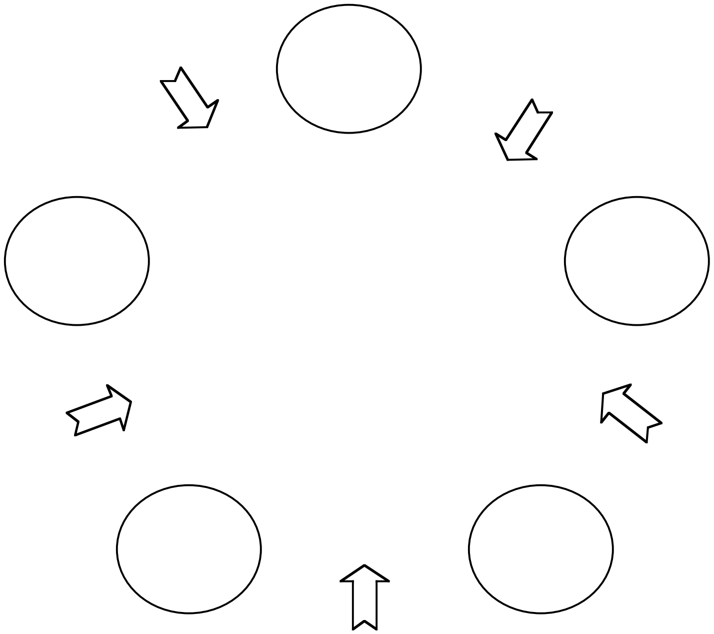
High-Level Synchronization

Dining Philosophers

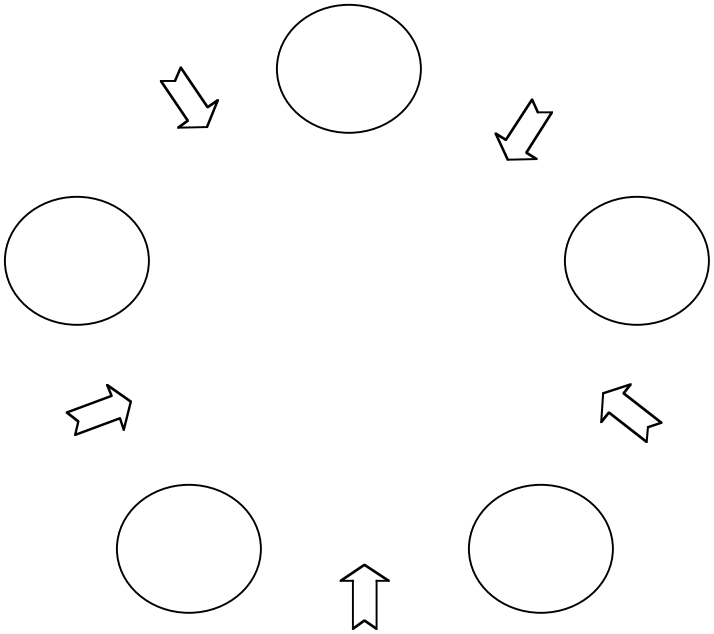


```
while(TRUE) {
  think();
  eat();
}
```

