Practical Approaches to Formally Verify Concurrent Software

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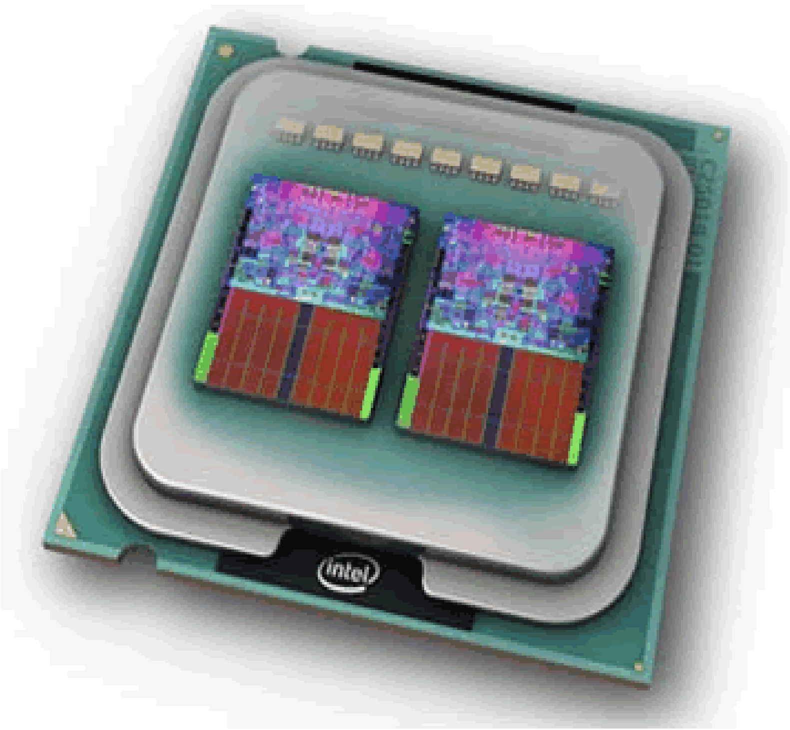
http://www.cs.utah.edu/formal_verification

(talk is kept at above URL under presentations/ce-junior-seminar-2008.pptx)

Multicores are the future!



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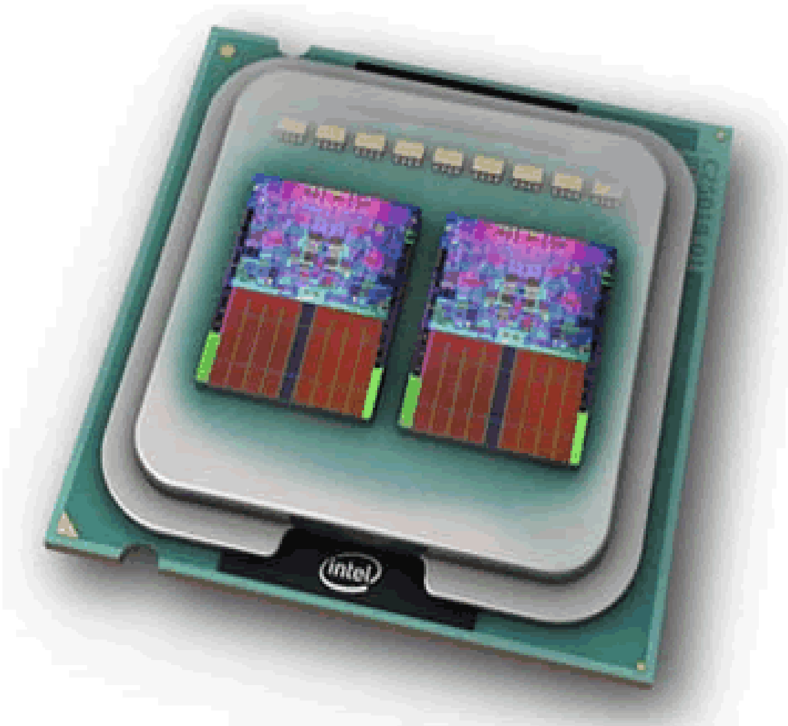
Why ?

- ☐

Multicores are the future!



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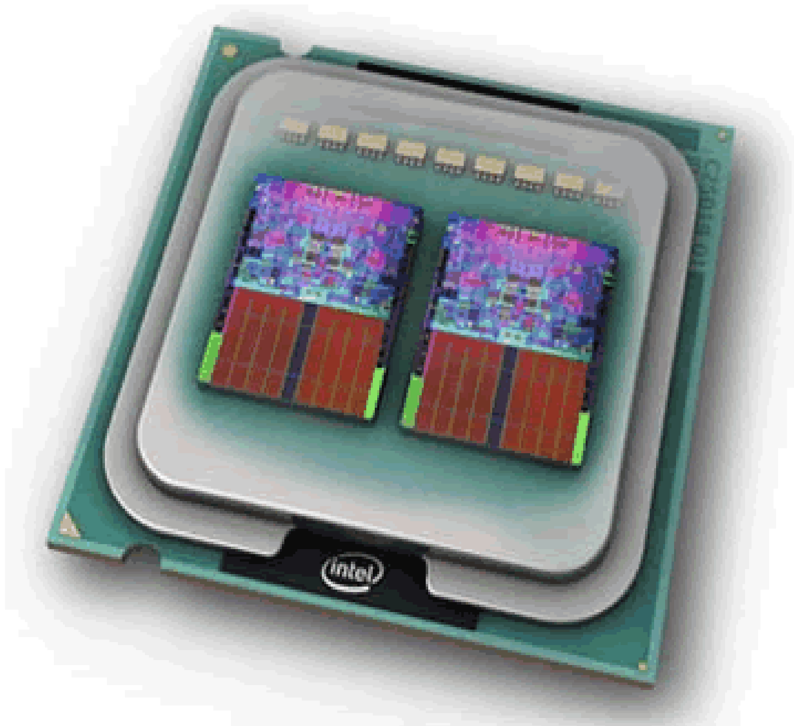
Why ?

- That is the only way to get more compute power
- Energy per compute operation lowered thru the use of parallelism
  - e.g. Today's DSP processors

How many different types of multicore CPUs?

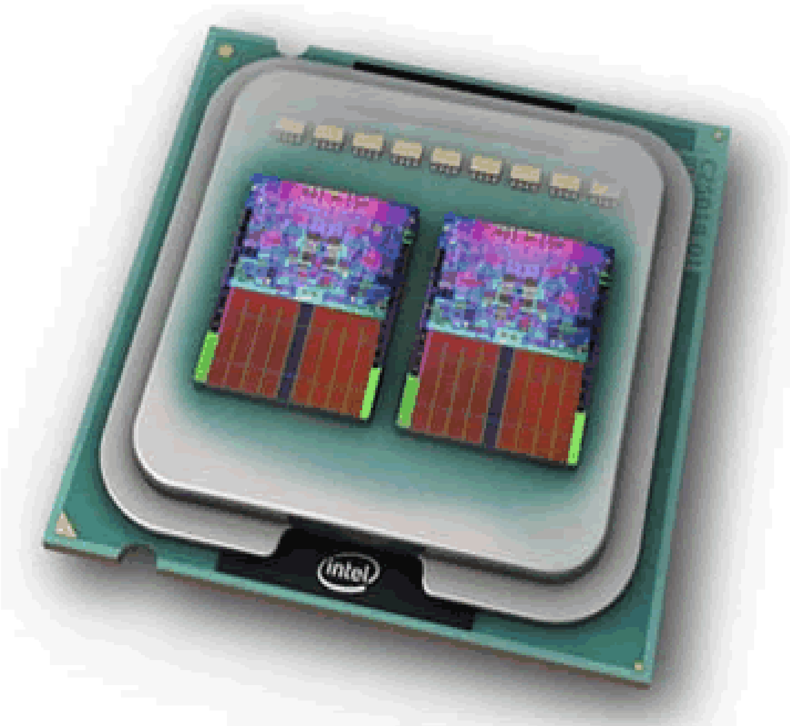


(photo courtesy of Intel Corporation.)

- Quite a variety
  - Use in cloud computing
  - Use in hand-helds
  - Use in embedded devices
  - Use in Graphics / Gaming
  - Use in HPC
  - …
- A plethora of SW and HW challenges

Multicore Challenges :

Need to employ / teach concurrent programming at an unprecedented scale!

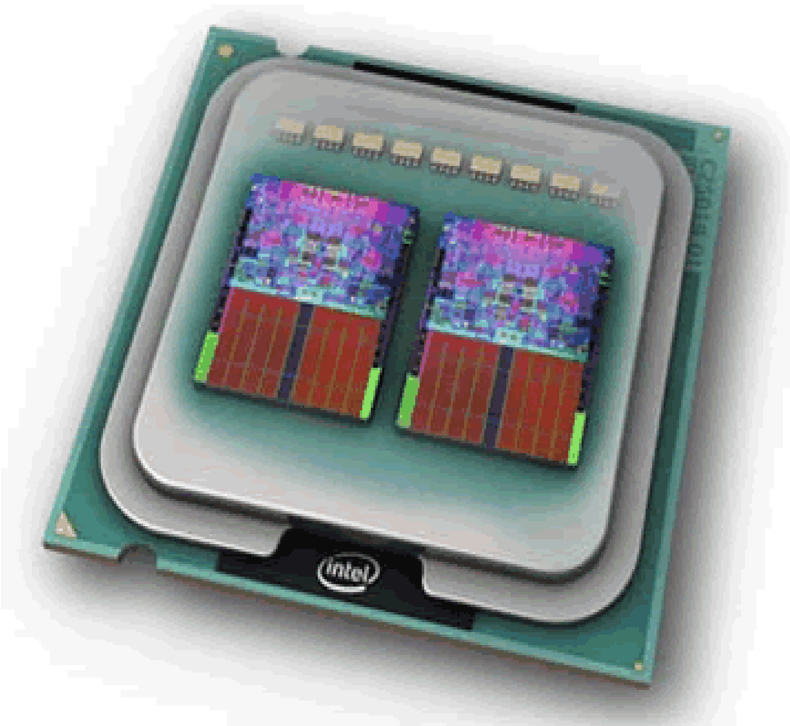


(photo courtesy of Intel Corporation.)

