Programming Shared Memory Multiprocessors with Deterministic Message-Passing Concurrency: Compiling SHIM to Pthreads

Stephen A. Edwards, Nalini Vasudevan
Columbia University

Olivier Tardieu
IBM

Main Points

- Scheduling-independent message passing works for parallel programming

  We use the SHIM language

- This paradigm helps to safely explore schedules

  Compiler catches race-related bugs

- Our compiler generates efficient pthreads (C) code

  Synthesizing communication the trick

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

  JPEG and FFT examples

A SHIM 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);
}
```

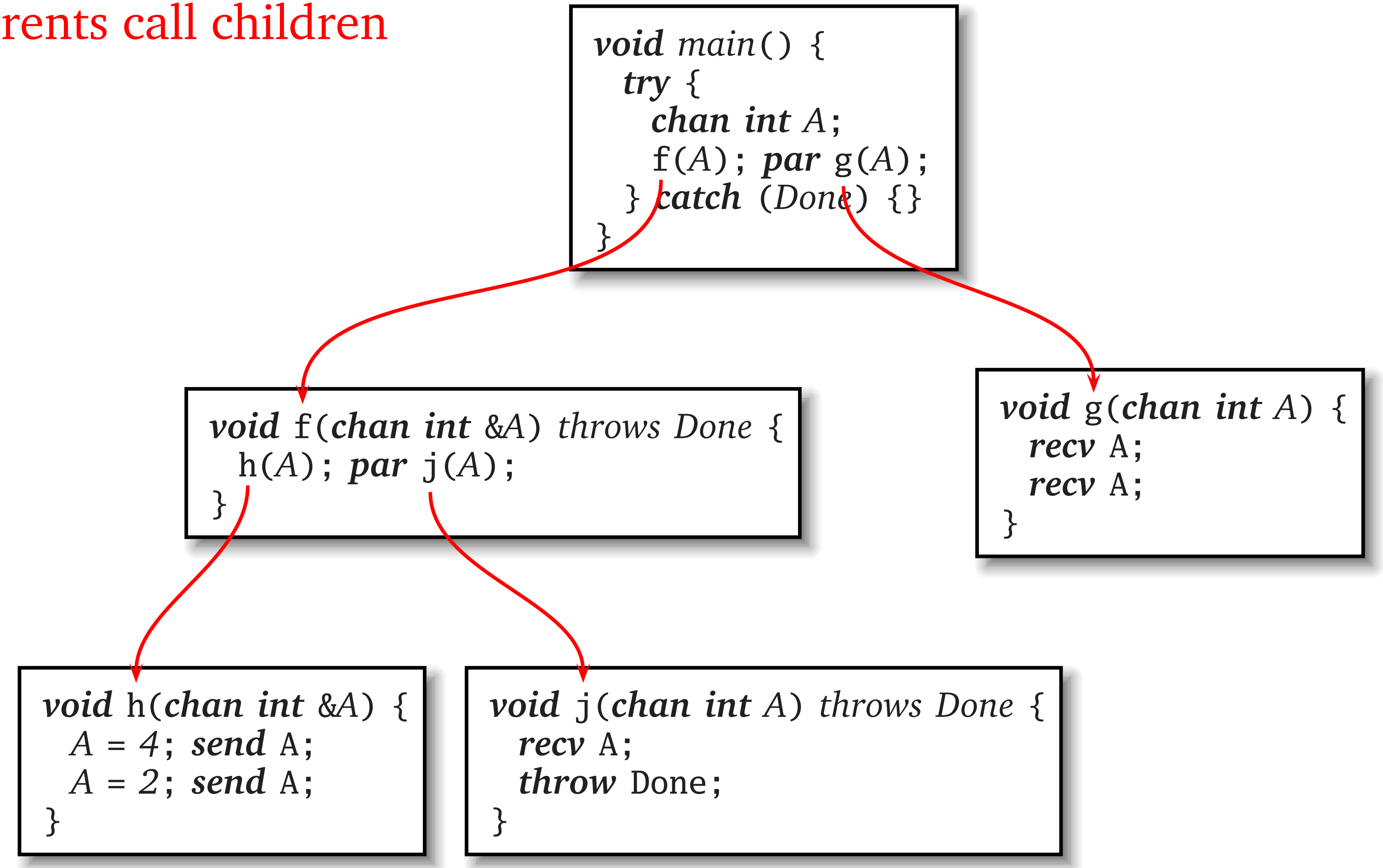
```
void g(chan int A) {
  recv A;
  recv A;
}
```

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

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

A SHIM example

Parents call children



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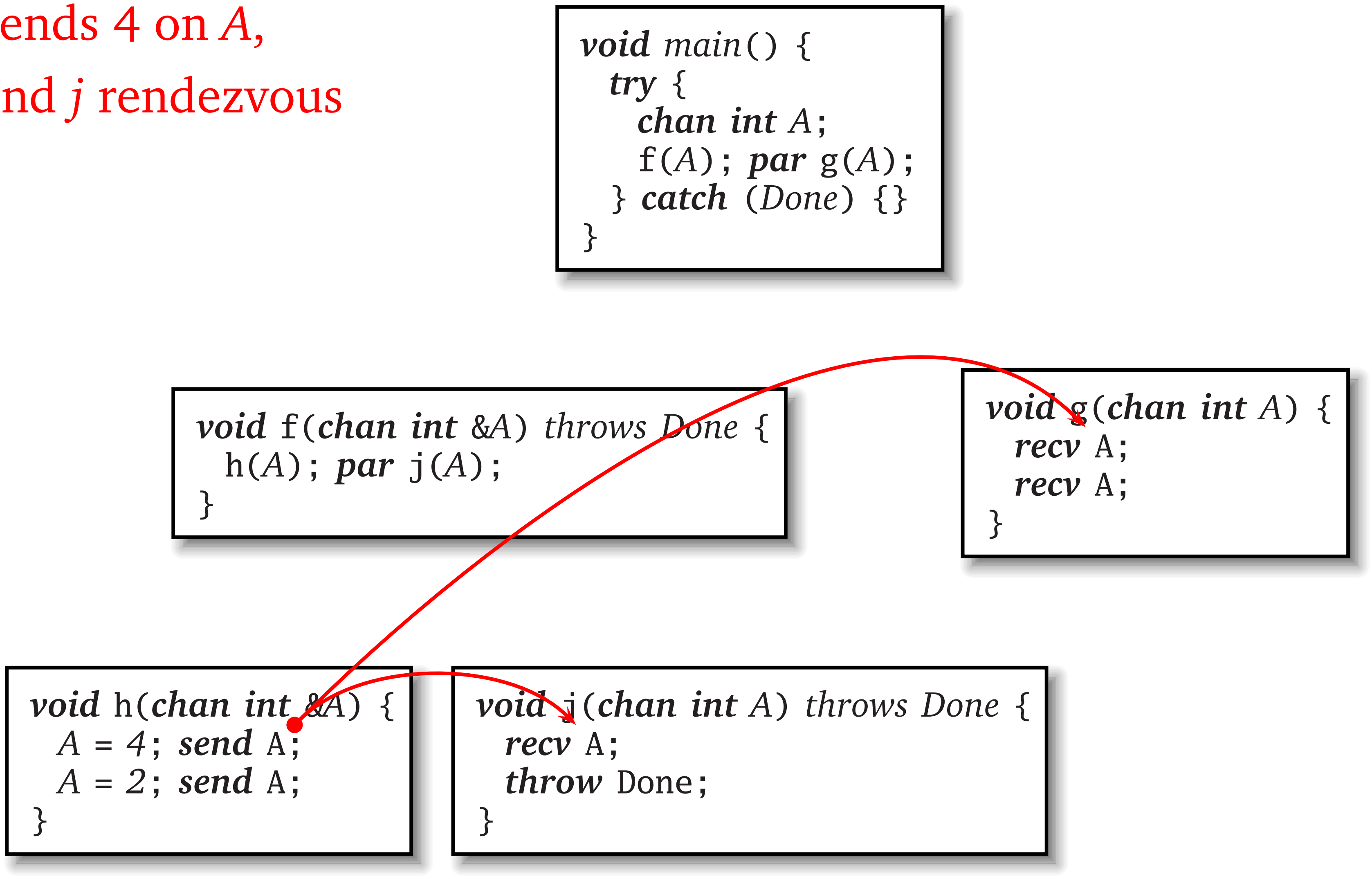
  throw Done;
}
```