Quiz: Write a synchronization schema for the problem

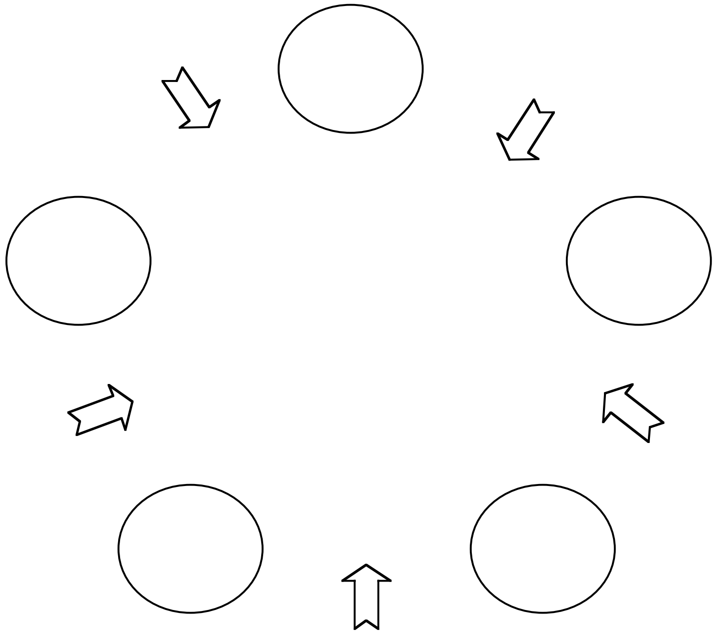
Dining Philosophers Problem

```
philosopher(int i) {
  while(TRUE) {
    // Think
    // Eat
    P(fork[i]);
      P(fork[(i+1) mod 5]);
        eat();
      V(fork[(i+1) mod 5]);
    V(fork[i]);
  }
}
semaphore fork[5] = (1,1,1,1,1);
fork(philosopher, 1, 0);
fork(philosopher, 1, 1);
fork(philosopher, 1, 2);
fork(philosopher, 1, 3);
fork(philosopher, 1, 4);
```



One Answer to the Quiz

```
philosopher(int i) {
  while(TRUE) {
    // Think
    // Eat
    j = i % 2;
    P(fork[(i+j) mod 5]);
      P(fork[(i+1-j) mod 5]);
        eat();
      V(fork[(i+1-j) mod 5]);
    V(fork[[(i+j) mod 5]);
  }
}
semaphore fork[5] = (1,1,1,1,1);
fork(philosopher, 1, 0);
fork(philosopher, 1, 1);
fork(philosopher, 1, 2);
fork(philosopher, 1, 3);
fork(philosopher, 1, 4);
```



Abstracting Semaphores

- Relatively simple problems, such as the dining philosophers problem, can be very difficult to solve
- Look for abstractions to simplify solutions
  - AND synchronization
  - Events
  - Monitors
  - … there are others ...

AND Synchronization

- Given two resources, R_1 and R_2
- Some processes access R_1, some R_2, some both in the same critical section
- Need to avoid deadlock due to ordering of P operations
- $P_{simultaneous}(S_1, \ldots, S_n)$

AND Synchronization (cont)

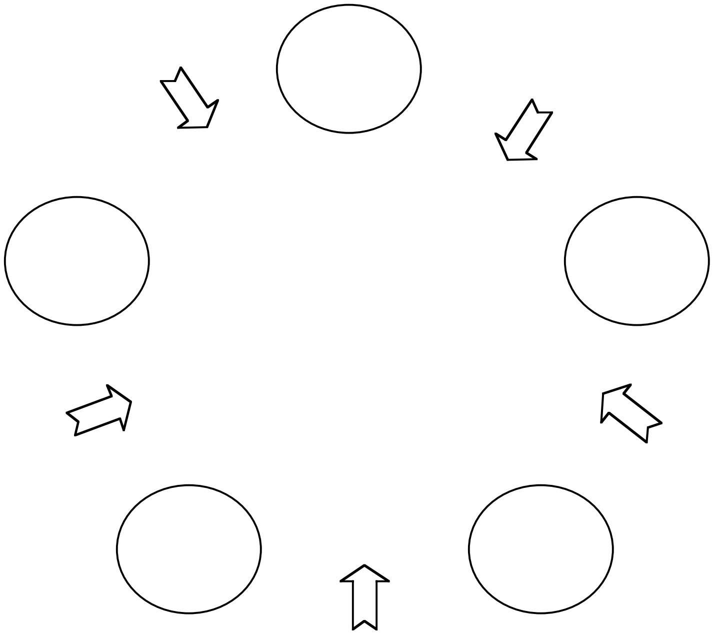
```
semaphore mutex = 1;
semaphore block = 0;
```

```
P.sim(int S, int R) {
  P(mutex);
    S--;
    R--;
    if((S < 0) || (R < 0)) {
      V(mutex);
      P(block);
    }
    else
      V(mutex);
}
```

```
V.sim(int S, int R) {
  P(mutex);
    S++;
    R++;
    if(((S >= 0) &&
        (R >= 0)) &&
       ((S == 0) ||
        (R == 0)))
          V(block);
      V(mutex);
}
```