Some of today's proposals:

- Threads (various)
- Message Passing (various)
- Transactional Memory (various)
- OpenMP
- MPI
- Intel's Ct
- Microsoft's Parallel Fx
- Cilk Arts's Cilk
- Intel's TBB
- Nvidia's Cuda
- …

Multicore Challenges :
What about HARDWARE VERIFICATION?



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Some of today's successes :

* Execution unit verification can be done using Formal Methods !

Latest Example: The entire Nehalem execution unit has been formally verified using Symbolic Trajectory Evaluation (within the power of the STE method, of course, but still exhaustive for MANY aspects)

* Control unit verification remains a HUGE challenge; but even here, verification of controller MODELS is being done formally…

Sequential program verification remains hard!

```
main(){ int Z1, Z2, Z3;
int x1, x2;
 int z11, z12, z13, z21, z22, z23;
/* x1 = x2; */
z11 = z21; z12 = z22; z13 = z23;

if (x1 == 1) z11 = Z1; if (x1 == 2) z12 = Z2; if (x1 == 3) z13 = Z3;

if (x2 == 1) z21 = Z1; else if (x2 == 2) z22 = Z2; else if (x2 == 3) z23 = Z3;

assert((z11 + z12 + z13) == (z21 + z22 + z23)); }
```

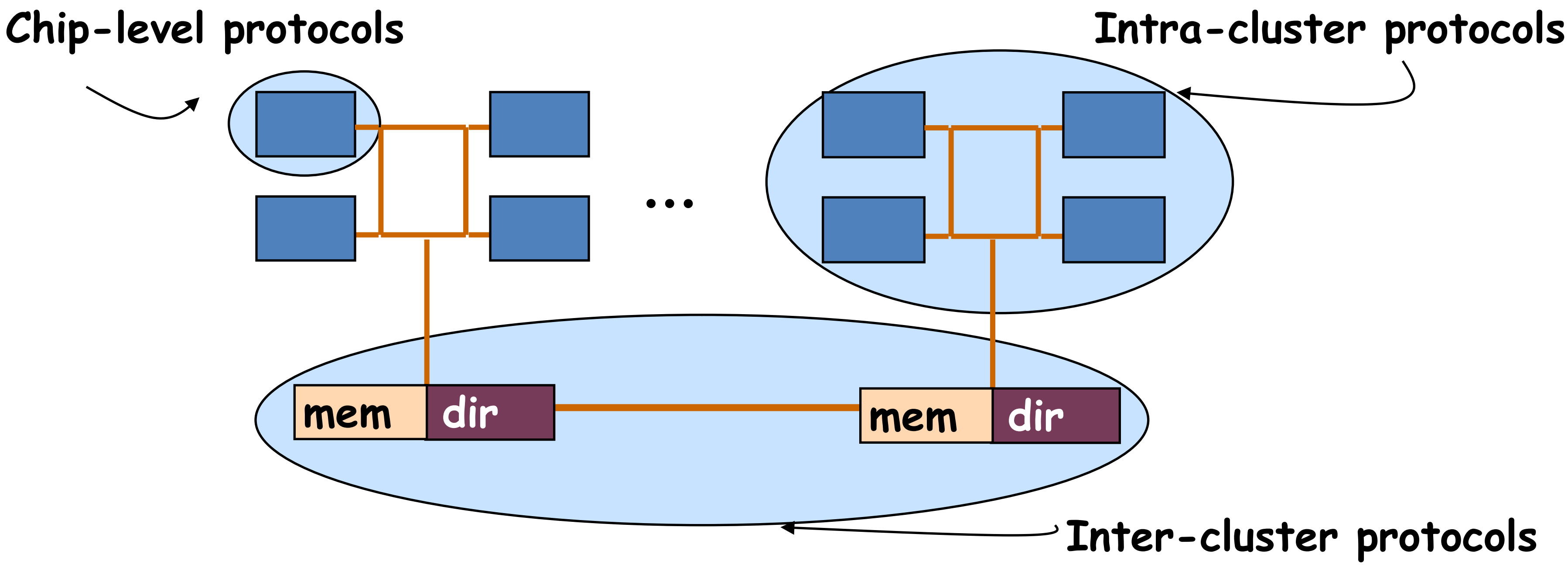
How might we prove / disprove the assertion for ALL possible initial values of the variables ?

Welcome to symbolic verification – a Formal Verification Method (STE is very similar to this style of reasoning…)

HW Control Verification Challenges (e.g.)

Cache Coherence Protocols are becoming VERY complex.

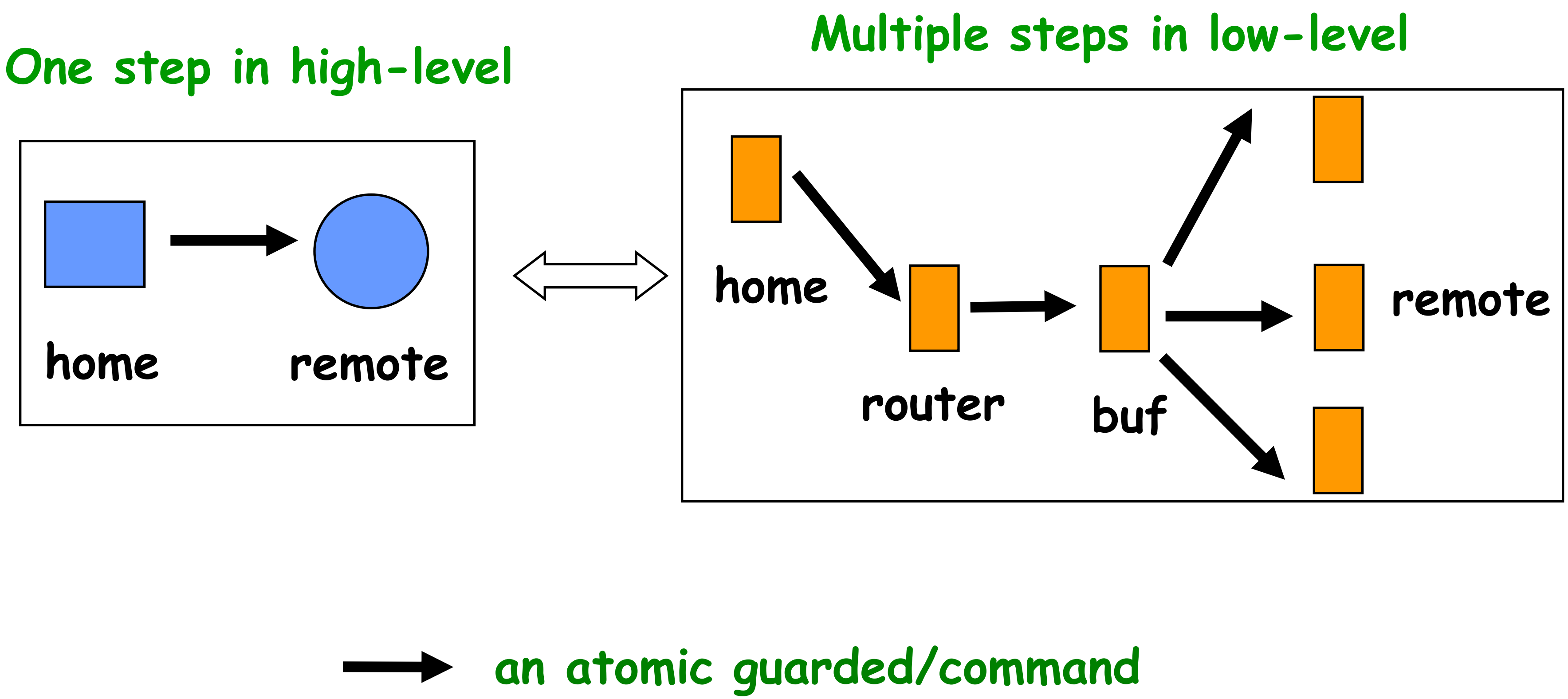
No industry builds a microprocessor without formally verifying them at a high level (conceptual level) of “guard / action” rules…



State Space grows multiplicatively across the hierarchy!

Verification will become harder

HW implementations of cache coherence protocols exhibit fine-grained concurrency – again formal methods are enjoying growing successes (but a lot remains to be done).



Other issues in HW verification : growing analog behavior of “digital components”

Back to our main topic – CONCURRENCY!

Concurrency verification is harder !!

```
main(){ int Z1, Z2, Z3;
int x1, x2;
 int z11, z12, z13, z21, z22, z23;
/* x1 = x2; */
z11 = z21; z12 = z22; z13 = z23;

if (x1 == 1) z11 = Z1; if (x1 == 2) z12 = Z2; if (x1 == 3) z13 = Z3;

if (x2 == 1) z21 = Z1; else if (x2 == 2) z22 = Z2; else if (x2 == 3) z23 = Z3;
assert((z11 + z12 + z13) == (z21 + z22 + z23)); }
```

At each “; “ lurks a bug !!
*see below

(* More specifically: at each “grain boundary” of atomicity lurks a potential interleaving that was not considered…)

Q: Why is concurrent program debugging hard ?

