
    f(A); par g(A);
  } catch (Done) {}
}
```

```
void f(chan int &A) throws Done {
  h(A); par j(A);
}
```

```
void g(chan int A) {
  recv A;
  recv A;
}
```

```
void h(chan int &A) {
  A = 4; send A;
  A = 2; send A;
}
```

```
void j(chan int A) throws Done {
  recv A;
  throw Done;
}
```

Another Example

Concurrent processes terminate, control passed to exception handler

```
void main() {
  try {
    chan int A;
    f(A); par g(A);
  } catch (Done) {}
}
```

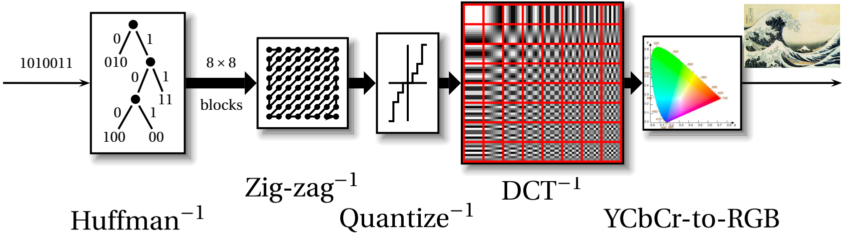
```
void f(chan int &A) throws Done {
  h(A); par j(A);
}
```

```
void g(chan int A) {
  recv A;
  recv A;
}
```

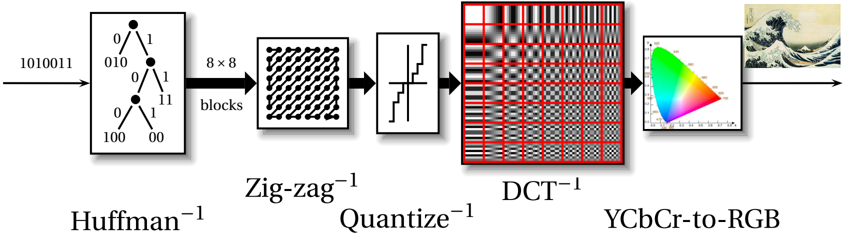
```
void h(chan int &A) {
  A = 4; send A;
  A = 2; send A;
}
```

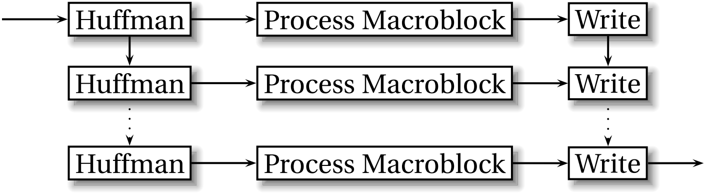
```
void j(chan int A) throws Done {
  recv A;
  throw Done;
}
```

JPEG Decoding

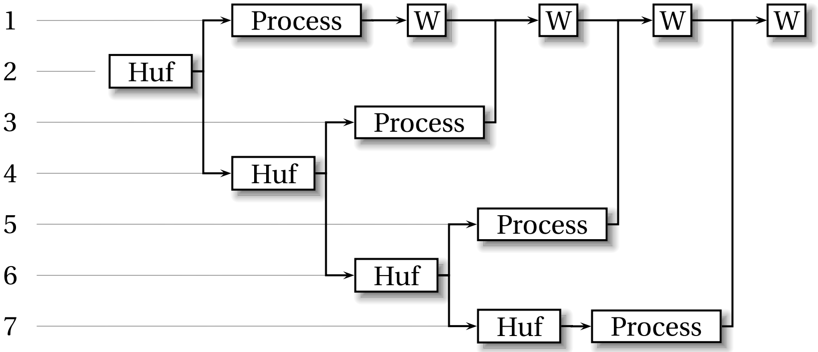


JPEG Decoding



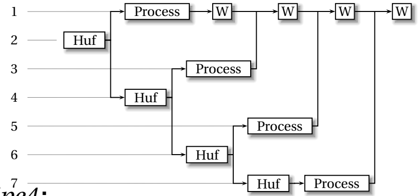


Seven-task JPEG schedule



Idea: minimize communication events

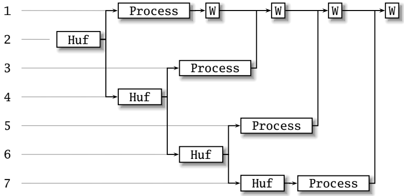
SHIM for the Seven-task Schedule