Dining Philosophers Problem

```
philosopher(int i) {
  while(TRUE) {
    // Think
    // Eat
    $P_{simultaneous}$(fork[i], fork [(i+1) mod 5]);
      eat();
    $V_{simultaneous}$(fork[i], fork [(i+1) mod 5]);
  }
}
semaphore fork[5] = (1,1,1,1,1);
fork(philosopher, 1, 0);
fork(philosopher, 1, 1);
fork(philosopher, 1, 2);
fork(philosopher, 1, 3);
fork(philosopher, 1, 4);
```



Events

- May mean different things in each OS
- A process can *wait* on an event until another process *signals* the event
- Have *event descriptor* (“event control block”)
- Active approach
  - Multiple processes can wait on an event
  - Exactly one process is unblocked when a signal occurs
  - A signal with no waiting process is ignored
- May have a *queue* function that returns number of processes waiting on the event

Example

```
class Event {
  …
public:
  void signal();
  void wait()
  int queue();
}
```

```
shared Event topOfHour;
. . .
// Wait until the top of the hour before proceding
topOfHour.wait();
// It’s the top of the hour ...
```

```
shared Event topOfHour;
. . .
while(TRUE)
  if(isTopOfHour())
    while(topOfHour.queue() > 0)
      topOfHour.signal();
}
. . .
```

UNIX Signals

- A UNIX signal corresponds to an event
  - It is *raised* by one process (or hardware) to call another process's attention to an event
  - It can be *caught* (or ignored) by the subject process
- Justification for including signals was for the OS to inform a user process of an event
  - User pressed `delete` key
  - Program tried to divide by zero
  - Attempt to write to a nonexistent pipe
  - etc.

More on Signals

- Each version of UNIX has a fixed set of signals (Linux has 31 of them)
- `signal.h` defines the signals in the OS
- App programs can use `SIGUSR1` & `SIGUSR2` for arbitrary signalling
- Raise a signal with `kill(pid, signal)`
- Process can let default handler catch the signal, catch the signal with own code, or cause it to be ignored

More on Signals (cont)

- OS signal system call
  - To ignore: `signal(SIG#, SIG_IGN)`
  - To reinstate default: `signal(SIG#, SIG_DFL)`
  - To catch: `signal(SIG#, myHandler)`
- Provides a facility for writing your own event handlers in the style of interrupt handlers

Signal Handling

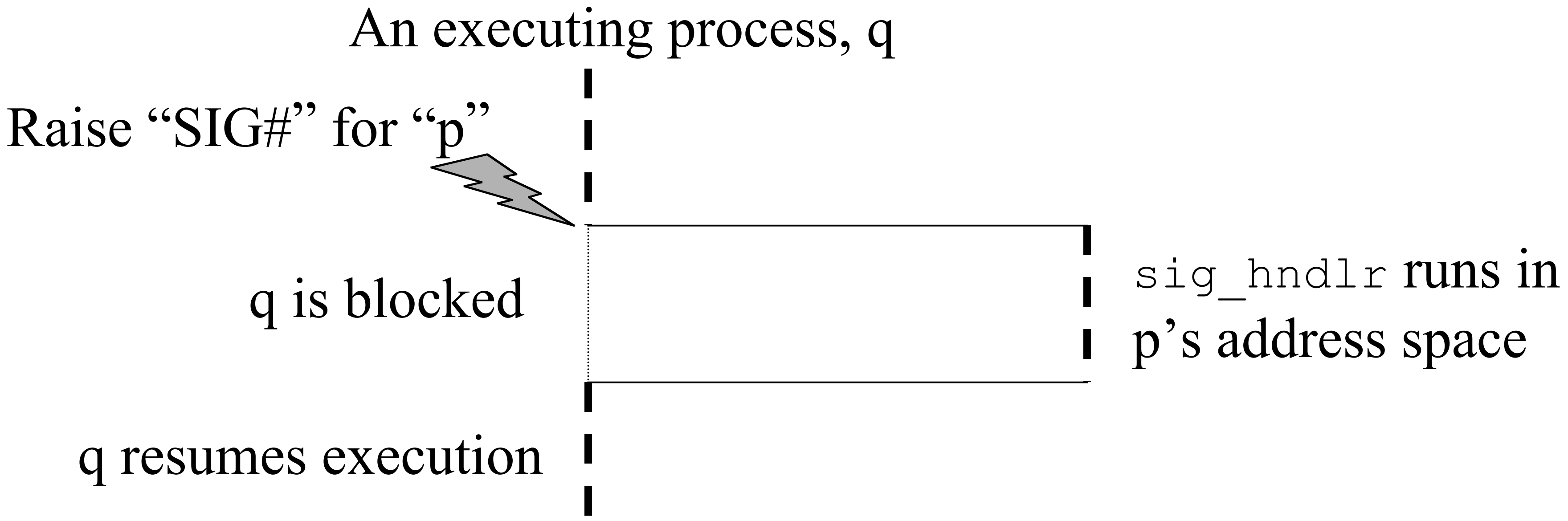
```
/* code for process p
. . .
signal(SIG#, sig_hndlr);
. . .
/* ARBITRARY CODE */
```

```
void sig_hndlr(...) {
/* ARBITRARY CODE */
}
```