A: Too many interleavings !!

Card Deck 0	Card Deck 1
0:	0:
1:	1:
2:	2:
3:	3:
4:	4:
5:	5:

- Suppose only the interleavings of the red cards matter
- Then don’t try all riffle-shuffles (12!) / ((6!) (6!)) = 924
- Instead just try TWO shuffles of the decks !!

The Growth of $(n.p)! / (n!)^p$

Thread 1	....	Thread p
1:		1:
2:		2:
3:		3:
4:		4:
...		...
n:		n:

- Unity / Murphi “guard / action” rules : n=1, p=R ⇨ R! interleavings
- p = 3, n = 5 ⇨ 10^6 interleavings
- p = 3, n = 6 ⇨ $17 * 10^6$ interleavings
- p = 4, n = 5 ⇨ 10^{10} interleavings

Ad-hoc Testing is INEFFECTIVE for thread verification !

Thread 1	….	Thread p
1:		1:
2:		2:
3:		3:
4:		4:
…		…
n:		n:

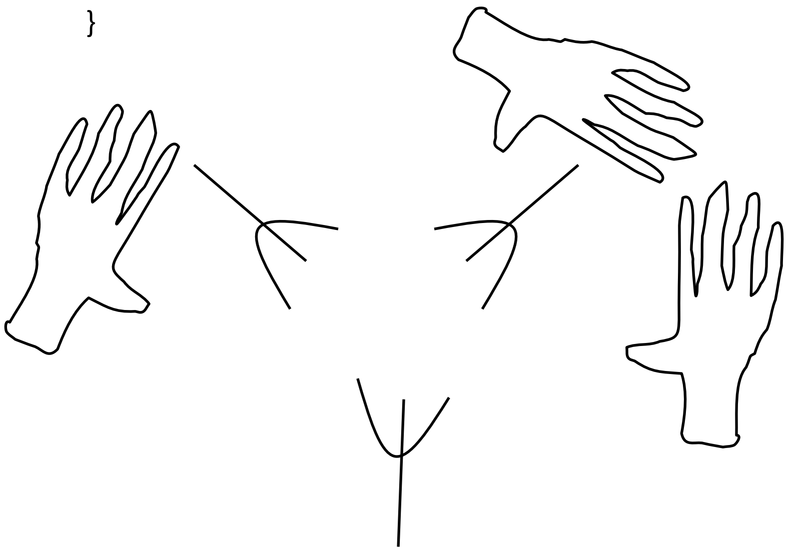
- MUST reduce the number of interleavings considered
- Rigorous proof to back omitting interleavings
- DYNAMIC PARTIAL ORDER REDUCTION achieves both

Example: Dining Philosophers in C / PThreads...

```
#include <stdlib.h>     // Dining Philosophers with no deadlock
#include <pthread.h>    // all phils but "odd" one pickup their
#include <stdio.h>      // left fork first; odd phil picks
#include <string.h>     // up right fork first
#include <malloc.h>
#include <errno.h>
#include <sys/types.h>
#include <assert.h>

#define NUM_THREADS 3

pthread_mutex_t mutexes[NUM_THREADS];
pthread_cond_t conditionVars[NUM_THREADS];
int permits[NUM_THREADS];
pthread_t tids[NUM_THREADS];

int data = 0;

void * Philosopher(void * arg){
 int i;
 i = (int)arg;

 // pickup left fork
 pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
 while (permits[i%NUM_THREADS] == 0) {
  printf("P%d : tryget F%d\n", i, i%NUM_THREADS);

pthread_cond_wait(&conditionVars[i%NUM_THREADS],&mutexes[i%N
UM_THREADS]);
 }
permits[i%NUM_THREADS] = 0;
 printf("P%d : get F%d\n", i, i%NUM_THREADS);
 pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);

 // pickup right fork
 pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
 while (permits[(i+1)%NUM_THREADS] == 0) {
  printf("P%d : tryget F%d\n", i, (i+1)%NUM_THREADS);

pthread_cond_wait(&conditionVars[(i+1)%NUM_THREADS],&mutexes[
(i+1)%NUM_THREADS]);
 }
 permits[(i+1)%NUM_THREADS] = 0;
 printf("P%d : get F%d\n", i, (i+1)%NUM_THREADS);
 pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);

 //printf("philosopher %d thinks \n",i);
 printf("%d\n", i);

 //  data = 10 * data + i;

 fflush(stdout);


 // putdown right fork
 pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
 permits[(i+1)%NUM_THREADS] = 1;
 printf("P%d : put F%d\n", i, (i+1)%NUM_THREADS);
 pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
 pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);
```

…Philosophers in PThreads

```
// putdown left fork
 pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
 permits[i%NUM_THREADS] = 1;
 printf("P%d : put F%d \n", i, i%NUM_THREADS);
 pthread_cond_signal(&conditionVars[i%NUM_THREADS]);
 pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);

 // putdown right fork
 pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
 permits[(i+1)%NUM_THREADS] = 1;
 printf("P%d : put F%d \n", i, (i+1)%NUM_THREADS);
 pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
 pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);


 return NULL;

}

int main(){
 int i;

 for (i = 0; i < NUM_THREADS; i++)
  pthread_mutex_init(&mutexes[i], NULL);
 for (i = 0; i < NUM_THREADS; i++)
  pthread_cond_init(&conditionVars[i], NULL);
 for (i = 0; i < NUM_THREADS; i++)
  permits[i] = 1;

 for (i = 0; i < NUM_THREADS-1; i++){
  pthread_create(&tids[i], NULL,  Philosopher, (void*)(i) );
 }

 pthread_create(&tids[NUM_THREADS-1], NULL,
  OddPhilosopher, (void*)(NUM_THREADS-1) );

 for (i = 0; i < NUM_THREADS; i++){
   pthread_join(tids[i], NULL);
  }

 for (i = 0; i < NUM_THREADS; i++){
   pthread_mutex_destroy(&mutexes[i]);
 }
 for (i = 0; i < NUM_THREADS; i++){
   pthread_cond_destroy(&conditionVars[i]);
 }

 //printf(" data = %d \n", data);

 //assert( data != 201);
 return 0;
}
```

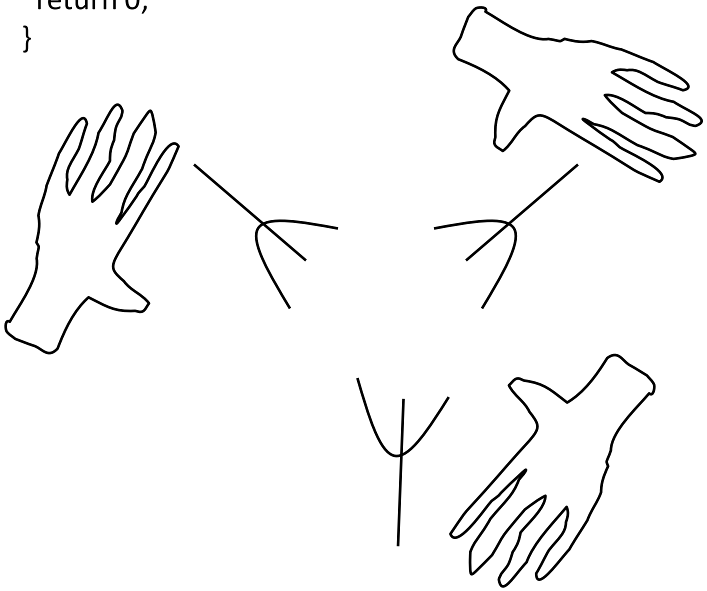


‘Plain run’ of Philosophers

```
gcc -g -O3 -o nobug examples/Dining3.c  -L ./lib -lpthread -lstdc++ -lssl

% time nobug

P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P1 : put F2
P1 : put F1
P2 : get F0
P2 : get F2
2
P2 : put F2
P2 : put F0

real        0m0.075s
user        0m0.001s
sys         0m0.008s
```

…Buggy Philosophers in PThreads

```
// putdown left fork
 pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
 permits[i%NUM_THREADS] = 1;
 printf("P%d : put F%d \n", i, i%NUM_THREADS);
 pthread_cond_signal(&conditionVars[i%NUM_THREADS]);
 pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);

 // putdown right fork
 pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
 permits[(i+1)%NUM_THREADS] = 1;
 printf("P%d : put F%d \n", i, (i+1)%NUM_THREADS);
 pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
 pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);


 return NULL;

}

int main(){
 int i;

 for (i = 0; i < NUM_THREADS; i++)
   pthread_mutex_init(&mutexes[i], NULL);
 for (i = 0; i < NUM_THREADS; i++)
   pthread_cond_init(&conditionVars[i], NULL);
 for (i = 0; i < NUM_THREADS; i++)
   permits[i] = 1;

 for (i = 0; i < NUM_THREADS-1; i++){
   pthread_create(&tids[i], NULL,  Philosopher, (void*)(i) );
 }

 pthread_create(&tids[NUM_THREADS-1], NULL,
   Philosopher, (void*)(NUM_THREADS-1) );

 for (i = 0; i < NUM_THREADS; i++){
   pthread_join(tids[i], NULL);
 }

 for (i = 0; i < NUM_THREADS; i++){
   pthread_mutex_destroy(&mutexes[i]);
 }
 for (i = 0; i < NUM_THREADS; i++){
   pthread_cond_destroy(&conditionVars[i]);
 }

 //printf(" data = %d \n", data);

 //assert( data != 201);
 return 0;
}
```