A SHIM example

h sends 4 on *A*,

g and *j* rendezvous



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  } catch (Done) {}
}
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}
```
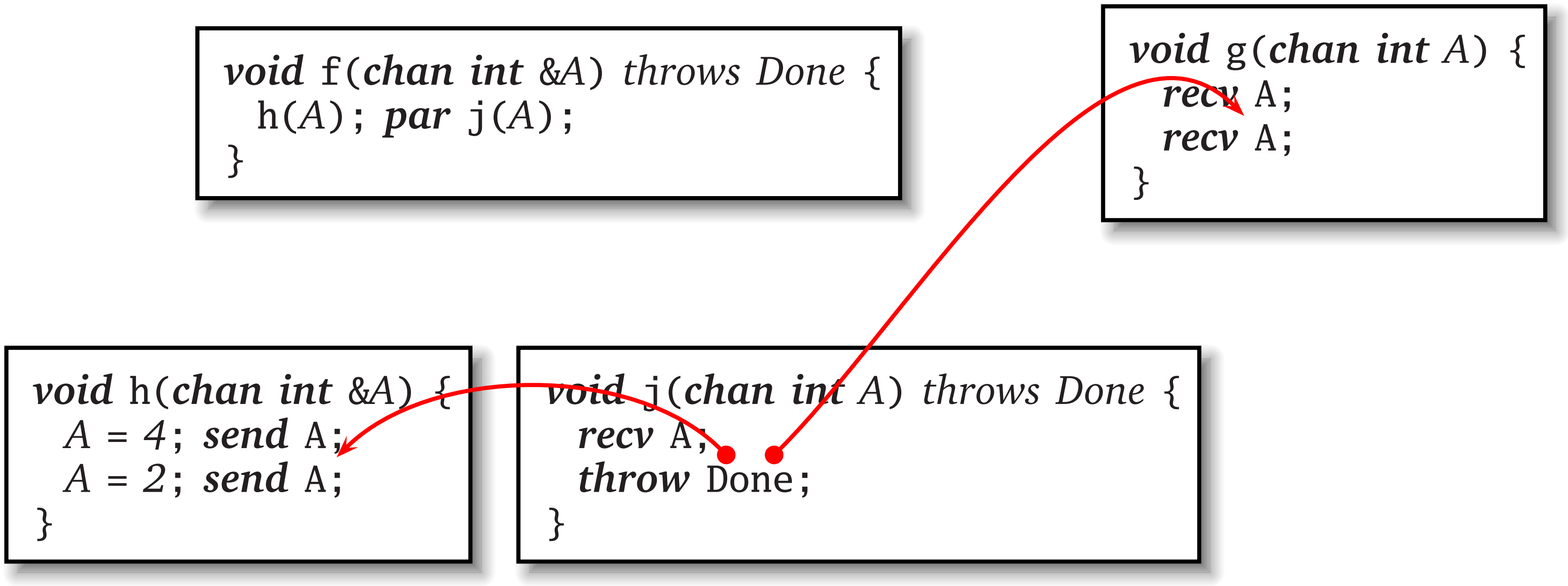

A SHIM example

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

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



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  h(A); par j(A);
}
```

```
void g(chan int A) {
  recv A;
  recv A;
}
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void h(chan int &A) {
  A = 4; send A;
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void j(chan int A) throws Done {
  recv A;
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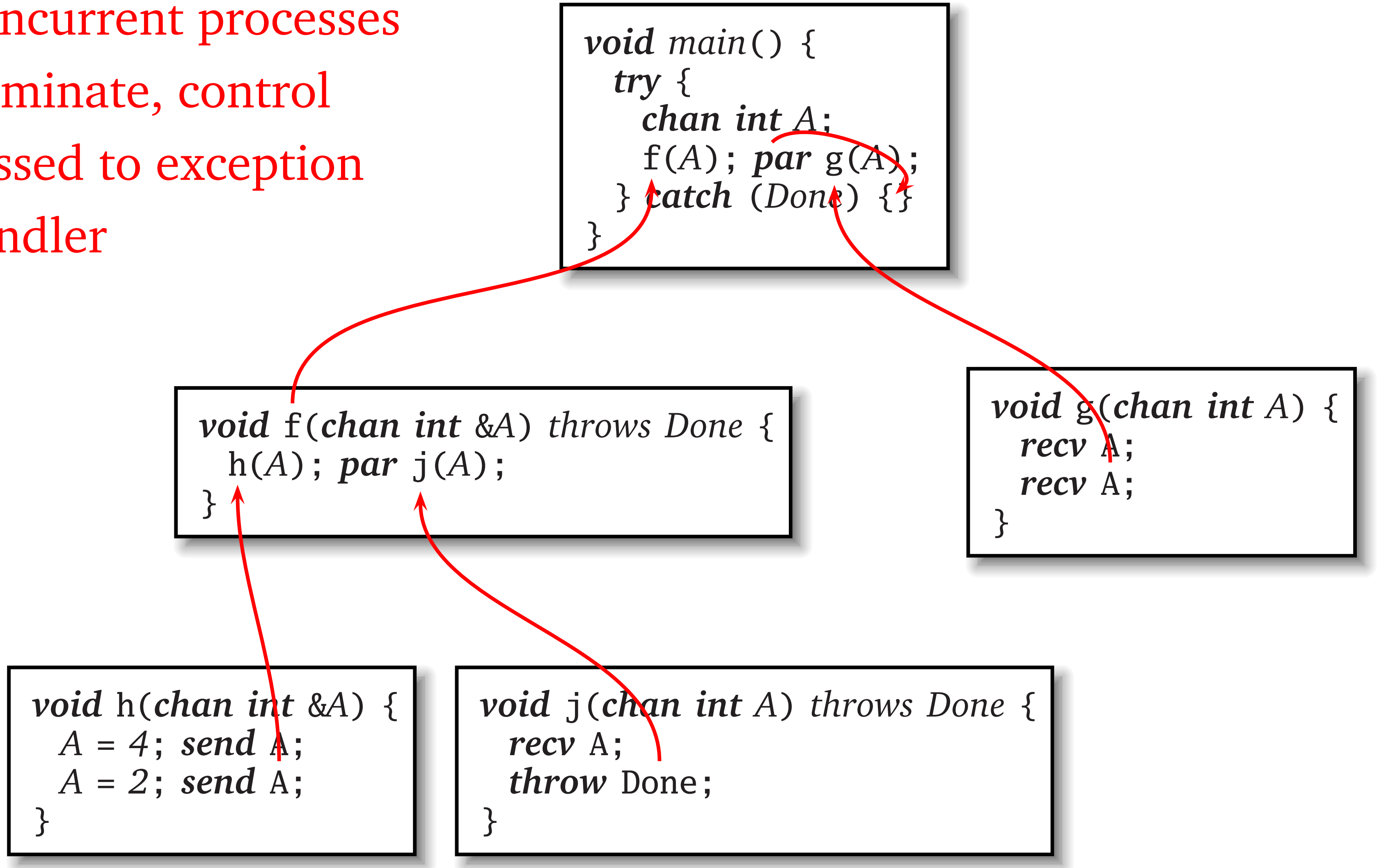
}
```