Signal Handling

```
/* code for process p
. . .
signal(SIG#, sig_hndlr);
. . .
/* ARBITRARY CODE */
```

```
void sig_hndlr(...) {
/* ARBITRARY CODE */
}
```



An executing process, q

Raise “SIG#” for “p”

q is blocked

`sig_hndlr` runs in p’s address space

q resumes execution

Toy Signal Handler (Fig 9.4)

```
#include    <signal.h>
static void sig_handler(int);
int main () {
  int i, parent_pid, child_pid, status;
  if(signal(SIGUSR1, sig_handler) == SIG_ERR)
    printf(“Parent: Unable to create handler for SIGUSR1\n”);
  if(signal(SIGUSR2, sig_handler) == SIG_ERR)
    printf(“Parent: Unable to create handler for SIGUSR2\n”);
  parent_pid = getpid();
  if((child_pid = fork()) == 0) {
    kill(parent_pid, SIGUSR1);
    for (;;) pause();
  } else {
    kill(child_pid, SIGUSR2);
    printf(“Parent: Terminating child … \n”);
    kill(child_pid), SIGTERM);
    wait(&status);
    printf(“done\n”);
  }
}
```

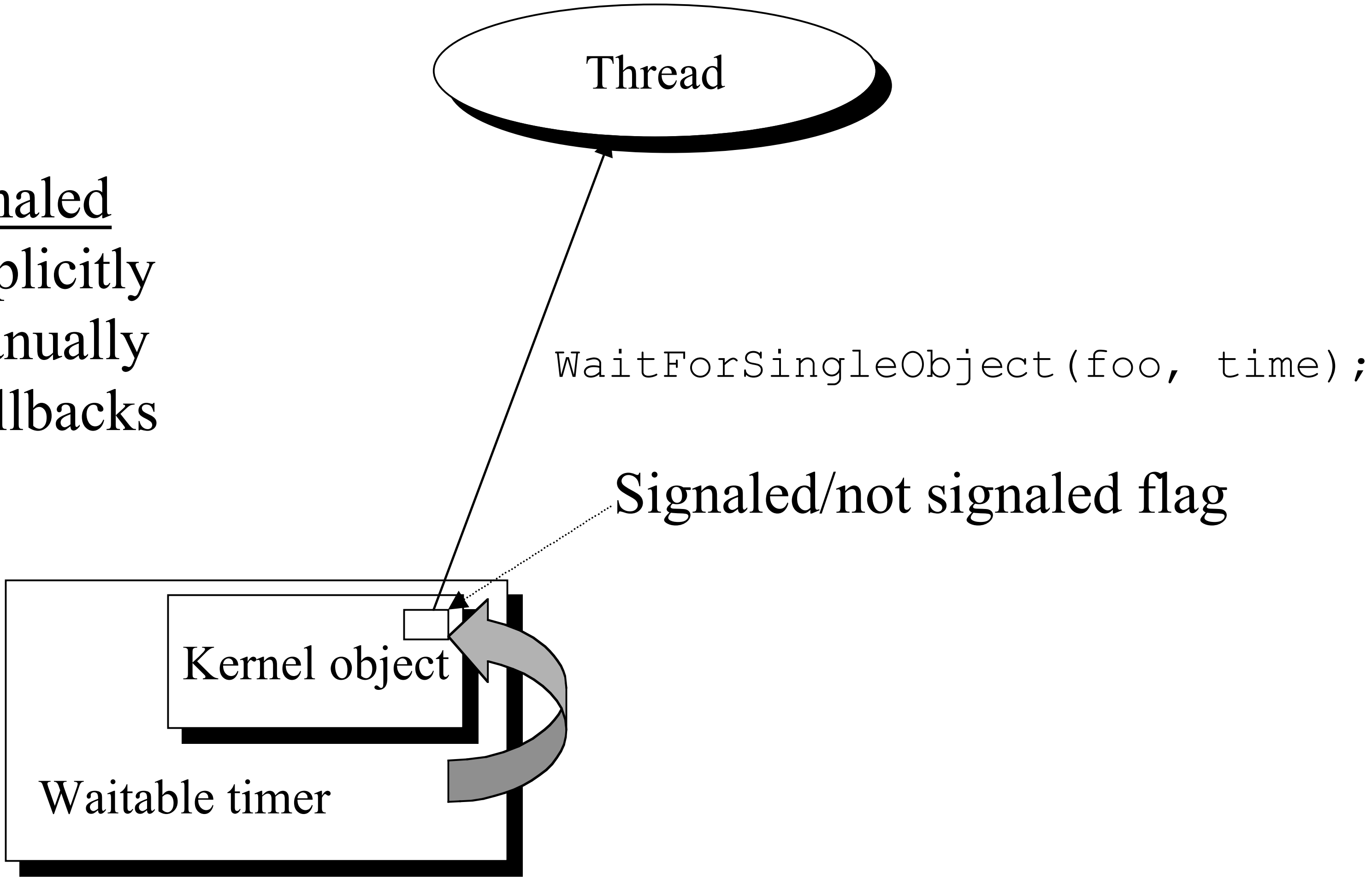
Toy Signal Handler (Fig 9.4)

```
static void sig_handler(int signo) {
  switch(signo) {
  case SIGUSR1:  /* Incoming SIGUSR1 */
    printf(“Parent: Received SIGUSER1\n”);
    break;
  case SIGUSR2:  /* Incoming SIGUSR2 */
    printf(“Child: Received SIGUSER2\n”);
    break;
  default: break;
  }
  return
}
```