‘Plain run’ of buggy philosopher .. bugs missed by testing

```
gcc -g -O3 -o buggy examples/Dining3Buggy.c  -L ./lib -lpthread -lstdc++ -lssl

% time buggy

P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P1 : put F2
P1 : put F1
P2 : get F2
P2 : get F0
2
P2 : put F0
P2 : put F2

real      0m0.084s
user      0m0.002s
sys       0m0.011s
```

Jiggling Schedule in Buggy Philosopher..

```
#include <stdlib.h>    // Dining Philosophers with no deadlock
#include <pthread.h>   // all phils but "odd" one pickup their
#include <stdio.h>     // left fork first; odd phil picks
#include <string.h>    // up right fork first
#include <malloc.h>
#include <errno.h>
#include <sys/types.h>
#include <assert.h>

#define NUM_THREADS 3

pthread_mutex_t mutexes[NUM_THREADS];
pthread_cond_t conditionVars[NUM_THREADS];
int permits[NUM_THREADS];
pthread_t tids[NUM_THREADS];

int data = 0;

void * Philosopher(void * arg){
  int i;
  i = (int)arg;

  // pickup left fork
  pthread_mutex_lock(&mutexes[i%NUM_THREADS]);
  while (permits[i%NUM_THREADS] == 0) {
    printf("P%d : tryget F%d\n", i, i%NUM_THREADS);

pthread_cond_wait(&conditionVars[i%NUM_THREADS],&mutexes[i%N
UM_THREADS]);
  }
permits[i%NUM_THREADS] = 0;
  printf("P%d : get F%d\n", i, i%NUM_THREADS);
  pthread_mutex_unlock(&mutexes[i%NUM_THREADS]);
```

nanosleep (0) added here

```
  // pickup right fork
  pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
  while (permits[(i+1)%NUM_THREADS] == 0) {
    printf("P%d : tryget F%d\n", i, (i+1)%NUM_THREADS);

pthread_cond_wait(&conditionVars[(i+1)%NUM_THREADS],&mutexes[
(i+1)%NUM_THREADS]);
  }
  permits[(i+1)%NUM_THREADS] = 0;
  printf("P%d : get F%d\n", i, (i+1)%NUM_THREADS);
  pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);

  //printf("philosopher %d thinks \n",i);
  printf("%d\n", i);

  //  data = 10 * data + i;

  fflush(stdout);

  // putdown right fork
  pthread_mutex_lock(&mutexes[(i+1)%NUM_THREADS]);
  permits[(i+1)%NUM_THREADS] = 1;
  printf("P%d : put F%d\n", i, (i+1)%NUM_THREADS);
  pthread_cond_signal(&conditionVars[(i+1)%NUM_THREADS]);
  pthread_mutex_unlock(&mutexes[(i+1)%NUM_THREADS]);
```

'Plain runs' of buggy philosopher – bug still very dodgy …

gcc -g -O3 -o
buggynsleep examples/Dining3BuggyNanosleep0.c
 -L ./lib -lpthread -lstdc++ -lssl

% buggysleep

P0 : get F0
P0 : sleeping 0 ns
P1 : get F1
P1 : sleeping 0 ns
P2 : get F2
P2 : sleeping 0 ns
P0 : tryget F1
P2 : tryget F0
P1 : tryget F2

buggysleep

P0 : get F0
P0 : sleeping 0 ns
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : sleeping 0 ns
P2 : get F2
P2 : sleeping 0 ns
P1 : tryget F2
P2 : get F0
2
P2 : put F0
P2 : put F2
P1 : get F2
1
P1 : put F2
P1 : put F1

First run deadlocked – second did not ..

Dijkstra’s famous quote

- Testing only confirms the presence of errors…   never its absence

- MUCH MORE TRUE for concurrent software

Some terminology and an overview

- Concurrent includes Parallel (aka shared memory) and Distributed (aka message passing)
- In our research group, we have developed tools to verify PRACTICAL Parallel and Distributed software
- Currently for Pthreads (parallel) and MPI (distributed)
- This talk mainly focusses on Parallel (Pthreads / C) software verification

An important use of message passing

(BlueGene/L - Image courtesy of IBM / LLNL)

The scientific community is increasingly employing expensive supercomputers that employ distributed programming libraries….

…to program large-scale simulations in all walks of science, engineering, math, economics, etc.

(Image courtesy of Steve Parker, CSAFE, Utah)

Verification Realities

Code written using mature libraries (MPI, OpenMP, PThreads, …)

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Runtime semantics determined by realistic Compilers and Runtimes

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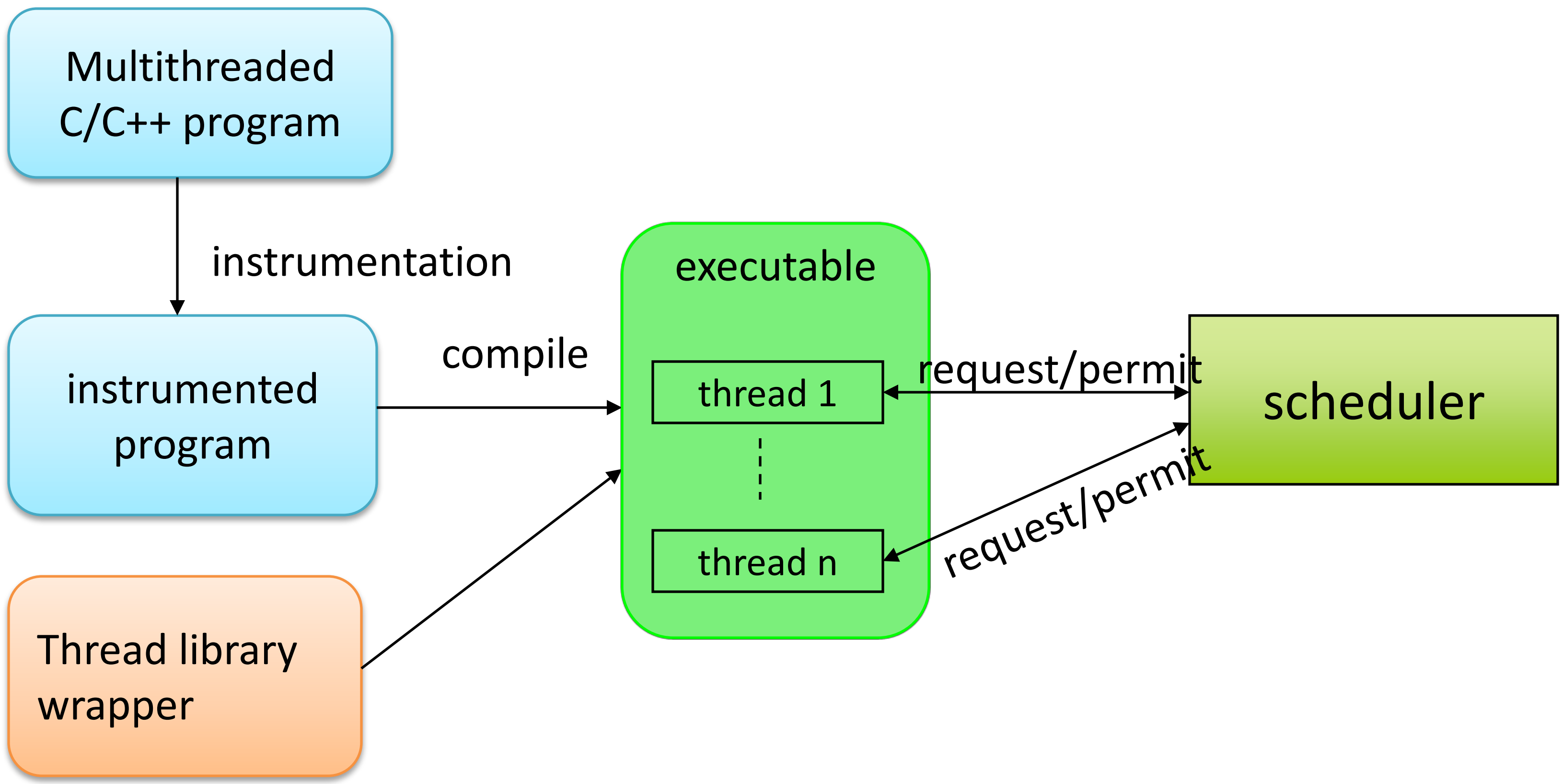
API calls made from real programming languages (C, Fortran, C++)

Runtime semantics determined by realistic Compilers and Runtimes

How best to verify codes that will run on actual platforms?

Workflow of Parallel Software Verification tool “Inspect”



Result of instrumentation

```
void * Philosopher(void * arg){
 int i;
 i = (int)arg;
 ...
 pthread_mutex_lock(&mutexes[i%3]);
 ...
 while (permits[i%3] == 0) {
  printf("P%d : tryget F%d\n", i, i%3);
  pthread_cond_wait(...);
 }
 ...
 permits[i%3] = 0;
 ...
 pthread_cond_signal(&conditionVars[i%3]);

 pthread_mutex_unlock(&mutexes[i%3]);
 return NULL;
}
```

```
void *Philosopher(void *arg )
{ int i ;
 pthread_mutex_t *tmp ;
 {
 inspect_thread_start("Philosopher");
 i = (int )arg;
 tmp = & mutexes[i % 3]; …
 inspect_mutex_lock(tmp); …
 while (1) {
  __cil_tmp43 = read_shared_0(& permits[i % 3]);
  if (! __cil_tmp32) {
   break;
  }
  __cil_tmp33 = i % 3; …
  tmp___0 = __cil_tmp33; …
  inspect_cond_wait(...);
 }
 ...
 write_shared_1(& permits[i % 3], 0);
 ...
 inspect_cond_signal(tmp___25);
 ...
 inspect_mutex_unlock(tmp___26);
 ...
 inspect_thread_end();
 return (__retres31);
}
```

Inspect of nonbuggy and buggy Philosophers ..

