Pulse: A Dynamic Deadlock Detection Mechanism Using Speculative Execution

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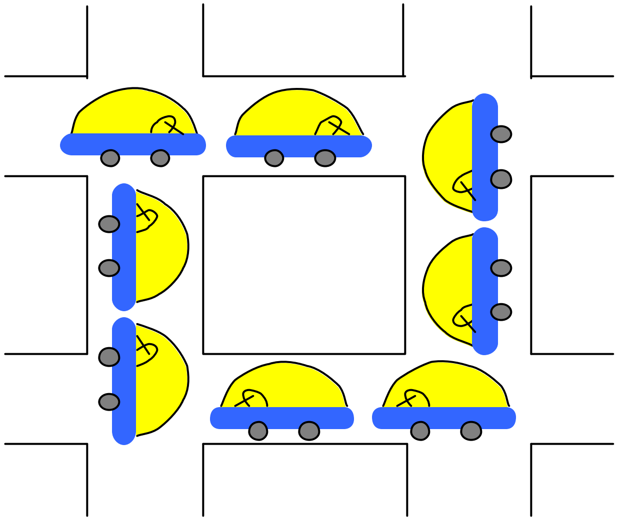
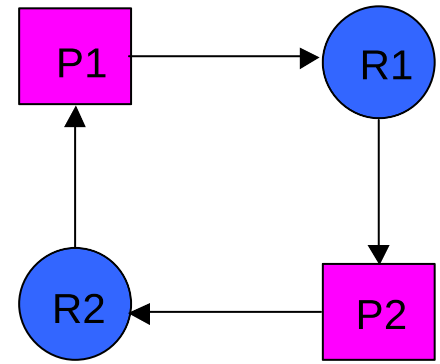
Motivation

- Deadlock is potential problem for all multithreaded programs
- Existing detection techniques have limitations
- Goals
  - Increase the types of deadlocks that can be detected
  - Provide insights into cause of deadlock

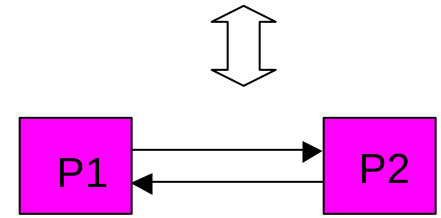


Limitations of Existing Techniques

- Dynamic deadlock detection
  - Timeouts
    - Inaccurate, no insight about cause of deadlock
  - Wait-for-graphs (WFGs)
    - General resource graphs with single-unit reusable resources
    - Often applied to lock-like resources
- Static deadlock detection
  - Model checking
    - Accurate, but state space too large
  - RacerX (Engler and Ashcraft SOSP 2003)
    - Practical, but only lock-like resources
- Both WFGs and RacerX consider only lock-like resources



General resource graph



Wait-for-graph

Systems & Architecture

Beyond Locks

- Need to handle non-lock-like (consumable) resources
- Why is it challenging?
  - Consumable resources have no owners
    - Pipes, synchronization semaphores, etc.
  - Any process could be a producer at some future time
    - Any process could write to a pipe or “up” a semaphore

Process 1	Process 2	Process 3
P(sem) // block	…	…
	V(sem)	V(sem)

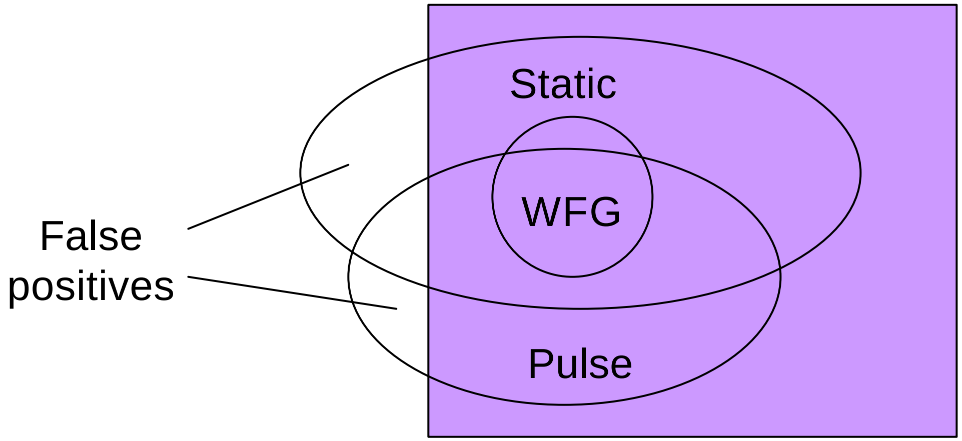
- Knowing only the present state is not enough for identifying all dependences!