A SHIM example

Concurrent processes terminate, control passed to exception handler



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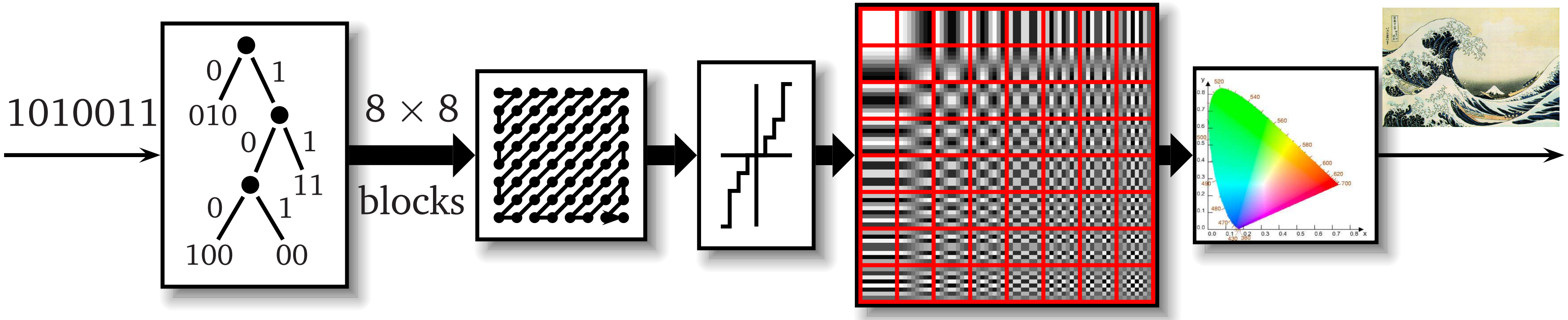
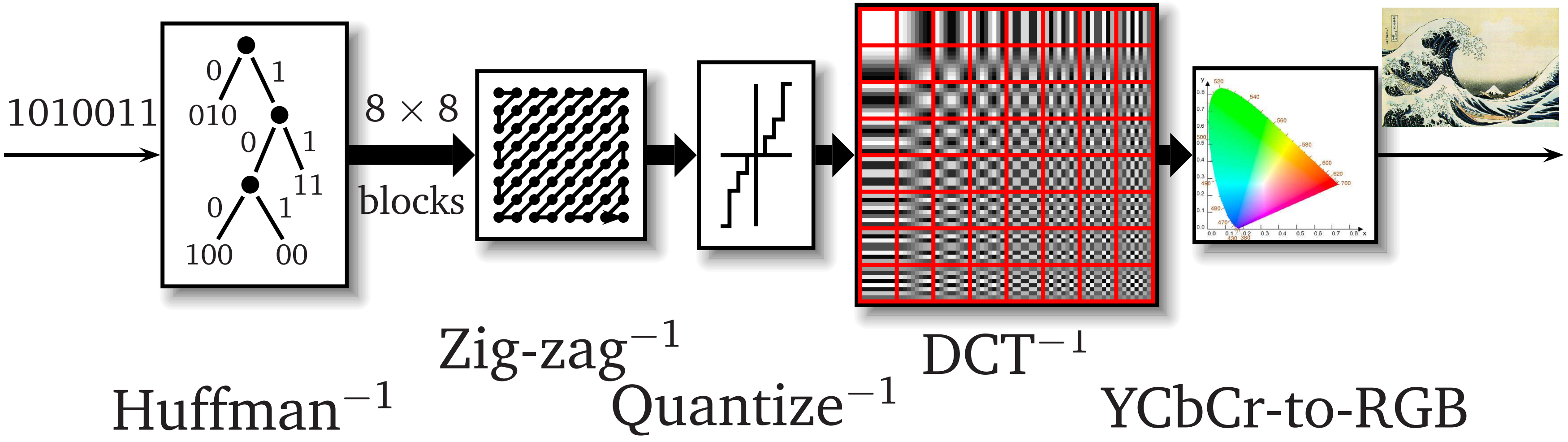
JPEG Decoding