```
unpacker_state ustate;
writer_state wstate;

stripe stripe1, stripe2, stripe3, stripe4;

pixels pixels1; // to writer
chan pixels pixels2, pixels3, pixels4;

void unpack(unpacker_state &state, stripe &stripe) { ... } // Huffman Decode

void process(const stripe &stripe, pixels &pixels) { ... } // IDCT, etc.

void write(writer_state &wstate, const pixels &pixels) { ... } // Write to file
```

SHIM for the Seven-task Schedule

```
unpack(ustate, stripe1); // 2
{
  process(stripe1, pixels1); write(wstate, pixels1); // 1
  recv pixels2; write(wstate, pixels2);
  recv pixels3; write(wstate, pixels3);
  recv pixels4; write(wstate, pixels4);
} par {
  unpack(ustate, stripe2); // 4
  {
    process(stripe2, pixels2); send pixels2; // 3
  } par {
    unpack(ustate, stripe3); // 6
    {
      process(stripe3, pixels3); send pixels3; // 5
    } par {
      unpack(ustate, stripe4); // 7
      process(stripe4, pixels4); send pixels4;
} } }
```

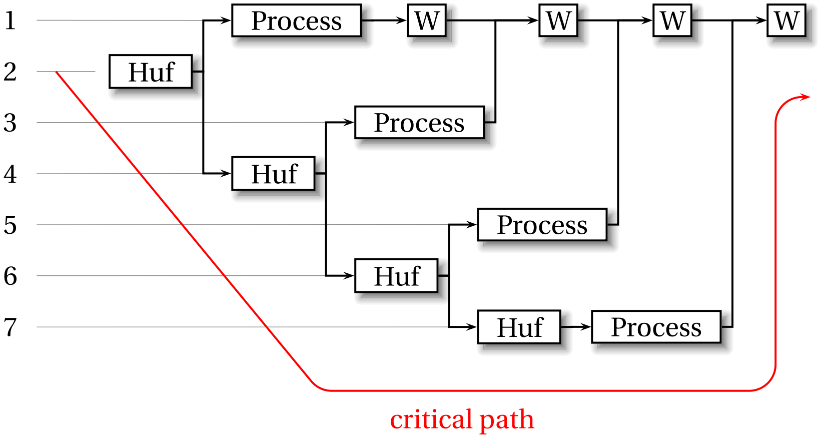


SHIM Enforces Dependencies