The Big Idea

- We need to look into the future
  - What would process X do if it were not blocked?
  - Would it unblock process Y in the future?
- If we can answer these questions, then we know how processes depend on each other
- Could use static tool, but state space explosion, variable aliasing, etc.
- We use dynamic scheme to look into the future

Introducing Pulse

- Speculatively unblock each blocked process
- Discover dependences by running ahead
- Construct general resource graph with consumable resources



Venn diagram of deadlocks detectable by static tools, WFG-based dynamic tools, and Pulse

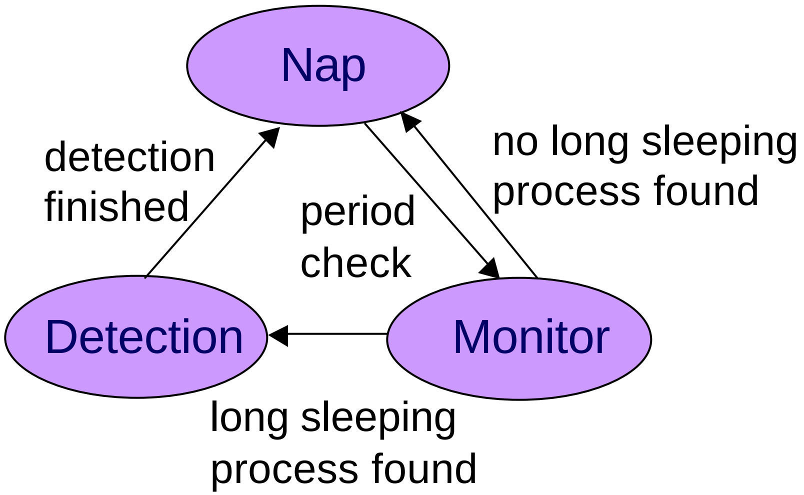
- Pulse can detect deadlocks that the other tools cannot

Outline

- Motivation
- Overview of Pulse
- Design
- Implementation
- Evaluation
- Conclusion

Overview of Pulse

- Features: Dynamic, speculative execution, general resource graph
- Pulse runs as a daemon process



- Three modes
  - Nap: sleeps in kernel
  - Monitor: looks for long-sleeping processes/threads
  - Detection
    - Long-sleeping processes are potentially deadlocked

Detection Mode

- Identify events long-sleeping processes are waiting for
  - E.g., *semaphore up*: V(sem)
- Fork each process to create a speculative process
- Unblock speculative process
  - E.g., “up” the semaphore in its own address space
- Record events generated by speculative processes
  - E.g., all *semaphore up* operations
- Construct general resource graph and check for cycle

Example: Smokers Problem

- Three smokers, one agent
- Three ingredients: paper, tobacco, matches
- Each smoker has one ingredient, but needs two more
- Agent puts out two at a time
- One smoker gets them and signals agent to continue

Smoker 1	Smoker 2	Smoker 3	Agent

while (1) {
  P(tobacco)
  P(paper) // block
  V(order)
}
	while (1) {
	  P(paper) // block
	  P(matches)
	  V(order)
	}
		while (1) {
		  P(matches)
		  P(tobacco) // block
		  V(order)
		}
			while (1) {
			  P(order) // block
			  V(one of tobacco, paper,
			    matches at random)
			  V(one of the three at
			    random but not above)
			}

- Semaphores for synchronization, not mutual exclusion

Constructing Process Nodes

- Enter detection mode after all blocked for a long time
- Construct a *process node* for each long-sleeping process