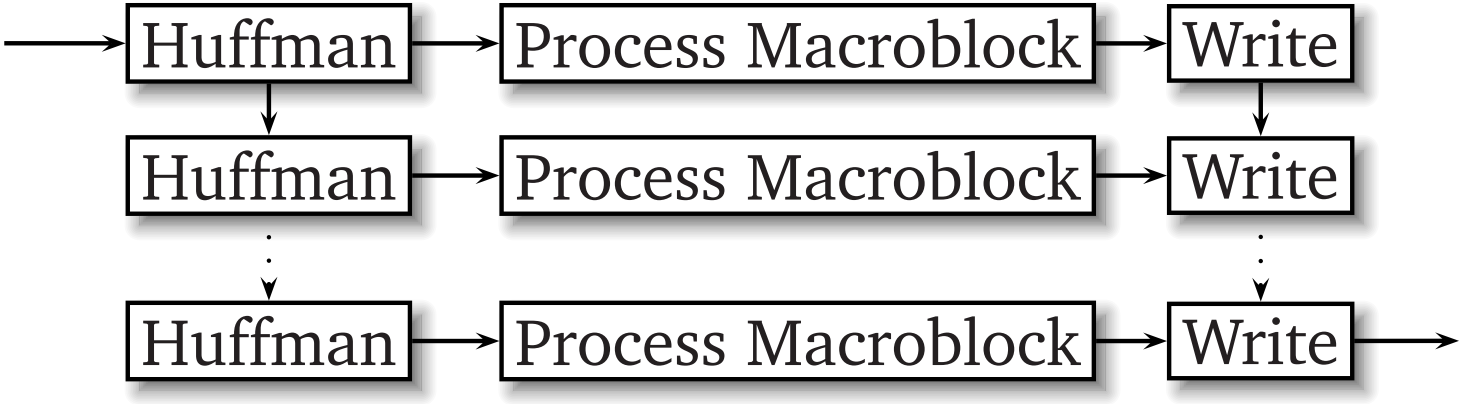
Zig-zag^{-1} DCT^{-1}

Huffman^{-1} Quantize^{-1} YCbCr-to-RGB

JPEG Decoding



Huffman^{-1} Zig-zag^{-1} Quantize^{-1} DCT^{-1} YCbCr-to-RGB



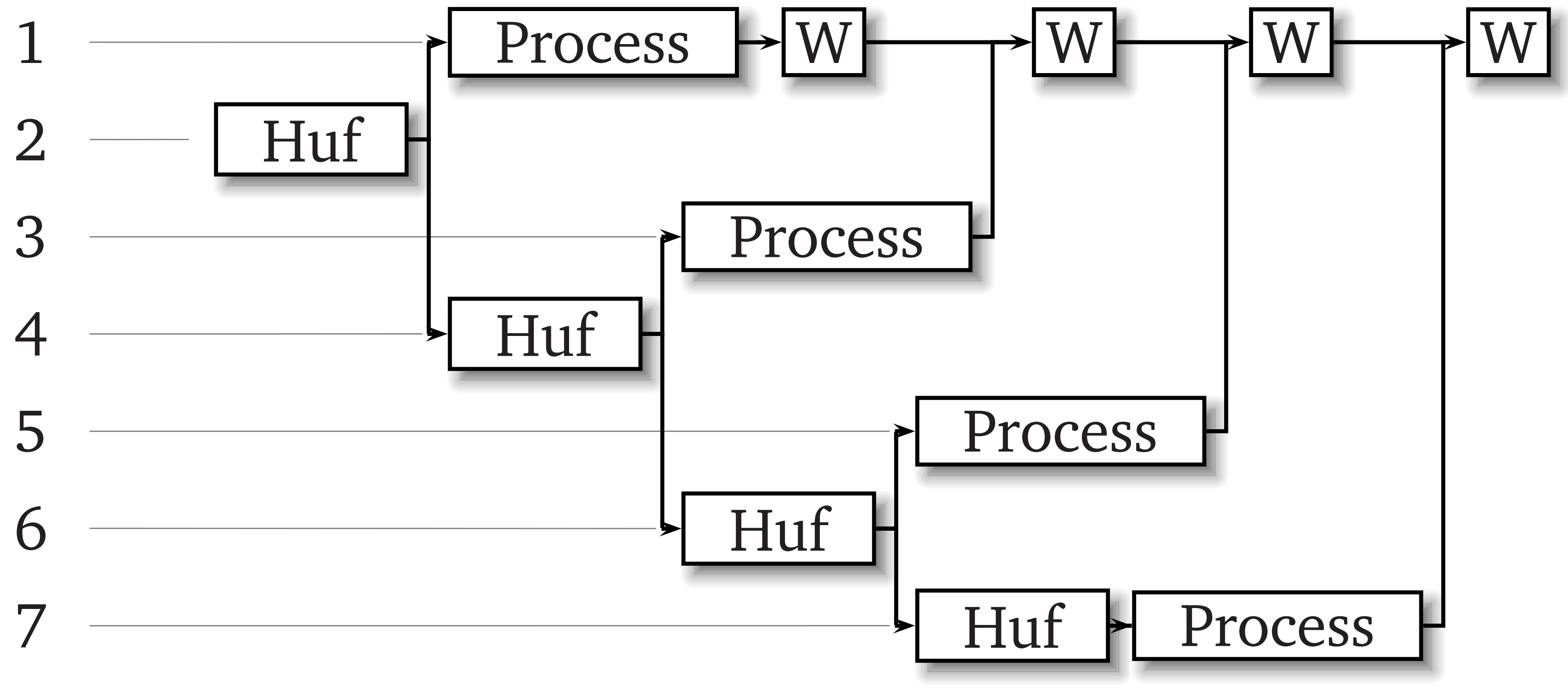
Huffman → Process Macroblock → Write

Huffman → Process Macroblock → Write

⋮

Huffman → Process Macroblock → Write

Seven-task JPEG schedule



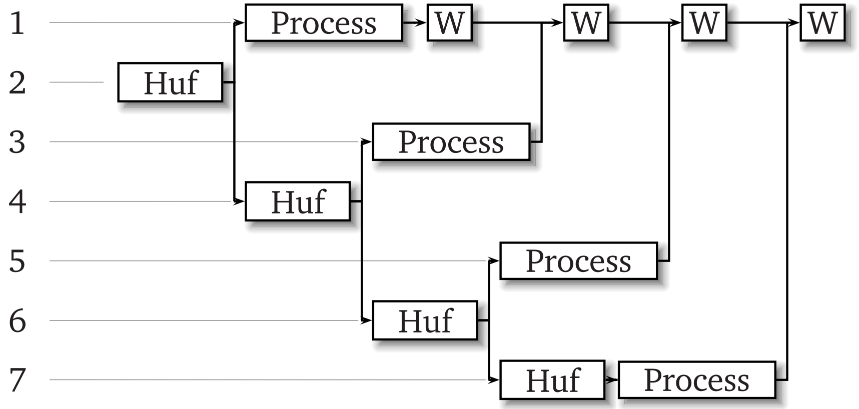
Idea: minimize communication events

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;
```



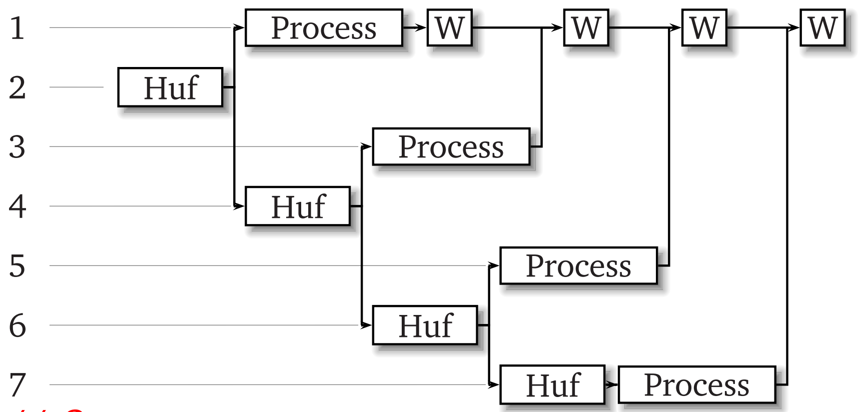
```
void unpack(unpacker_state &state, stripe &stripe) { ... } // Huffman Decode