```
unpack(ustate, stripe1);
{
  process(stripe1, pixels1); write(wstate, pixels1);
  recv pixels2; write(wstate, pixels2);
  recv pixels3; write(wstate, pixels3);
  recv pixels4; write(wstate, pixels4);
} par {
  unpack(ustate, stripe2);
  {
    process(stripe2, pixels2); send pixels2;
  } par {
    unpack(ustate, stripe3);
    {
      process(stripe3, pixels3); send pixels3;
    } par {
      unpack(ustate, stripe4);
      process(stripe4, pixels4); send pixels4;
} } }
```

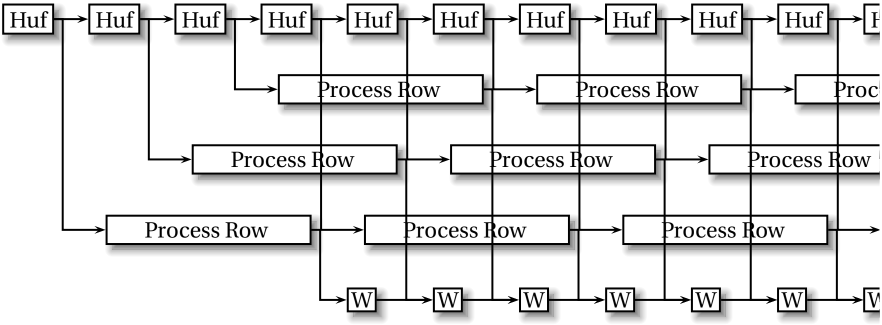
- Writer state local to one process
- Unpacker state can only be passed by reference once
- Trying to run *unpack* or *write* in parallel gives compiler error

Oops



Only achieved a 1.8× speedup

Pipelined JPEG

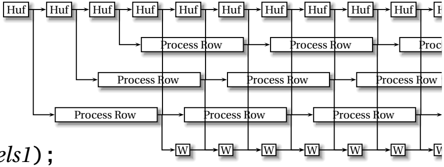


Process a row of blocks at a time (e.g., 64).

Reduce communication; accelerate start-up and termination.

SHIM for Pipelined JPEG

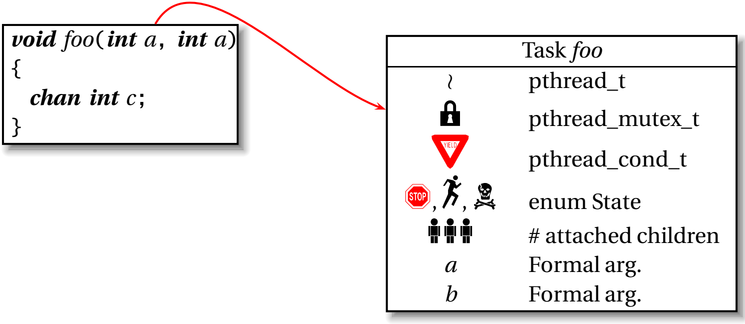
```
try {
  {
    for (;;) {
      unpack(ustate, row1); send row1; if (--rows == 0) break;
      unpack(ustate, row2); send row2; if (--rows == 0) break;
      unpack(ustate, row3); send row3; if (--rows == 0) break;
    } throw Done;
  } par
    process(row1, pixels1); par
    process(row2, pixels2); par
    process(row3, pixels3); par
  {
    for (;;) {
      recv pixels1; write(wstate, pixels1);
      recv pixels2; write(wstate, pixels2);
      recv pixels3; write(wstate, pixels3);
  } }
} catch (Done) {}
```



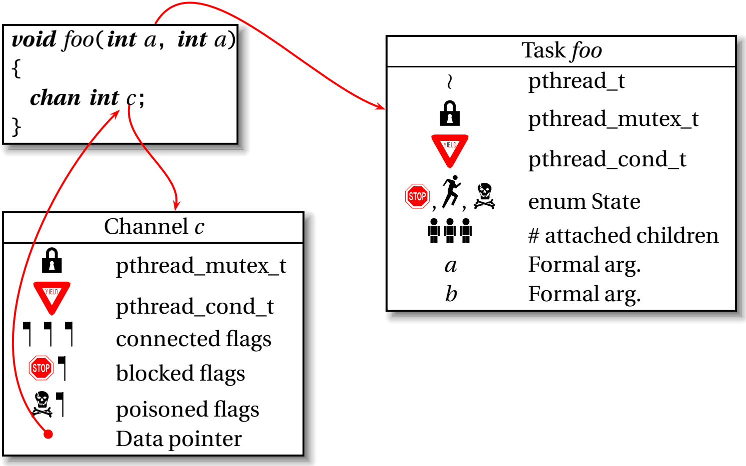
Pthreads Compiler: Task and Channel Structures