Smoker 1

```
while (1) {
  P(tobacco)
  P(paper) // block
  V(order)
}
```

Smoker 2

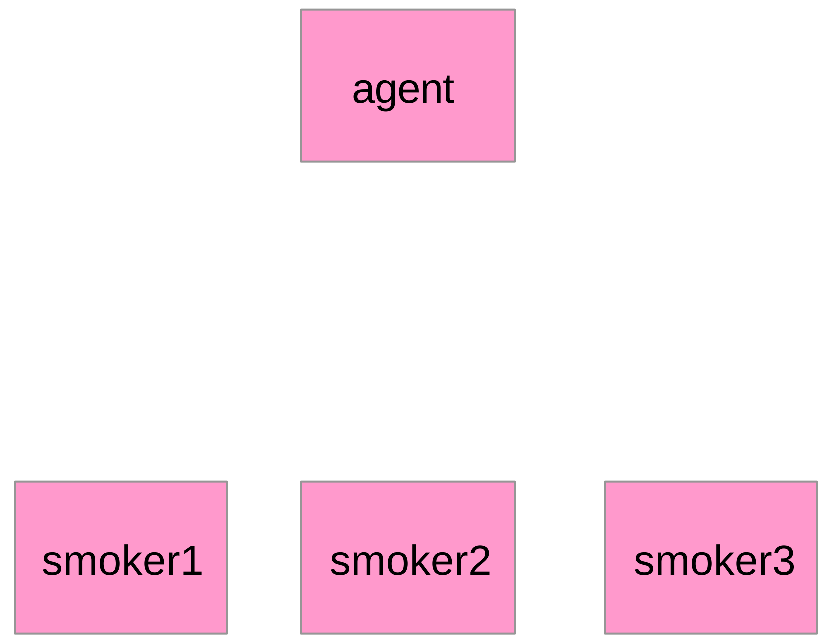
```
while (1) {
  P(paper) // block
  P(matches)
  V(order)
}
```

Smoker 3

```
while (1) {
  P(matches)
  P(tobacco) // block
  V(order)
}
```

Agent

```
while (1) {
  P(order) // block
  V(one of tobacco, paper,
     matches at random)
  V(one of the three at
     random but not above)
}
```



Constructing Event Nodes

- Construct an *event node* for the event each process is waiting for

Smoker 1

```
while (1) {
   P(tobacco)
   P(paper) // block
   V(order)
}
```

Smoker 2

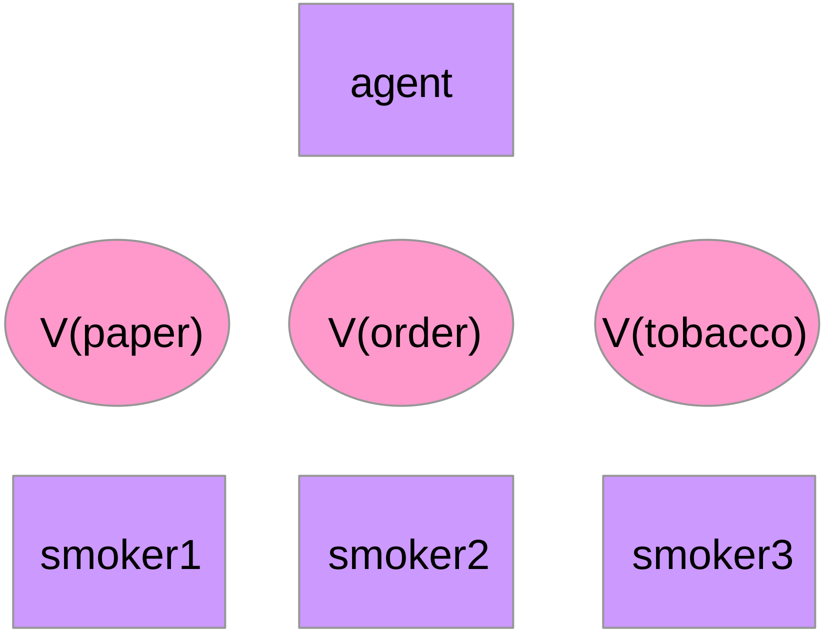
```
while (1) {
   P(paper) // block
   P(matches)
   V(order)
}
```

Smoker 3

```
while (1) {
   P(matches)
   P(tobacco) // block
   V(order)
}
```

Agent

```
while (1) {
   P(order) // block
   V(one of tobacco, paper,
      matches at random)
   V(one of the three at
      random but not above)
}
```