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

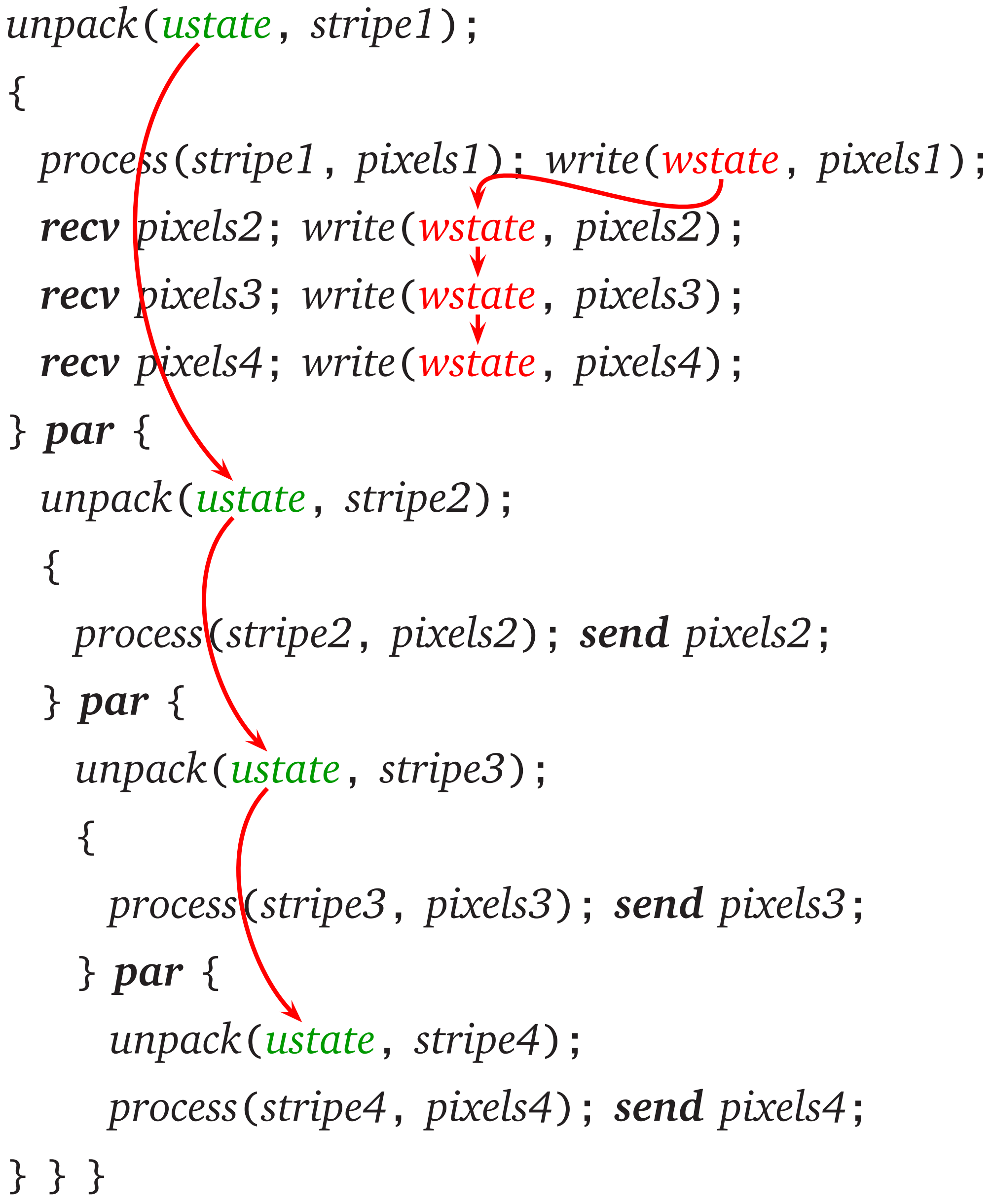
void write(writer_state &wstate, const pixels &pixels) { ... } // Write to file
```

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;
} } }
```



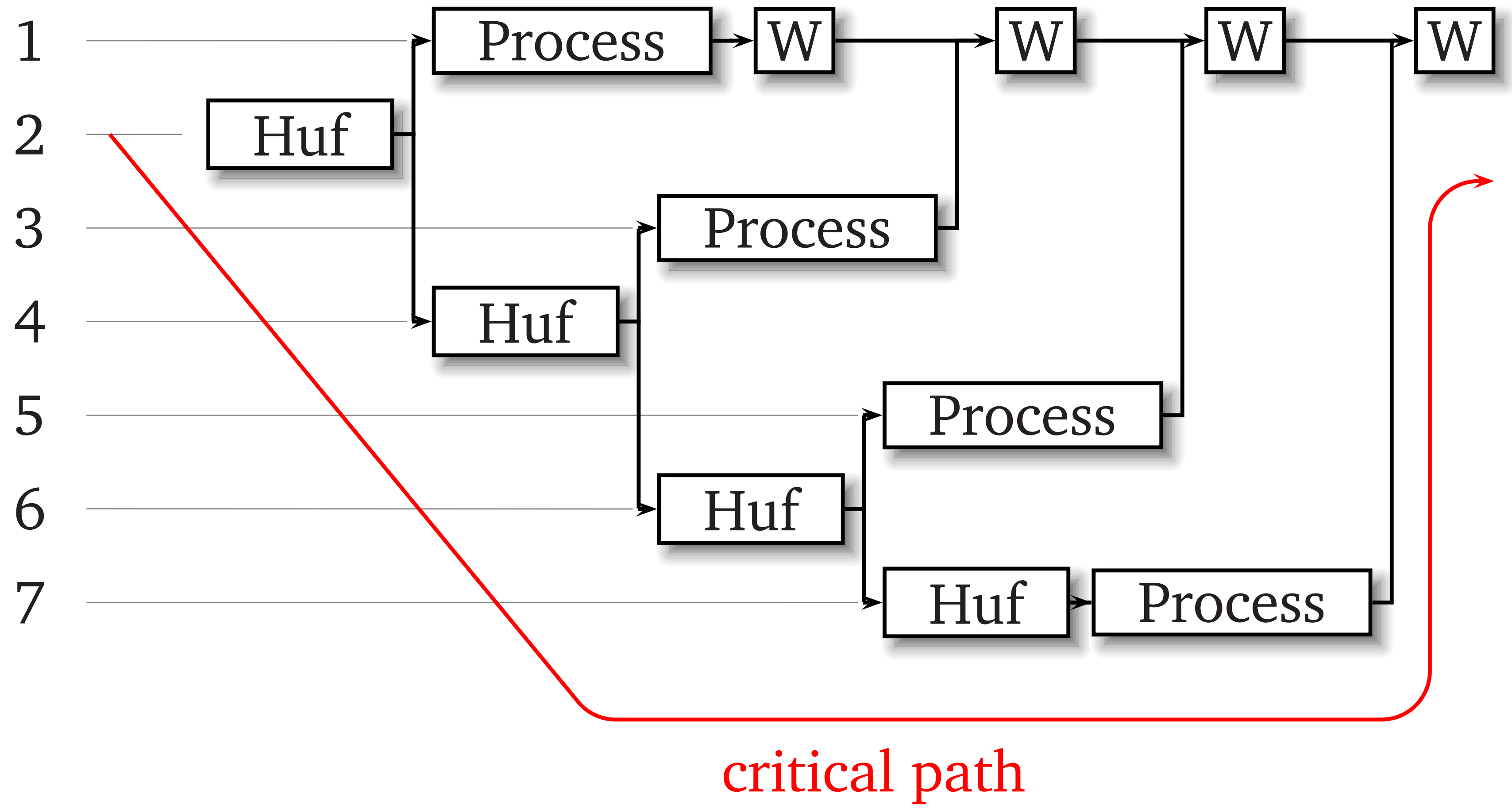
SHIM Enforces Dependencies



```
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;
} } }
```