./instrument file.c
./compile file.instr.c
./inspect ./target

P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P1 : put F2
P1 : put F1
P2 : get F0
P2 : get F2
2
P2 : put F2
P2 : put F0
num of threads = 1
=== run 2 ===
P0 : get F0

…

P1 : put F1

…
=== run 48 ===
P2 : get F0
P2 : get F2
2
P2 : put F2
P2 : put F0
P0 : get F0
P0 : get F1
0
P1 : tryget F1
<<
Total number of runs: 48,
Transitions explored: 1814
Used time (seconds): 7.999327

=== run 1 ===
P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P1 : put F2
P1 : put F1
P2 : get F2
P2 : get F0
2
P2 : put F0
P2 : put F2
=== run 2 ===
P0 : get F0
P0 : get F1
0
P0 : put F1
P0 : put F0
P1 : get F1
P1 : get F2
1
P2 : tryget F2
P1 : put F2
P1 : put F1

=== run 28 ===
P0 : get F0
P1 : get F1
P0 : tryget F1
P2 : get F2
P1 : tryget F2
P2 : tryget F0
Found a deadlock!!
(0, thread_start)
(0, mutex_init, 5)
(0, mutex_init, 6)
(0, mutex_init, 7)
(0, cond_init, 8)
(0, cond_init, 9)
(0, cond_init, 10)
(0, obj_write, 2)
(0, obj_write, 3)
(0, obj_write, 4)
(0, thread_create, 1)
(0, thread_create, 2)
(0, thread_create, 3)
(1, mutex_lock, 5)
(1, obj_read, 2)
(1, obj_write, 2)
(1, mutex_unlock, 5)
(2, mutex_lock, 6)
(2, obj_read, 3)
(2, obj_write, 3)
(2, mutex_unlock, 6)
(1, mutex_lock, 6)
(1, obj_read, 3)
(1, mutex_unlock, 6)
(3, mutex_lock, 7)
(3, obj_read, 4)
(3, obj_write, 4)
(3, mutex_unlock, 7)
(2, mutex_lock, 7)
(2, obj_read, 4)
(2, mutex_unlock, 7)
(3, mutex_lock, 5)
(3, obj_read, 2)
(3, mutex_unlock, 5)
(-1, unknown)

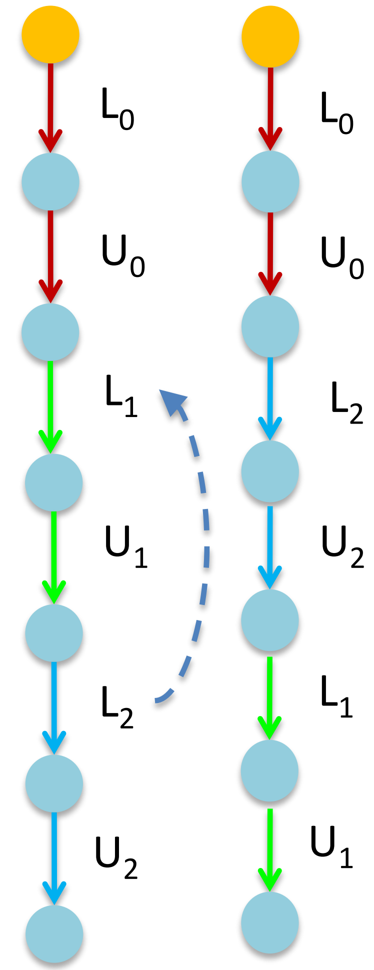
Total number of runs: 29,
killed-in-the-middle runs: 4
Transitions explored: 1193
Used time (seconds): 5.990523

The Growth of (n.p)! / (n!)^p for Diningp.c illustrating the MAIN technology behind Inspect

- Diningp.c has n = 4 (roughly)
- p = 3 : We get 34,650 (loose upper-bound) versus 48 with DPOR
- p = 5 : We get 305,540,235,000 versus 2,375 with DPOR
- DPOR really works well in reducing the number of interleavings !!
- Testing will have to exhibit its cleverness among $3 * 10^{11}$ interleavings

Dynamic Partial Order Reduction (DPOR) "animatronics"

P0	P1	P2
lock(y)	lock(x)	lock(x)
....	....	....
unlock(y)	unlock(x)	unlock(x)

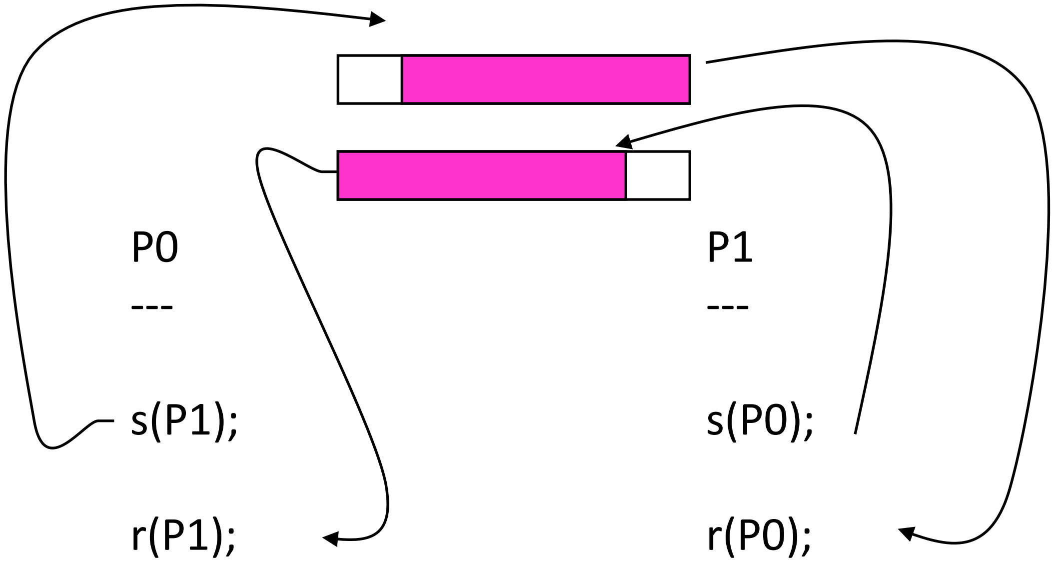


An Overview of ISP

ISP looks ONLY for "low-hanging" bugs

Three bug classes it looks for are presented next

Deadlock pattern…



P0	P1
---	---
Bcast;	Barrier;
Barrier;	Bcast;

Communication Race Pattern…

OK

P0	P1	P2
r(*);	s(P0);	s(P0);
r(P1);		

NOK

P0	P1	P2
r(*);	s(P0);	s(P0);
r(P1);		

Resource Leak Pattern…

P0

```
some_allocation_op(&handle);
```

FORGOTTEN DEALLOC !!

Why is even this much debugging hard?

The “crooked barrier” quiz will show you why…

P0	P1	P2
MPI_Isend (P2)	MPI_Barrier	MPI_Irecv (ANY)
MPI_Barrier	MPI_Isend(P2)	MPI_Barrier

Will P1’s Send Match P2’s Receive ?

MPI Behavior

The “crooked barrier” quiz

P0	P1	P2
---	---	---
MPI_Isend (P2)	MPI_Barrier	MPI_Irecv (ANY)
MPI_Barrier	MPI_Isend(P2)	MPI_Barrier

It will ! Here is the animation

MPI Behavior

The “crooked barrier” quiz

P0	P1	P2
---	---	---
MPI_Isend (P2)	MPI_Barrier	MPI_Irecv (ANY)
MPI_Barrier	MPI_Isend(P2)	MPI_Barrier

MPI Behavior

The “crooked barrier” quiz

P0	P1	P2
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MPI_Isend (P2)	MPI_Barrier	MPI_Irecv (ANY)
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MPI Behavior