```
void foo(int a, int a)
{
  chan int c;
}
```

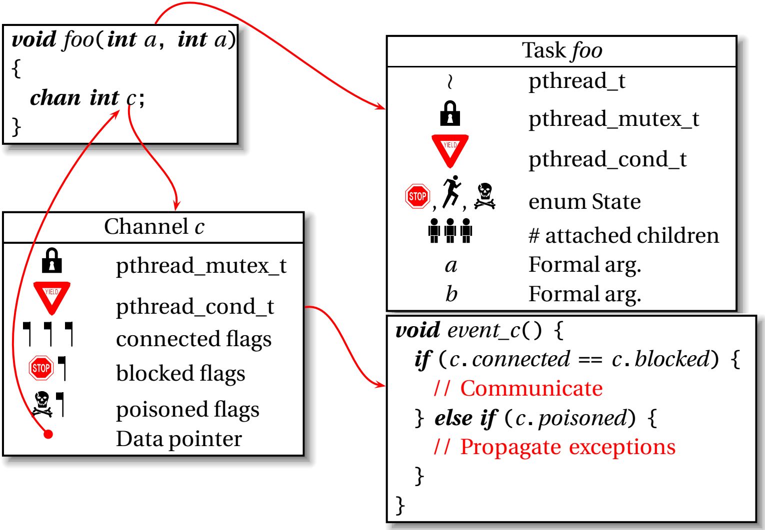
Pthreads Compiler: Task and Channel Structures



Pthreads Compiler: Task and Channel Structures

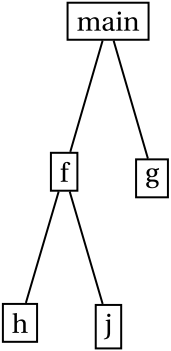


Pthreads Compiler: Task and Channel Structures



Code for *send A* in h()

```
pthread_mutex_lock(A.mutex);  // Lock for channel A

A.blocked |= (A_h|A_f|A_main);
// Block ancestors, too.
event_A();                    // Communicate if possible

while (A.blocked & A_h) {              // Are we ready?
  if (A.poisoned & A_h) {              // Were we poisoned?
    pthread_mutex_unlock(A.mutex);
    goto _poisoned;                    // Handle exception
  }
  pthread_cond_wait(A.cond, A.mutex);  // Yield
}

pthread_mutex_unlock(A.mutex);
```



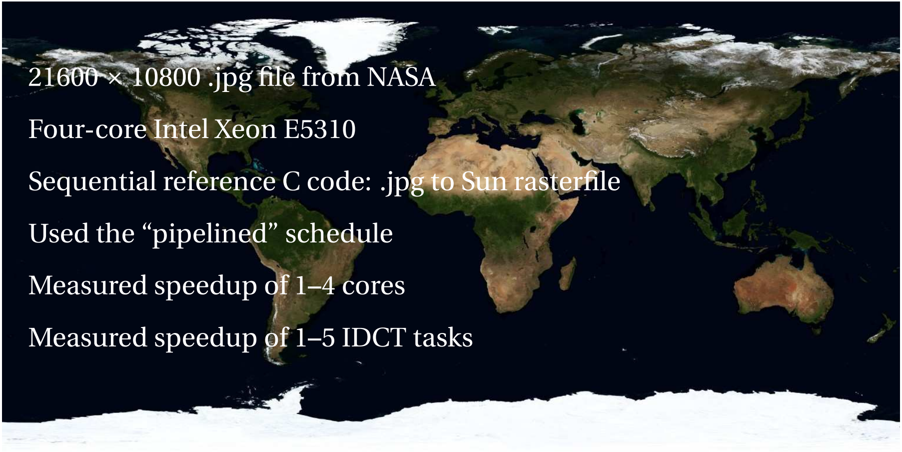
An Event Function

```
void event_A() {
  unsigned int can_die = 0, kill = 0;                    // Flags
  if (A.connected == A.blocked) {                        // Communicate