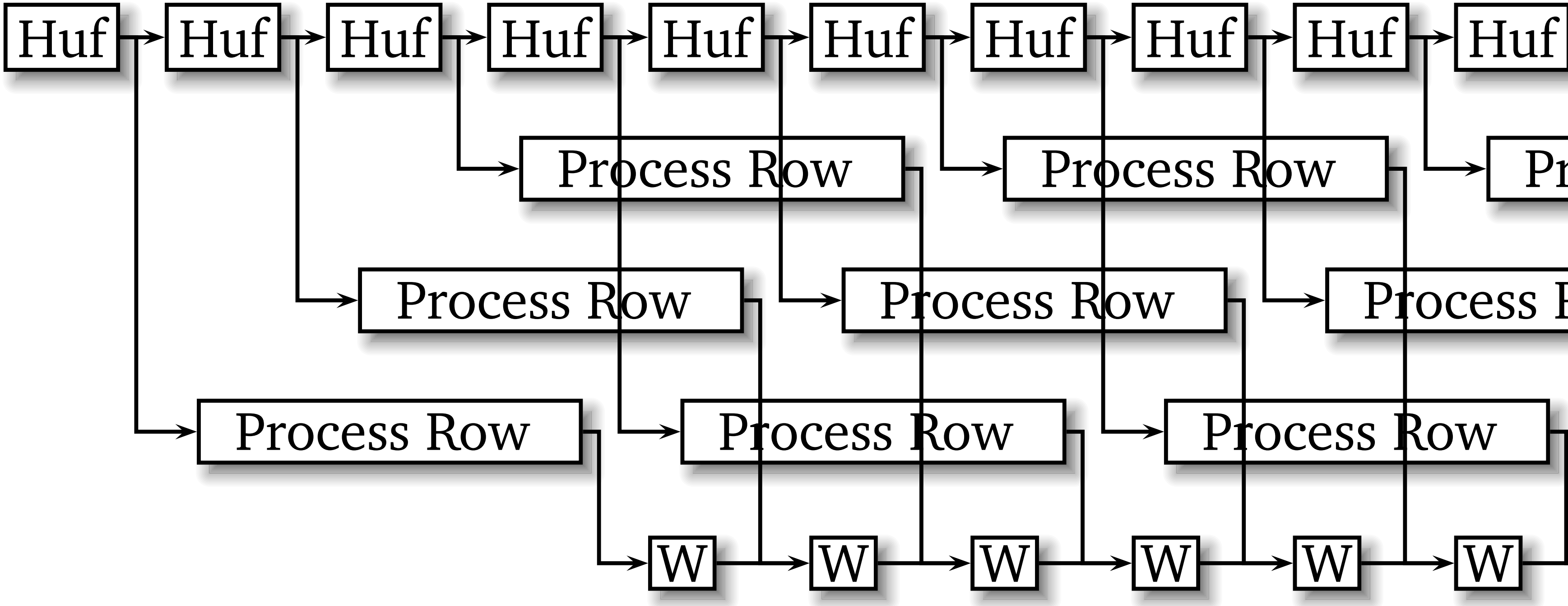
- Writer state local to one process
- Unpacker state can only be passed by reference once
- Trying to run *unpack* or *write* in parallel gives compiler error

Oops



Only achieved a 1.8× speedup

Pipelined JPEG

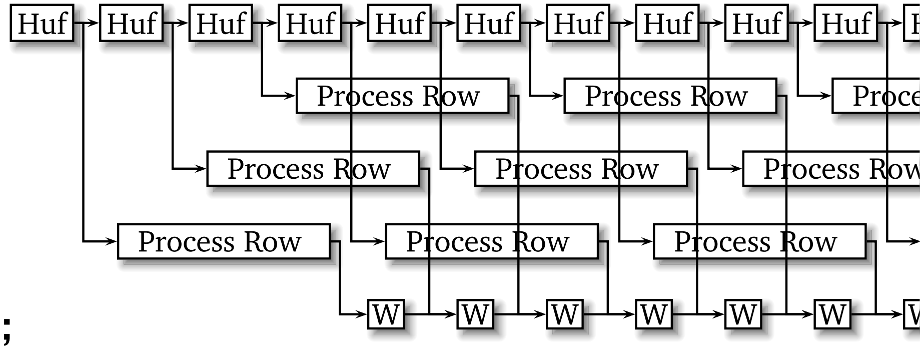


Process a row of blocks at a time (e.g., 64).

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) {}
```



Task and Channel Structures