The “crooked barrier” quiz

P0	P1	P2
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MPI Behavior

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MPI Behavior

The “crooked barrier” quiz

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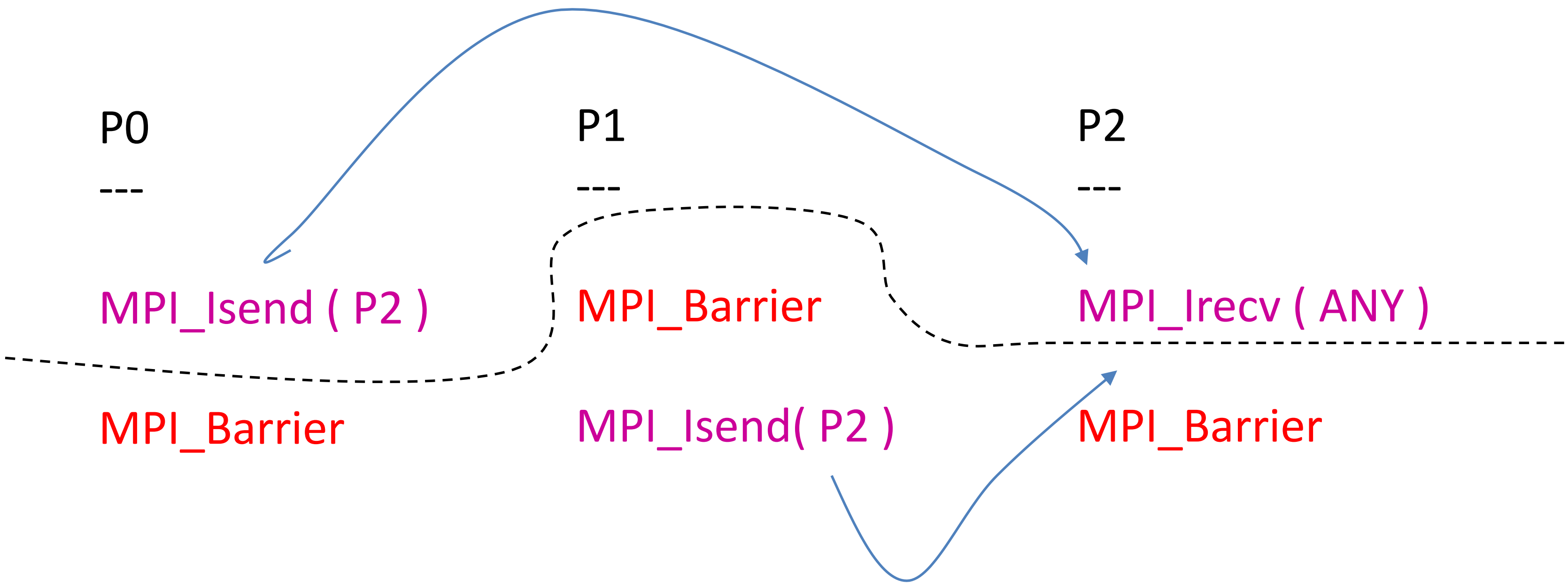
MPI_Barrier	MPI_Isend(P2)	MPI_Barrier

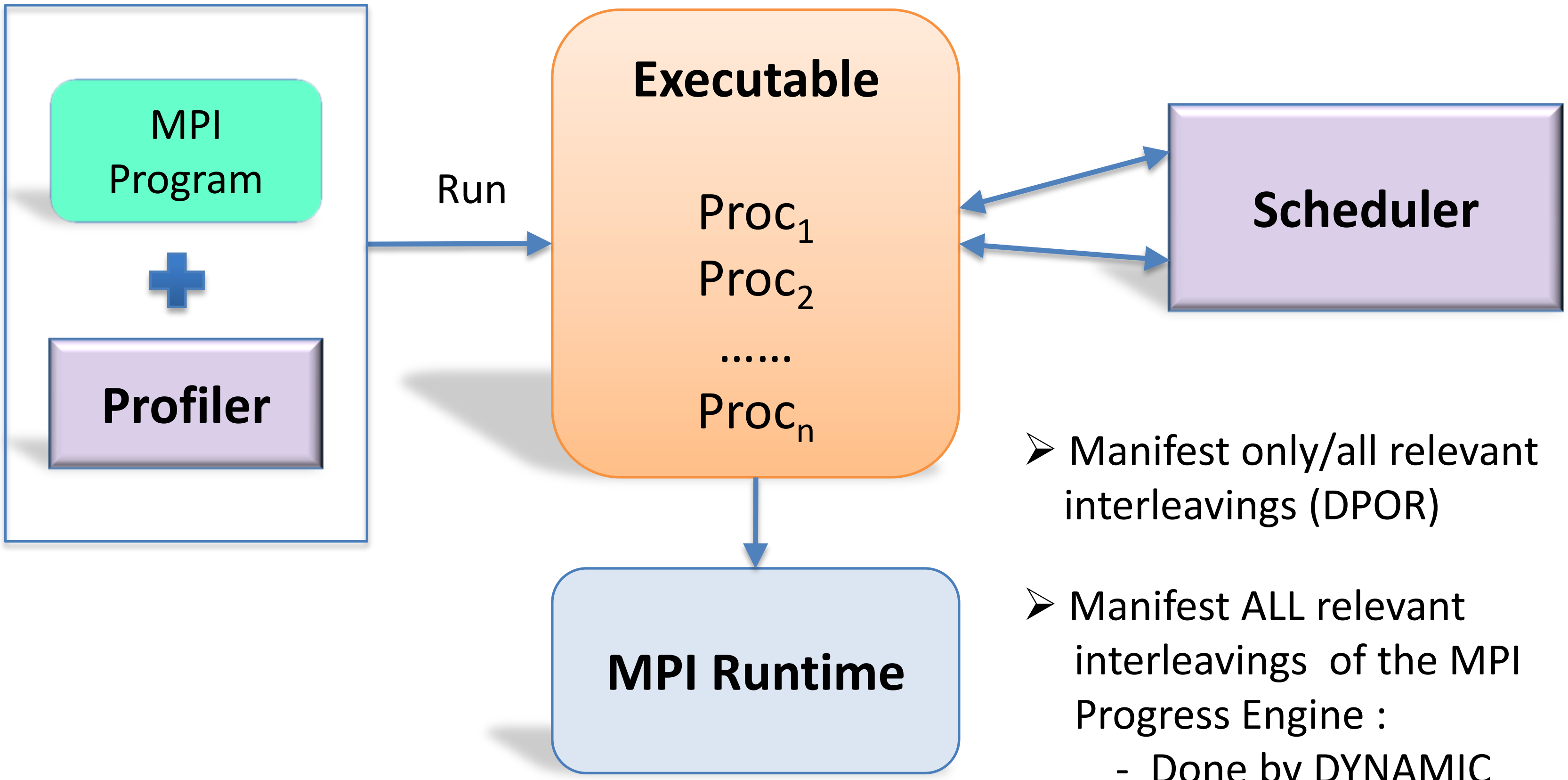
We need a dynamic verification approach to be aware of the details of the API behavior…

Reason why DPOR won't do : Can't replay with P1's send coming first!!



See our CAV 2008 paper for details (also EuroPVM / MPI 2008)

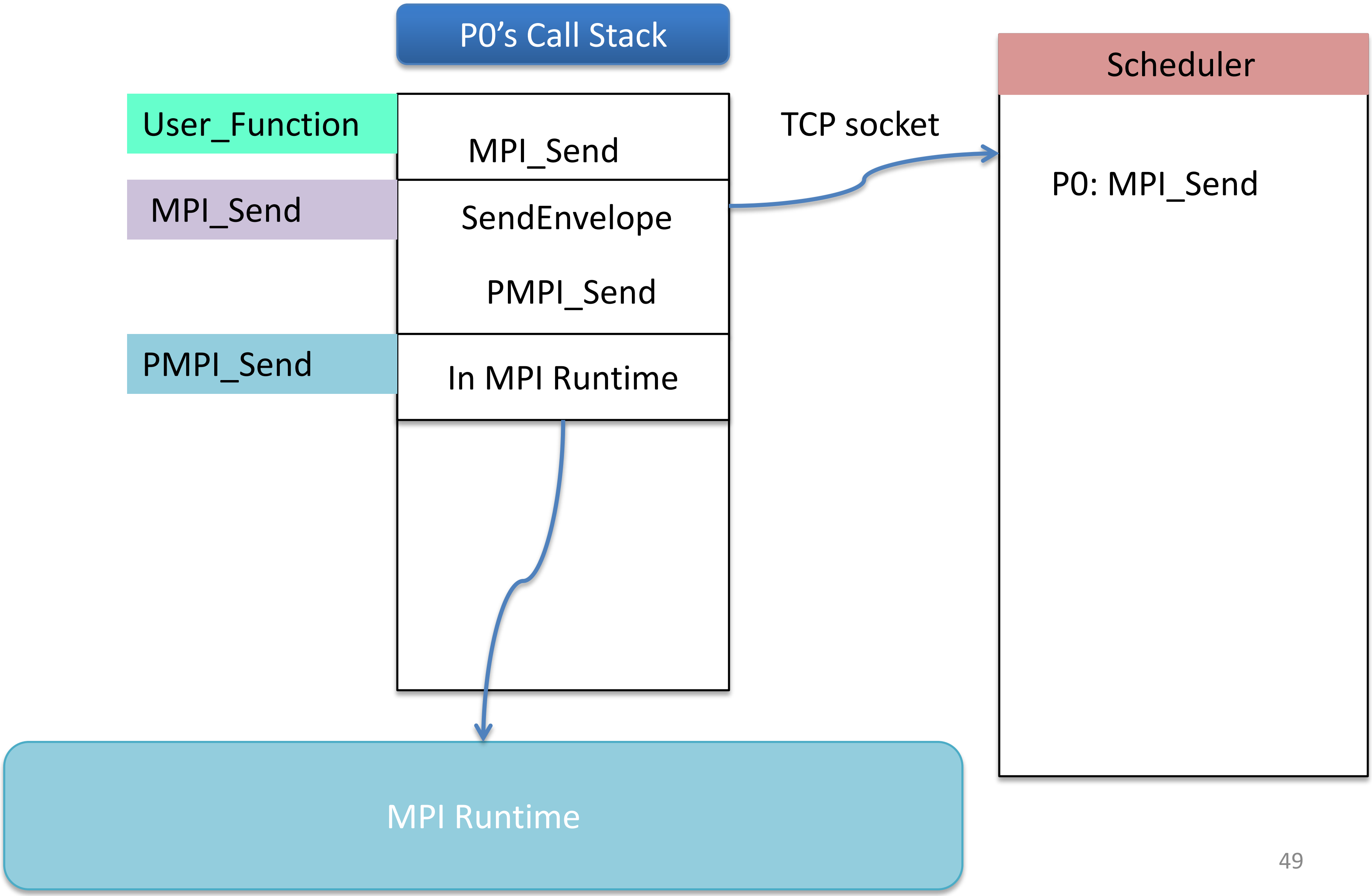
Workflow of ISP



- Manifest only/all relevant interleavings (DPOR)
- Manifest ALL relevant interleavings of the MPI Progress Engine :
  - Done by DYNAMIC REWRITING of WILDCARD Receives.