Constructing Request Edges

- Construct *request edge* from process node to event node

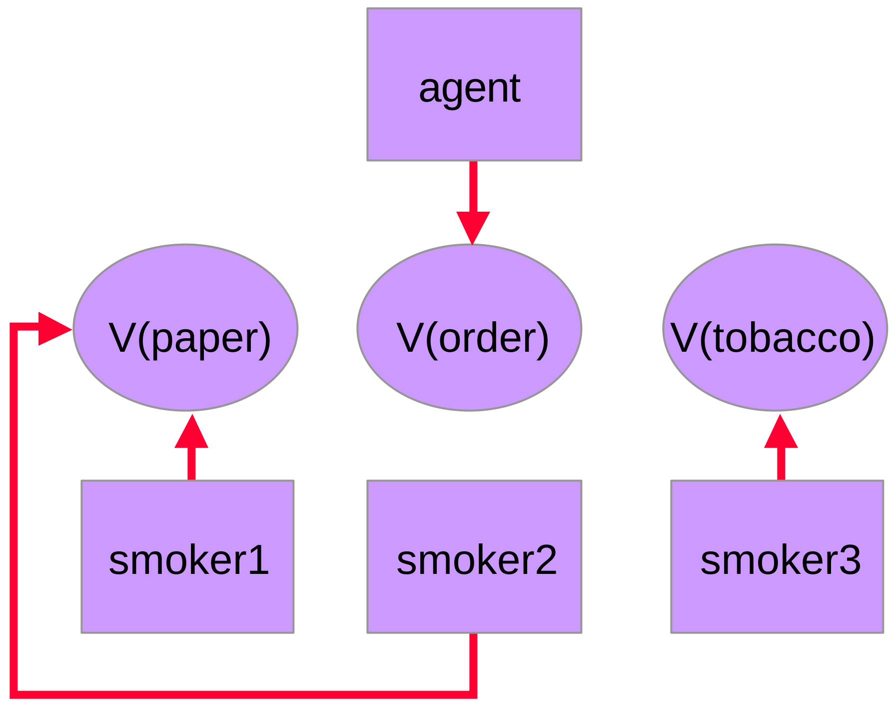
waiting for V(paper)

Smoker 1
```
while (1) {
  P(tobacco)
  P(paper) // block
  V(order)
}
```

Smoker 2
```
while (1) {
  P(paper) // block
  P(matches)
  V(order)
}
```

Smoker 3
```
while (1) {
  P(matches)
  P(tobacco) // block
  V(order)
}
```

Agent
```
while (1) {
  P(order) // block
  V(one of tobacco, paper,
     matches at random)
  V(one of the three at
     random but not above)
}
```



Constructing Producer Edges

- Speculatively execute processes ahead
- Smoker 1 produces V(order), agent produces V(paper)
- Construct *producer edge* from event to process node

Smoker 1

```
while (1) {
  P(tobacco)
  P(paper) // block
  V(order)
}
```

Smoker 2

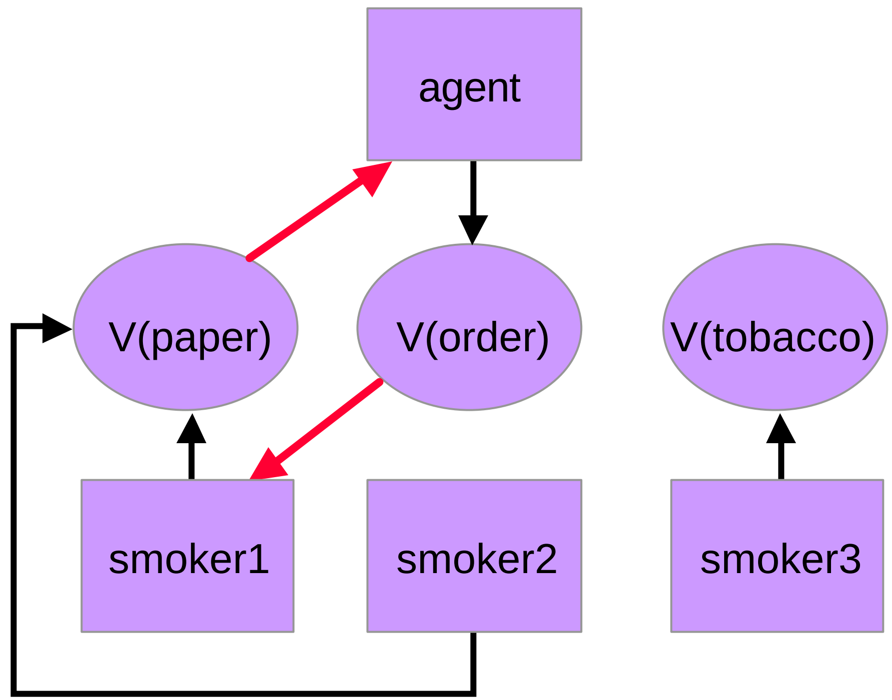
```
while (1) {
  P(paper) // block
  P(matches)
  V(order)
}
```