```
void foo(int a, int a)
{
  chan int c;
}
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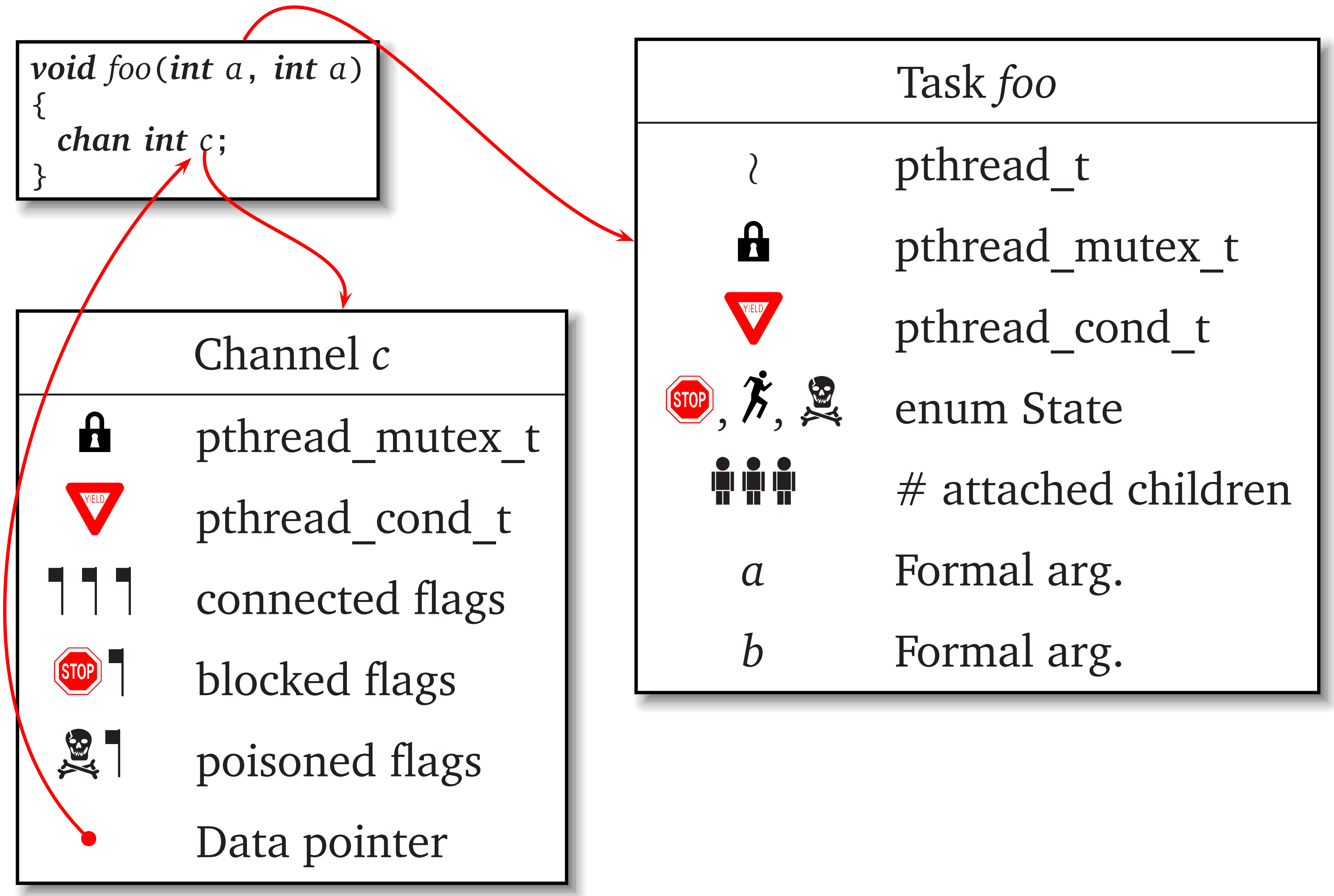
Task *foo*	
≀	pthread_t
🔒	pthread_mutex_t
▽ YIELD	pthread_cond_t
🛑, 🏃, ☠	enum State
👤👤👤	# attached children
a	Formal arg.
b	Formal arg.

Task and Channel Structures



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

Channel *c*	
🔒	pthread_mutex_t
YIELD	pthread_cond_t
⚑⚑⚑	connected flags
STOP ⚑	blocked flags
☠ ⚑	poisoned flags
●	Data pointer

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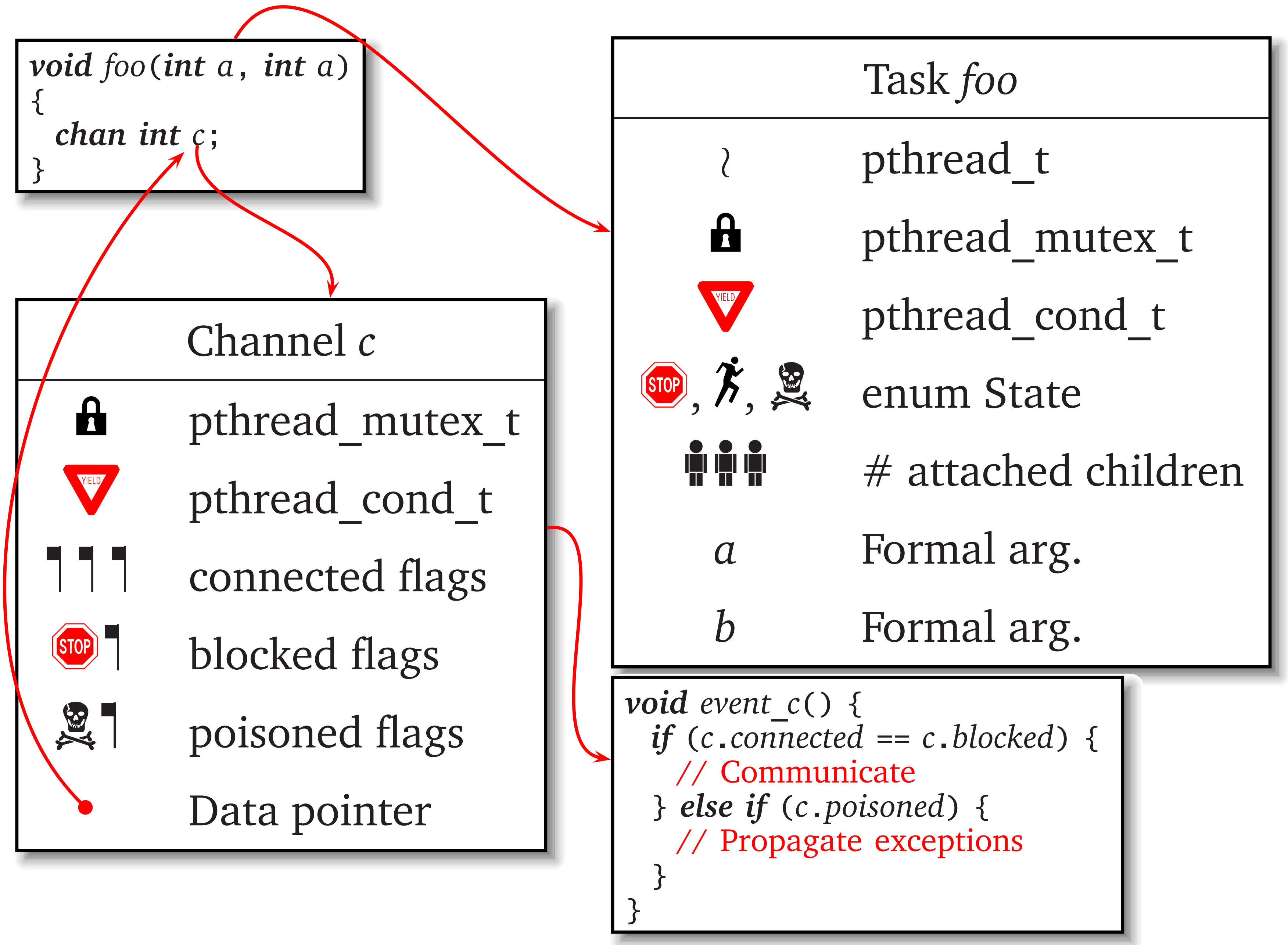
Task and Channel Structures