  } else if (A.poisoned) {                               // Propagate exceptions

} } }
```

An Event Function

```
void event_A() {
  unsigned int can_die = 0, kill = 0;                              // Flags
  if (A.connected == A.blocked) {                                  // Communicate

    A.blocked = 0;                                                 // Unblock everybody
    if (A.connected & A_g) *A.g = *A.main;                         // Copy data
    if (A.connected & A_j) *A.j = *A.main;
    pthread_cond_broadcast(A.cond);                                // Awaken blocked tasks

  } else if (A.poisoned) {                                         // Propagate exceptions

    can_die = blocked & (A_g|A_h|A_j);                             // Compute can_die
    if (can_die & (A_h|A_j) == A.connected & (A_h|A_j)) can_die |= blocked & A_f;
    if (A.poisoned & (A_f|A_g)) {                                  // Compute kill
      kill |= A_g; if (can_die & A_f) kill |= (A_f|A_h|A_j);
    }
    if (A.poisoned & (A_h|A_j)) { kill |= A_h; kill |= A_j; }
    if (kill &= can_die & ~A.poisoned) {                           // Anybody to poison?
      pthread_mutex_unlock(A.mutex);
      if (kill & A_g) {                                            // Poison g if necessary
        pthread_mutex_lock(g.mutex);
        g.state = POISON;
        pthread_mutex_unlock(g.mutex); }
      // also poison f, h, and j if in kill set...
      pthread_mutex_lock(A.mutex);
      A.poisoned |= kill; pthread_Cond_broadcast(A.cond);

} } }
```

JPEG Experiment



21600 × 10800 .jpg file from NASA

Four-core Intel Xeon E5310

Sequential reference C code: .jpg to Sun rasterfile

Used the “pipelined” schedule

Measured speedup of 1–4 cores

Measured speedup of 1–5 IDCT tasks

JPEG Results

Cores	Tasks	Time	Total	Total/Time	Speedup
1	1	25s	20s	0.8	1.0× (def)
1	1+3+1	24	24	1.0	1.04
2	1+3+1	13	24	1.8	1.9
3	1+3+1	11	24	2.2	2.3
4	1+3+1	8.7	25	2.9	2.9
4	1+1+1	16	24	1.5	1.6
4	1+2+1	9.3	25	2.7	2.7
4	1+3+1	8.7	25	2.9	2.9
4	1+4+1	8.2	25	3.05	3.05
4	1+5+1	8.6	25	2.9	2.9

FFT Experiment (testing roundoff)

40 MB .wav file (16-bit stereo)

$\downarrow$

1024-point 4.28 fixed-point FFT

$\downarrow$

inverse FFT

$\downarrow$

.wav file

- Same hardware as JPEG (Xeon Quad-core)
- Baseline: sequential C from *Numerical Recipes*
- 1–4 cores, “pipelined” with 1 1024-sample block
- 1–4 cores, “pipelined” with 16 1024-sample blocks

FFT Results

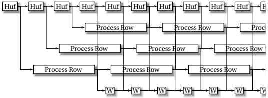
Code	Cores	Time	Total	Total/Time	Speedup
Handwritten C	1	2.0s	2.0s	1.0	1.0× (def)
Sequential SHIM	1	2.1	2.1	1.0	0.95
Parallel SHIM	1	2.1	2.1	1.0	0.95
Parallel SHIM	2	1.3	2.0	1.5	1.5
Parallel SHIM	3	0.92	2.1	2.2	2.2
Parallel SHIM	4	0.86	2.1	2.4	2.3
Parallel 16	1	1.9	1.9	1.0	1.1
Parallel 16	2	1.0	1.9	1.9	2.0
Parallel 16	3	0.88	1.9	2.1	2.2
Parallel 16	4	0.6	1.9	3.2	3.3

Conclusions

- Scheduling-independent message passing language

  SHIM

- Exploring schedules interesting, safe

- Our compiler generates C code with pthreads calls

- Efficient: 3.05 and 3.3× speedups on a four-core