The basic PMPI trick played by ISP

Using PMPI



P0's Call Stack
User_Function
MPI_Send
MPI_Send
SendEnvelope
PMPI_Send
PMPI_Send
In MPI Runtime
TCP socket
Scheduler
P0: MPI_Send
MPI Runtime

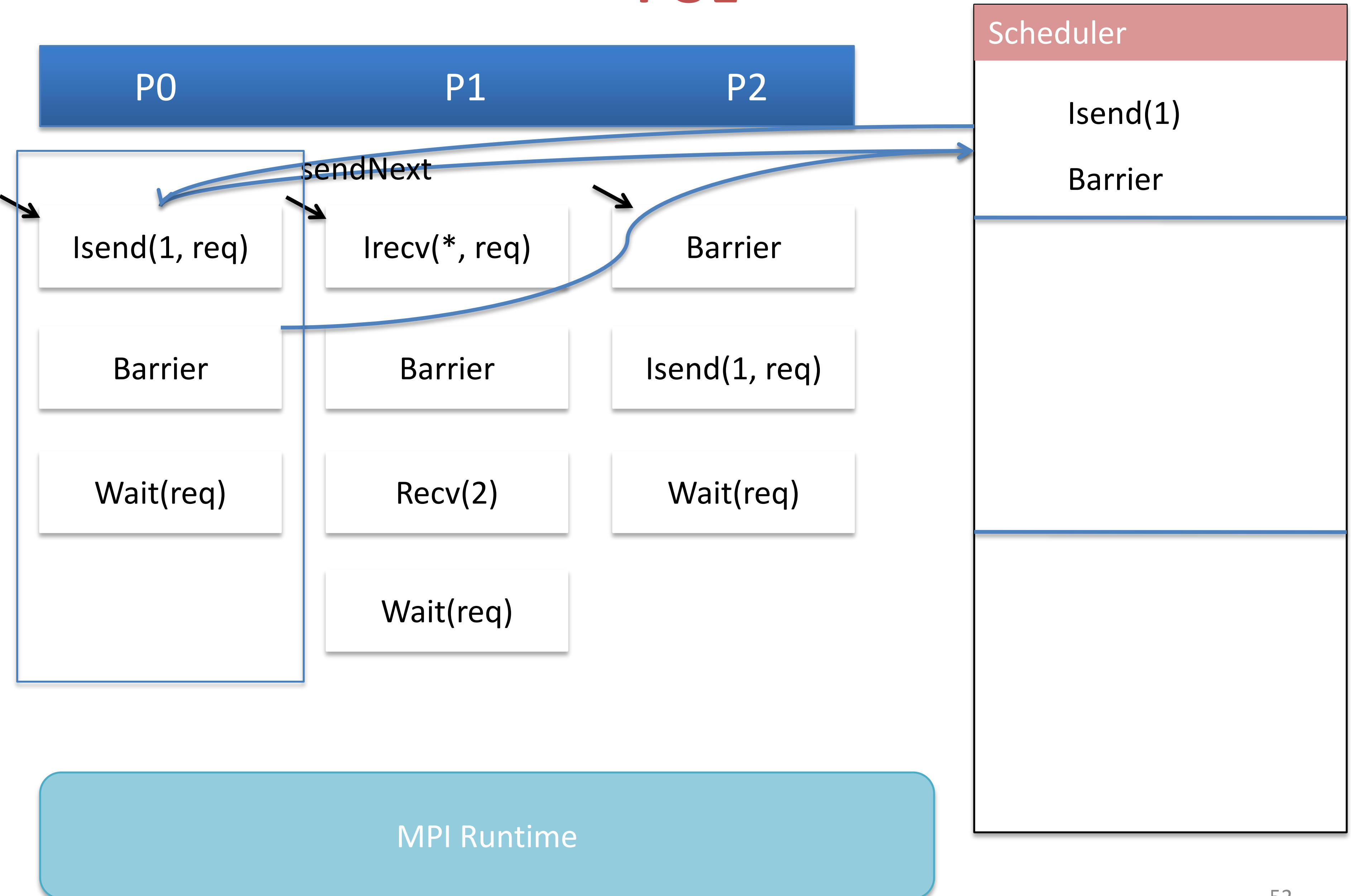
Main idea behind POE

- MPI has a pretty interesting out-of-order execution semantics
  - We “gleaned” the semantics by studying the MPI reference document, talking to MPI experts, reading the MPICH2 code base, AND using our formal semantics
- “Give MPI its own dose of medicine”
  - I.e. exploit the OOO semantics
  - Delay sending weakly ordered operations into the MPI runtime
  - Run a process, COLLECT its operations, DO NOT send it into the MPI runtime
  - SEND ONLY WHEN ABSOLUTELY POSITIVELY forced to send an action
  - This is the FENCE POINT within each process
- This way we are guaranteed to discover the maximal set of sends that can match a wildcard receive !!!

The POE algorithm

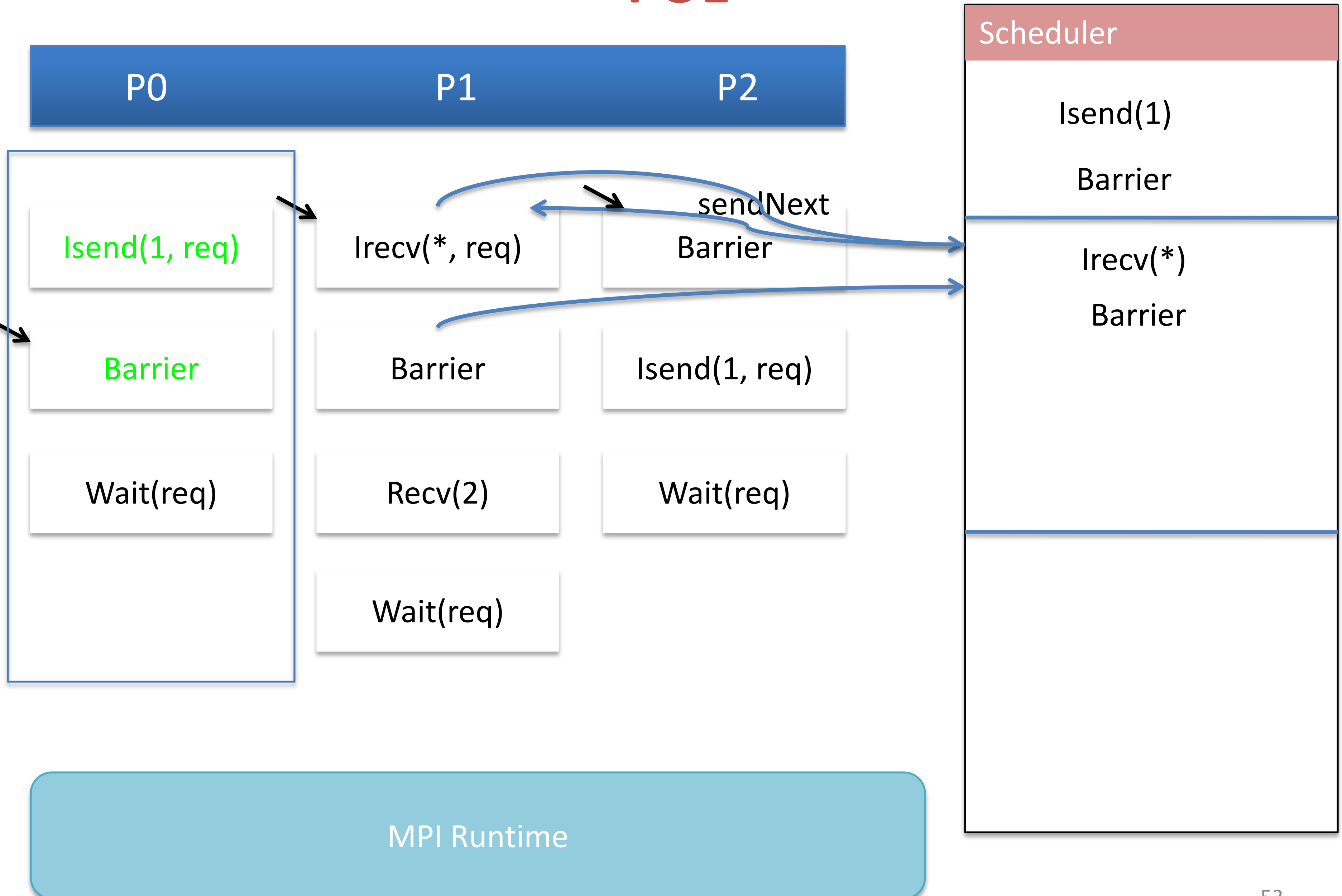
POE = Partial Order reduction avoiding Elusive Interleavings