Smoker 3

```
while (1) {
  P(matches)
  P(tobacco) // block
  V(order)
}
```

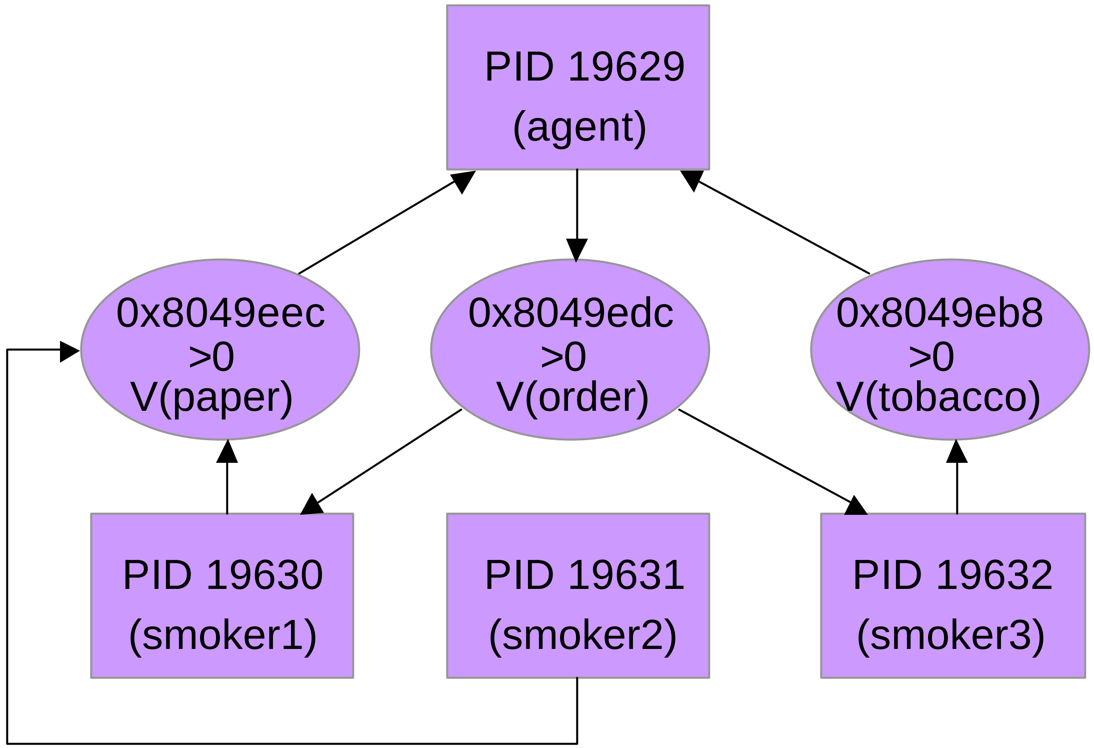
Agent

```
while (1) {
  P(order) // block
  V(one of tobacco, paper,
      matches at random)
  V(one of the three at
      random but not above)
}
```



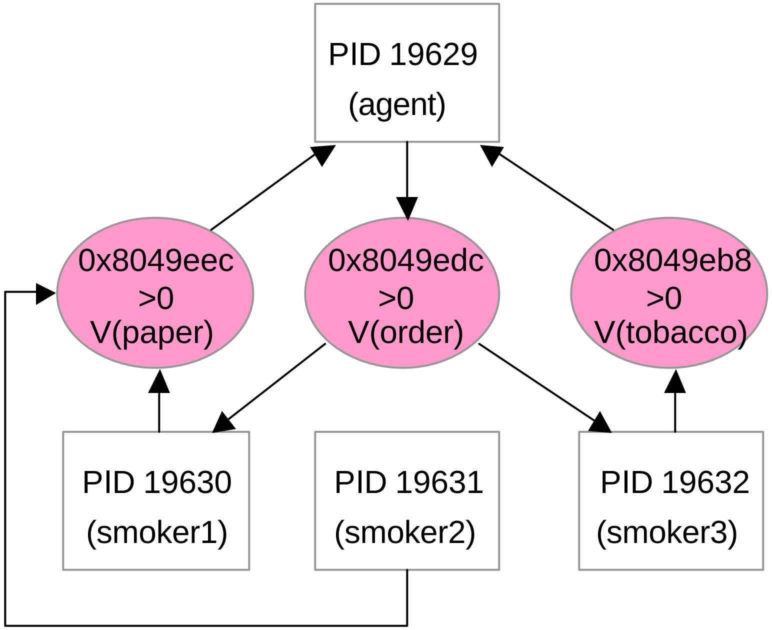
Final Resource Graph

- A cycle indicates potential deadlock
- Processes: represented by PIDs
- Events: (*resource*, *condition*) $\rightarrow$ (semaphore address, > 0)