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

Task *foo*	
≀	pthread_t
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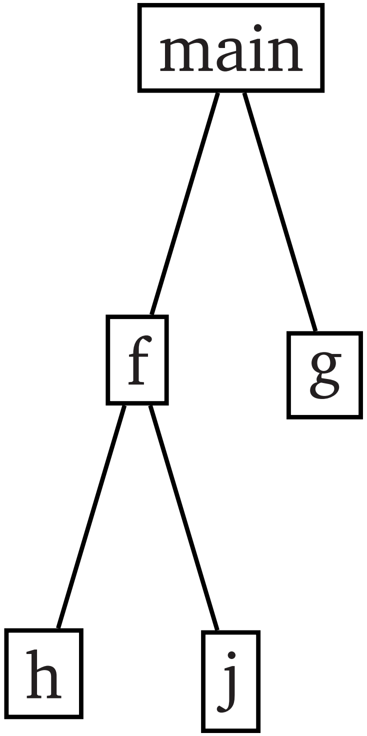
●	Data pointer

```
void event_c() {
  if (c.connected == c.blocked) {
    // Communicate
  } else if (c.poisoned) {
    // Propagate exceptions
  }
}
```

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);
} } }
```

Skeleton for Task *f*

restart:

Wait until my parent sets my state to RUN

Body of the task

terminated:

Disconnect from each of my channels

Set my state to STOP

goto detach

poisoned:

...

deatch:

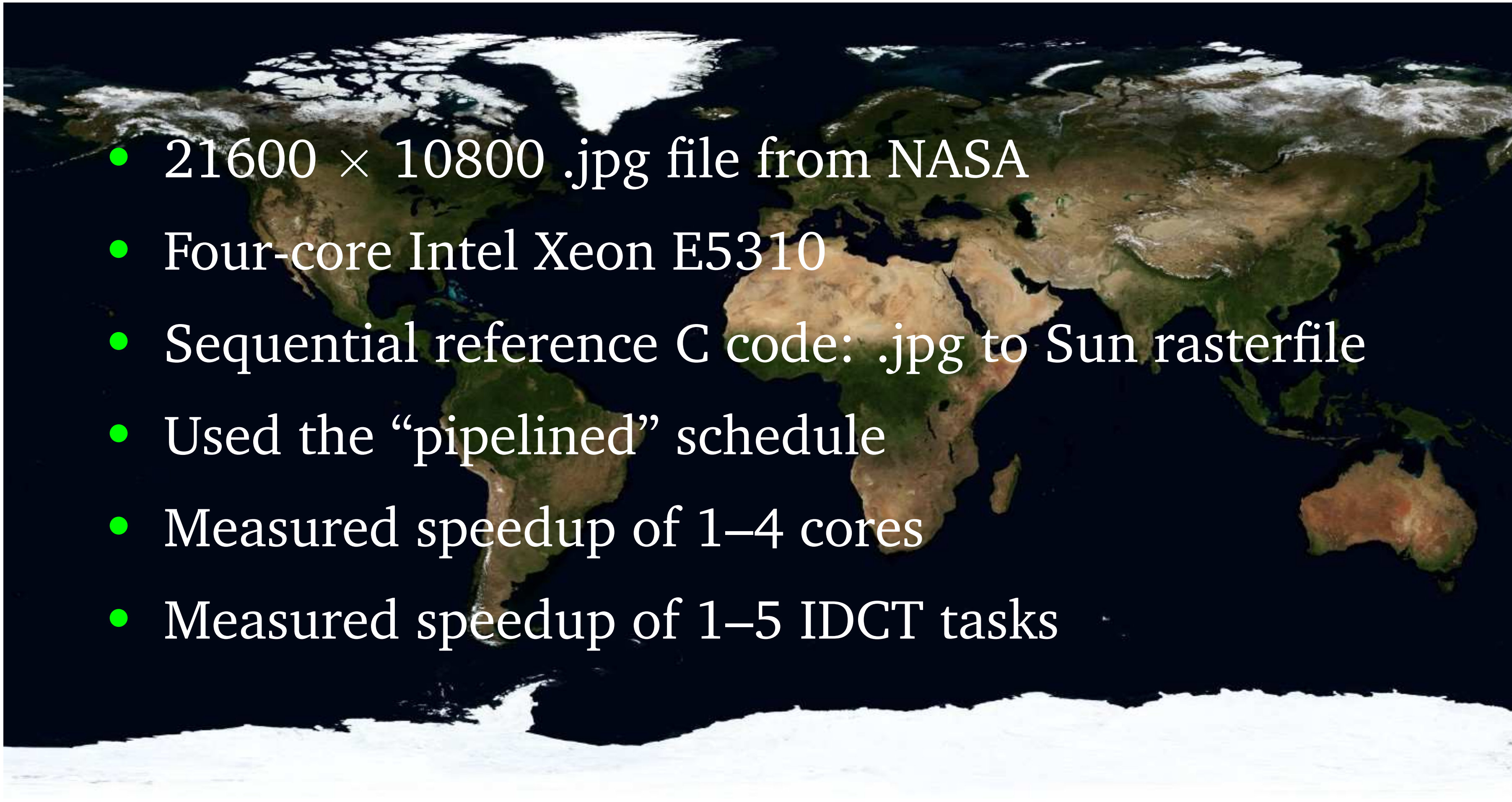
Tell my parent that I have detached

goto restart

Skeleton for Task *f*

```
void *_thread_f(void *_ignored) {
  int *A; // Actual argument

_restart: // Wait for RUN
  pthread_mutex_lock(f.mutex);
  while (f.state != RUN)
    pthread_cond_wait(f.cond, f.mutex);
  A = f.A;
  pthread_mutex_unlock(f.mutex);

  // body of f() ...

_terminated: // Disconnect f from channel A
  pthread_mutex_lock(A.mutex);
  A.connected &= ~A_f; event_A();
  pthread_mutex_unlock(A.mutex);

  pthread_mutex_lock(f.mutex); // State to STOP
  f.state = STOP;
  pthread_mutex_unlock(f.mutex);
  goto _detach;

_poisoned: // Handle poisoning
  // ...

_detach: // Detach from parent (main)
  pthread_mutex_lock(main.mutex);
  --main.attached_children;
  pthread_cond_broadcast(main.cond);
  pthread_mutex_unlock(main.mutex);
  goto _restart;
}
```

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)

↓

1024-point 4.28 fixed-point FFT

↓

inverse FFT

↓

.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

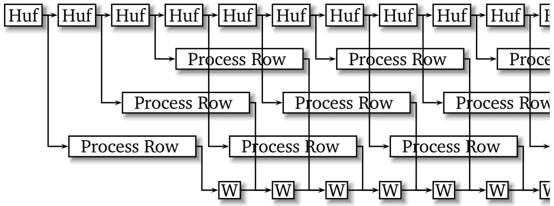
Code	Cores	Time	Total	Total/Time	Speedup
Handwritten C	1	2.0s	2.0s	1.0	1.0× (def
Sequential SHIM	1	2.1	2.1	1.0	0.95
Parallel SHIM	1	2.1	2.1	1.0	0.95
Parallel SHIM	2	1.3	2.0	1.5	1.5
Parallel SHIM	3	0.92	2.1	2.2	2.2
Parallel SHIM	4	0.86	2.1	2.4	2.3
Parallel 16	1	1.9	1.9	1.0	1.1
Parallel 16	2	1.0	1.9	1.9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

  ≀ 🔒 STOP YIELD ☠ ⚑

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