POE



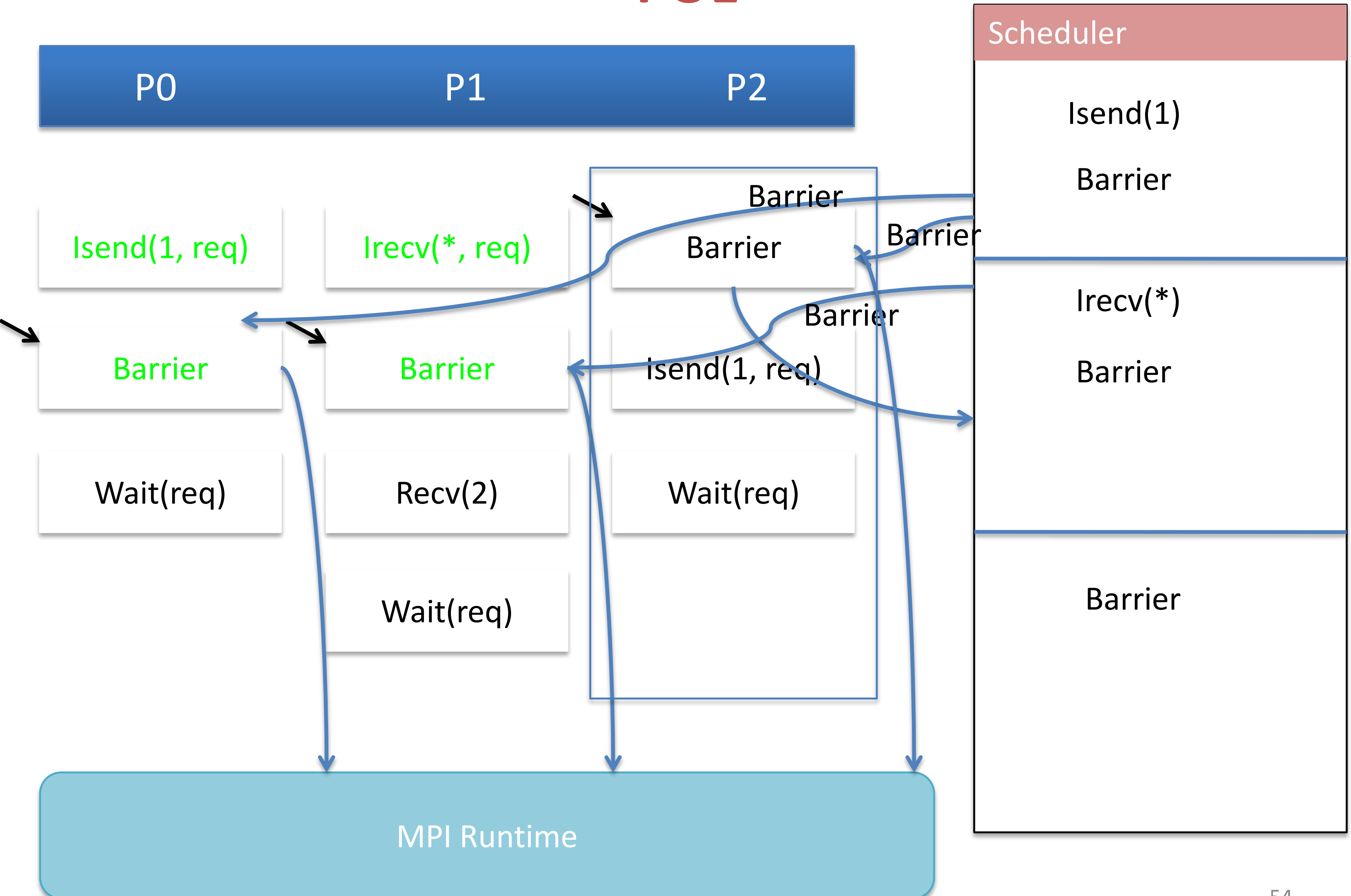
Scheduler
Isend(1)
Barrier
P0
P1
P2
sendNext
Isend(1, req)
Irecv(*, req)
Barrier
Barrier
Barrier
Isend(1, req)
Wait(req)
Recv(2)
Wait(req)
Wait(req)
MPI Runtime

POE

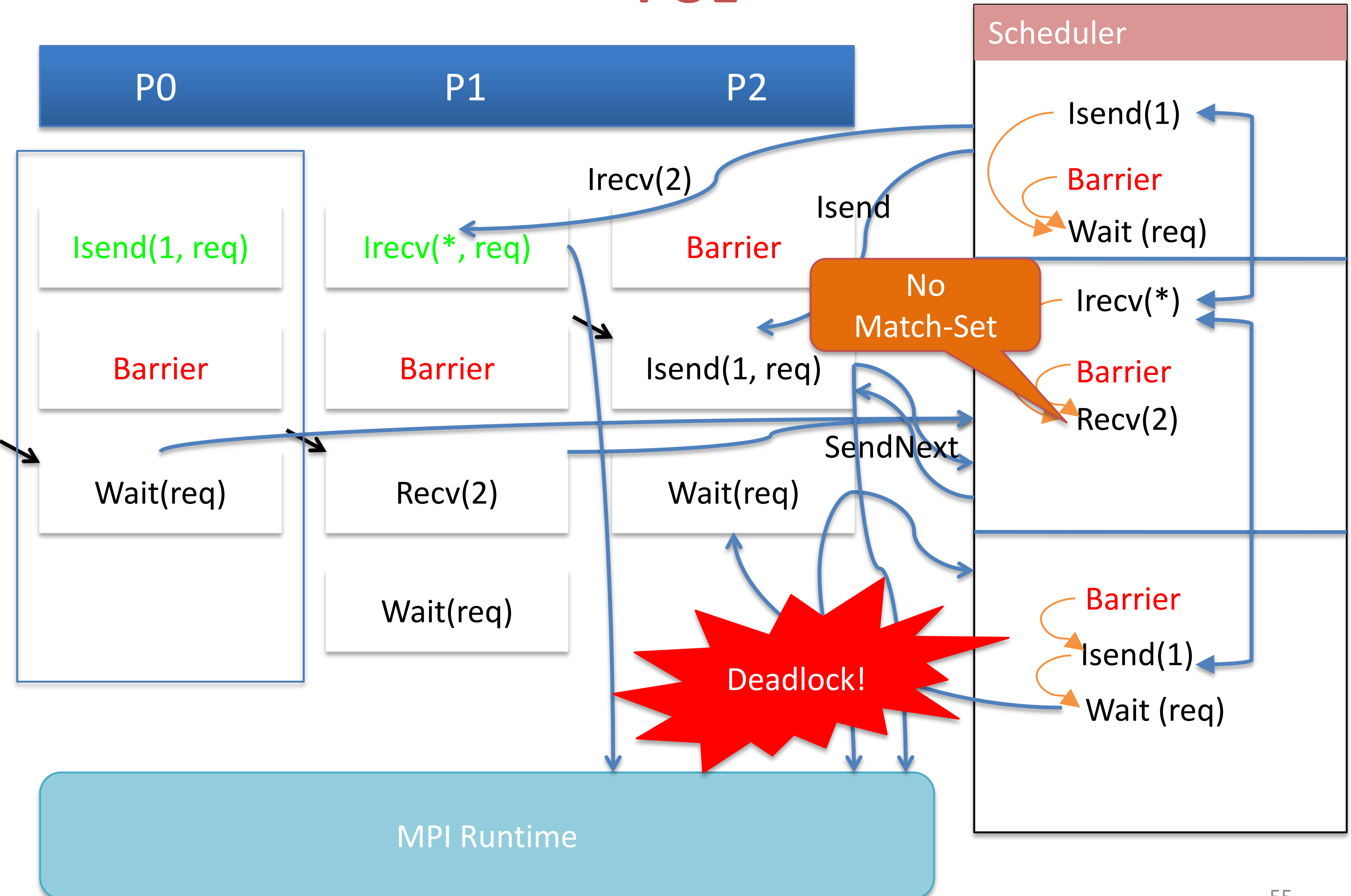


P0
P1
P2
Isend(1, req)
Irecv(*, req)
Barrier
sendNext
Barrier
Barrier
Isend(1, req)
Wait(req)
Recv(2)
Wait(req)
Wait(req)
MPI Runtime
Scheduler
Isend(1)
Barrier
Irecv(*)
Barrier

POE


P0
P1
P2
Scheduler
Isend(1)
Barrier
Irecv(*)
Barrier
Barrier
Barrier
Barrier
Barrier
Barrier
Isend(1, req)
Irecv(*, req)
Barrier
Barrier
Barrier
Isend(1, req)
Wait(req)
Recv(2)
Wait(req)
Wait(req)
MPI Runtime

POE



P0
P1
P2
Scheduler
Irecv(2)
Isend
Isend(1, req)
Irecv(*, req)
Barrier
Barrier
Barrier
Isend(1, req)
Wait(req)
Recv(2)
Wait(req)
Wait(req)
No Match-Set
SendNext
Isend(1)
Barrier
Wait (req)
Irecv(*)
Barrier
Recv(2)
Barrier
Isend(1)
Wait (req)
Deadlock!
MPI Runtime

Once ISP discovers the maximal set of sends that can match a wildcard receive, it employs DYNAMIC REWRITING of wildcard receives into SPECIFIC RECEIVES !!

Obtaining and Running Inspect and ISP

- From http://www.cs.utah.edu/formal_verification
- But get it from the authors for the latest versions (ISP will be released "today")
- http://www.cs.utah.edu/~yuyang/inspect
- May need to obtain libssl-dev
- Need Ocaml-3.10.2 or higher
- Remove the contents of the "cache directory" autom4te.cache in case "make" loops

- bin/instrument file.c
- bin/compile file.instr.c
- inspect –help
- inspect target
- inspect –s target

The demos to follow will show that these ideas do work !!

DEMO 1 : Seq C program verification

DEMO 2 : Inspect

DEMO 3 : ISP