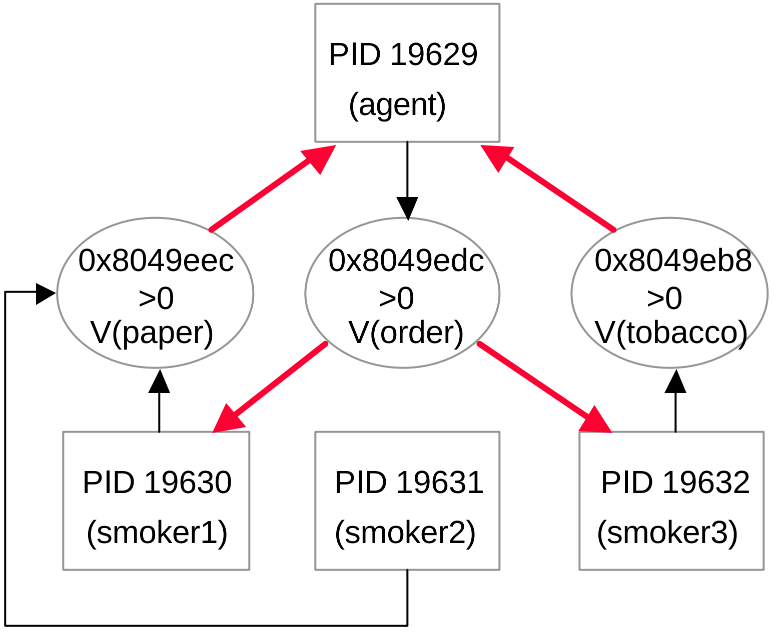
Design Issues – Constructing Nodes

- Process nodes
  - Those processes asleep for a long time
- Event nodes
  - Need to know the events for which a process is waiting
  - Modify all blocking system calls to record the events
  - Modified calls record events in a per-process structure



Design Issues – Constructing Edges

- Request edges
  - Constructed together with event nodes
- Producer edges
  - Need to know what events a process can produce
  - Modify all counterpart system calls (calls that unblock the blocking ones)
  - Record events in an event buffer until the speculative process terminates (normal exit, full buffer, timeout)



Safe Speculation

- Cannot change state of any other process
  - No change to memory state of other processes
  - No writes to file system (including I/O devices)
  - No signals to other processes

Solution:

- Similar to Fraser and Chang USENIX'03
- Fork with copy-on-write enabled
- Modify unsafe system calls (e.g., write, kill)
  - Speculative processes record the events they produce
  - Then return immediately

Limitations of Pulse

- False positives
  - Speculation may run unrealistic program paths
  - May have wrong cycles if resources are not consumable
  - For resources that are not single-unit reusable, a cycle is only necessary but not sufficient
- False negatives
  - Speculative processes miss relevant events
    - Programmer forgot V(sem)
    - Speculation not long enough
    - Event buffer full
    - Unrealistic program paths
  - Self-breaking mechanisms with timeouts

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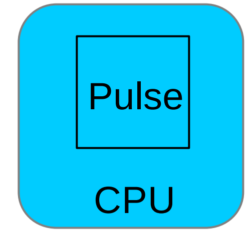
Implementation

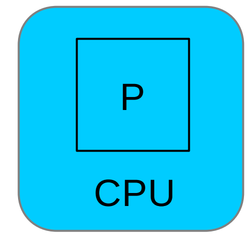
- Linux kernel 2.6.8.1
- Modified three blocking system calls
  - futex, write (to pipe), and poll
- Modified four counterpart system calls
  - futex, read, and write/writev
- Our approach can be applied easily to modify other syscalls
- Forking an arbitrary process: fork(*P*)
  - Existing fork copies the *caller process*
  - Adding a process argument to existing fork doesn't work
  - We use existing fork with only slight modifications

Forking Blocked Processes

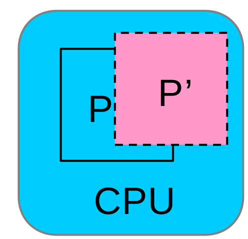
1. To fork process *P*, first switch *P* in using our own context-switch function



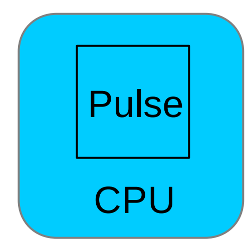
2. *P* calls the usual fork routine to create speculative process *P'*



3. *P'* fakes the awaited event, calls syscall_exit with success, and resumes *P*'s program



4. Finally, *P* switches the Pulse process back in and then *P* goes back to sleep



Evaluation

- All experiments on an 8-processor IBM x445 eServer
- Fork was the most involved part in coding
  - But only one-time effort
  - Code is small and efficient
    - 94 lines of C, 47 lines of inline assembly, 7 lines assembly
- Three deadlock benchmarks
  - Smokers Problem (discussed earlier)
  - Dining-philosophers Problem
  - Apache 2.0.49

Dining Philosophers Problem

- Deadlock if all philosophers take left forks at same time

Philosopher i

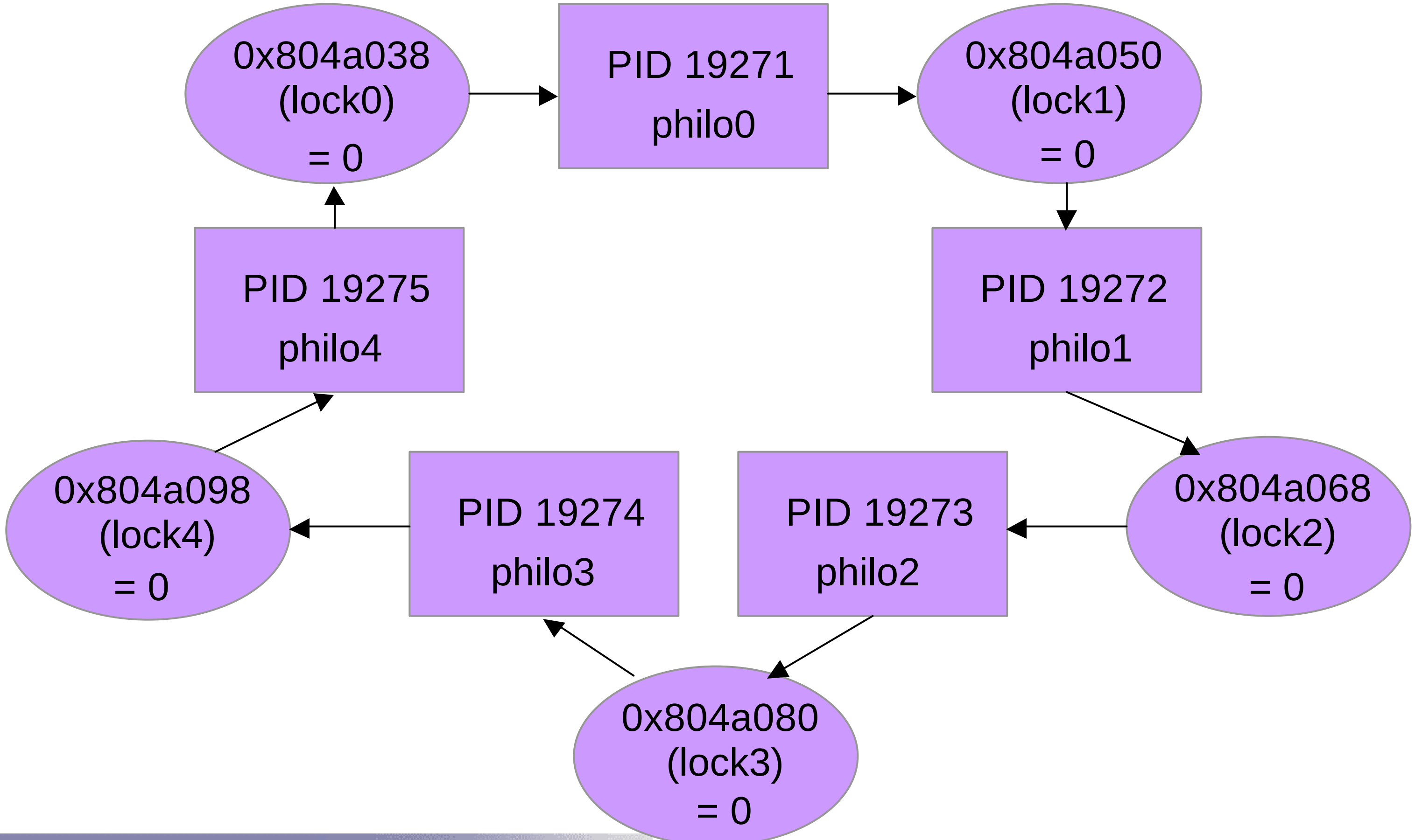
```
        while (1) {
            think()
            lock(fork[i])              // take left fork
block ➡     lock(fork[(i+1) % 5]       // take right fork
            eat();
            unlock(fork[i]);           // put left fork
            unlock(fork[(i+1) % 5]     // put right fork

        }
```

- All existing tools target this type of deadlock

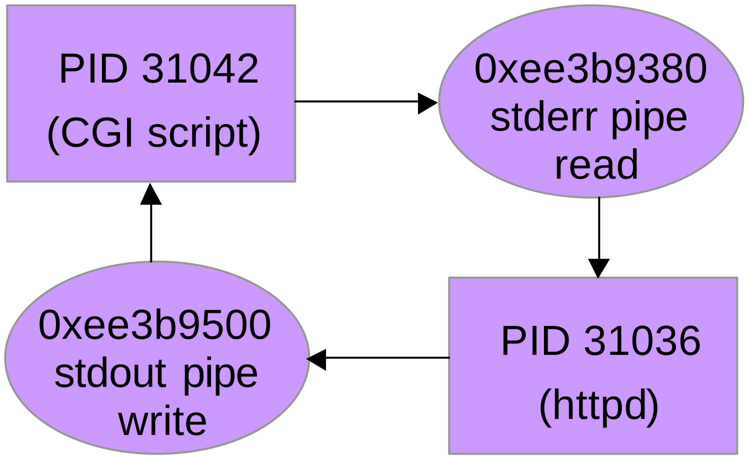
Dining Philosophers Problem

- Hex numbers are virtual addresses of lock variables
- Squares: processes, circles: events, edges: dependences



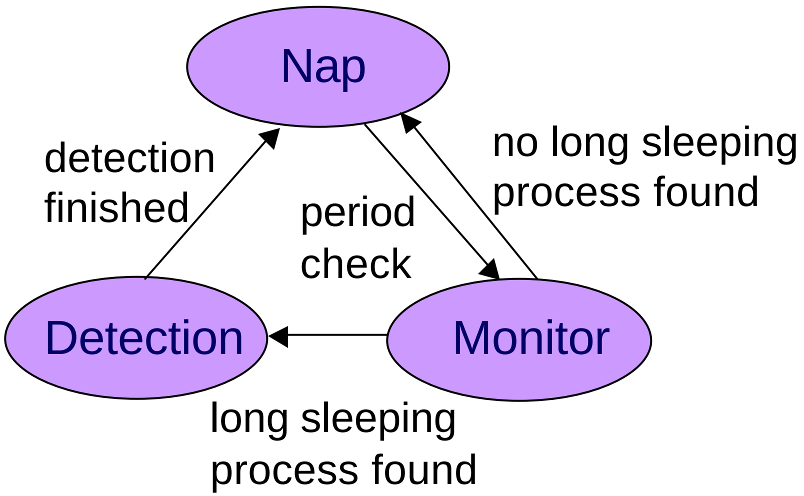
Apache Deadlock

- Apache 2.0.49 with prefork Multi-Processing Module (MPM)
- Two-process deadlock:
  - A CGI script's process blocks when writing to stderr pipe
  - An httpd process blocks when reading from stdout pipe
  - Each can be unblocked only by the other
- Not detectable by WFGs and RacerX
- Pulse successfully detects it
- Hex numbers are addresses of pipe inode structures



Performance Overhead

- Overhead of the modified system calls
  - Average slowdown per call: futex 0.2%, write 0.9%, poll 1%
- Overhead of periodic checking
  - Nap to monitor, and back to nap (5-min check interval): ~0.3 seconds for 2000 processes
  - Apache Bench (1-min interval): throughput difference < 0.2% w/ and w/o Pulse



- Overhead of deadlock detection
  - Less than 3 seconds from detection to finish

Conclusion

- Deadlock is potential problem for all multithreaded programs
- Existing detection tools focus on lock-like resources
- Pulse: dynamic, speculation, general resource graph
- Can detect deadlocks with non-lock-like resources
  - E.g., synchronization semaphores, pipes
- Linux implementation
- Evaluation
  - Dining-philosophers, smokers, Apache
  - Negligible performance overhead