NT Events

Signaled

- Implicitly
- Manually
- Callbacks



Thread

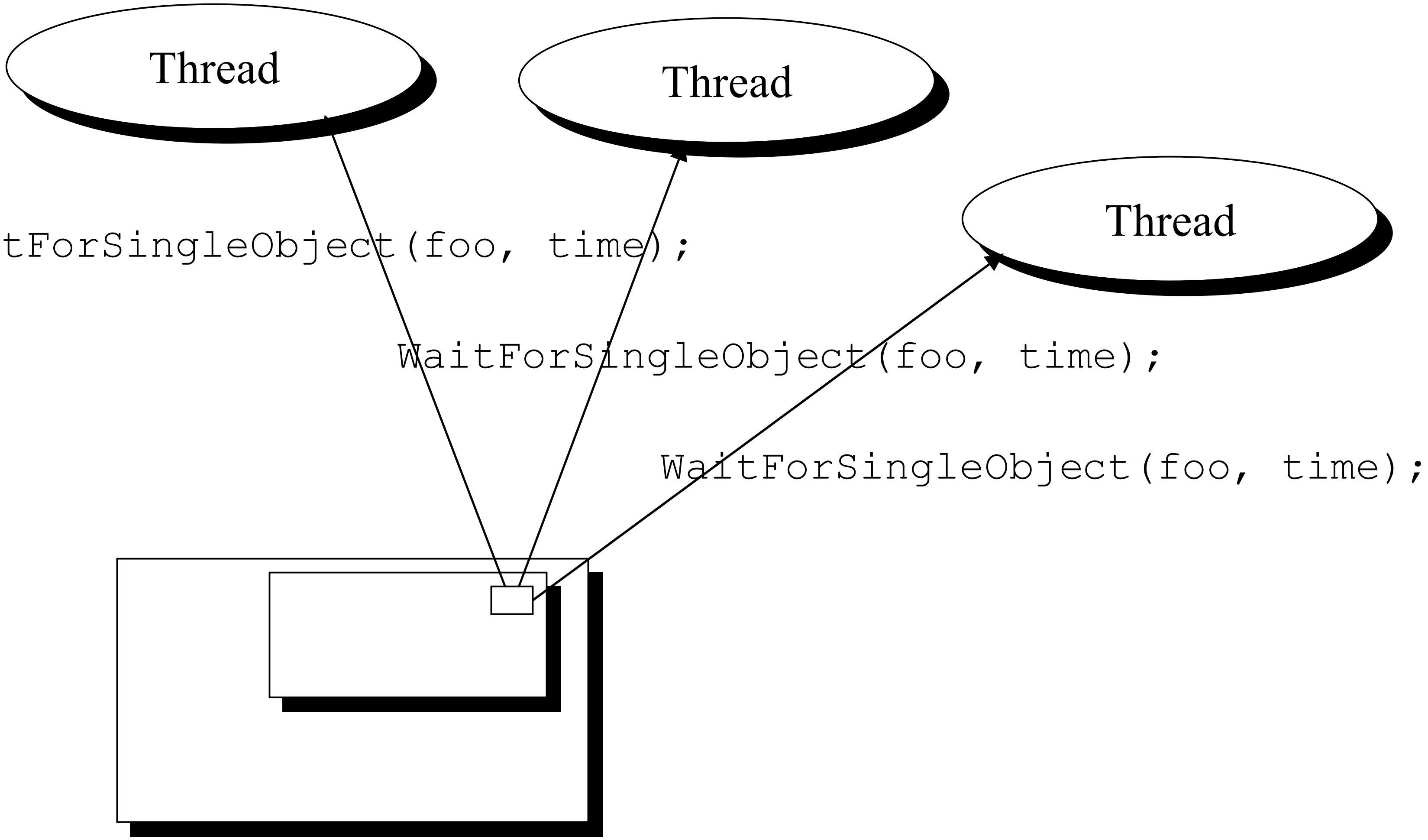
`WaitForSingleObject(foo, time);`

Signaled/not signaled flag

Kernel object

Waitable timer

NT Events



`WaitForSingleObject(foo, time);`

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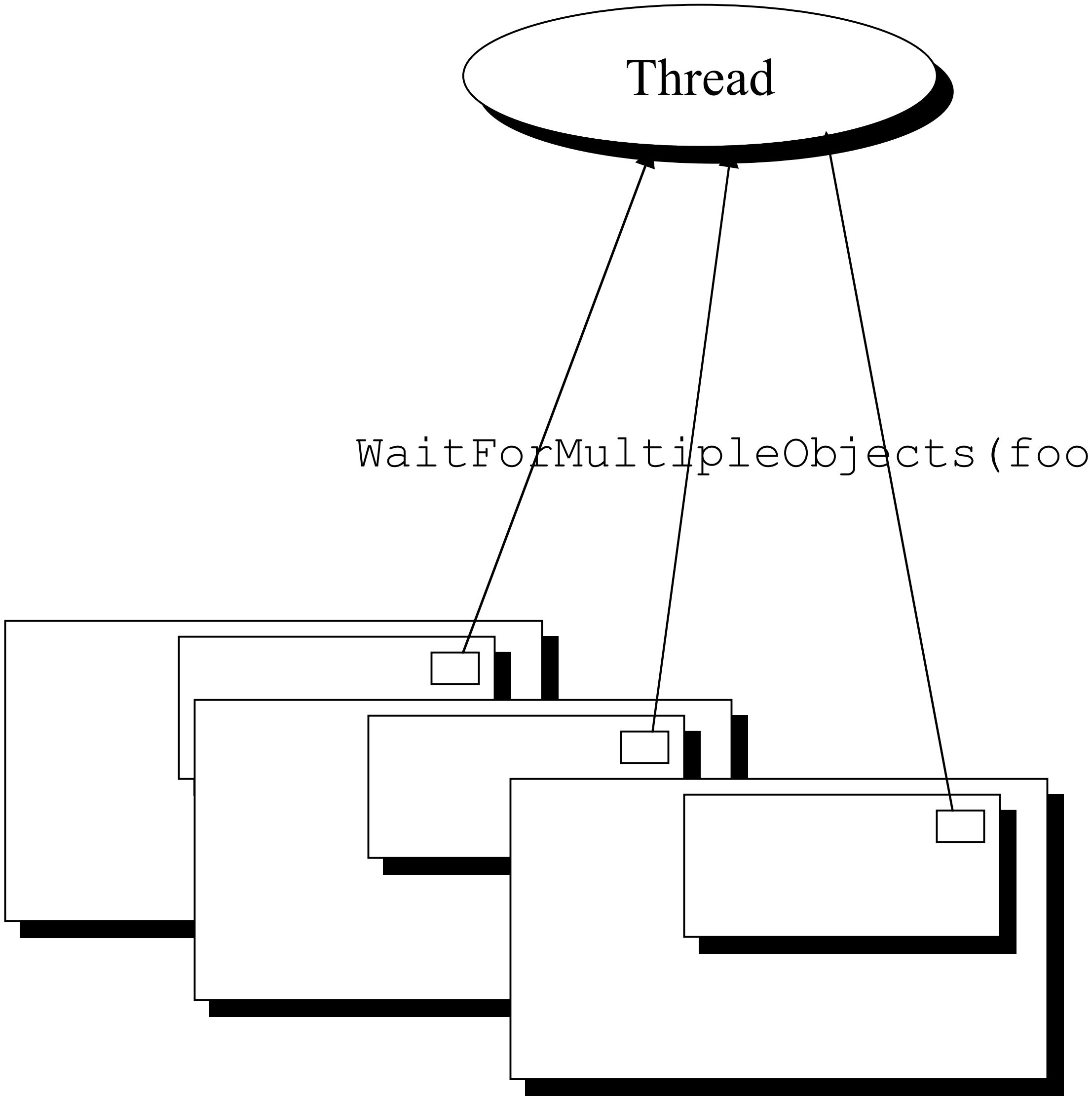
NT Events



`WaitForMultipleObjects(foo, time);`

Monitors

- Specialized form of ADT
  - Encapsulates implementation
  - Public interface (types & functions)
- Only one process can be executing in the ADT at a time

```
monitor anADT {
  semaphore mutex = 1;  // Implicit
  . . .
public:
  proc_i(…) {
    P(mutex);  // Implicit
      <processing for proc_i>;
    V(mutex);  // Implicit
  };
  . . .
};
```

Example: Shared Balance

```
monitor sharedBalance {
  double balance;
public:
  credit(double amount) {balance += amount;};
  debit(double amount) {balance -= amount;};
  . . .
};
```

Example: Readers & Writers

```
monitor readerWriter_1 {
  int numberOfReaders = 0;
  int numberOfWriters = 0;
  boolean busy = FALSE;
public:
  startRead() {
  };
  finishRead() {
  };
  startWrite() {
  };
  finishWrite() {
  };
};
```

```
reader(){         writer(){
  while(TRUE) {     while(TRUE) {
    . . .             . . .
    startRead();      startWriter();
    finishRead();     finishWriter();
    . . .             . . .
}                 }
fork(reader, 0);
. . .
fork(reader, 0):
fork(writer, 0);
. . .
fork(writer, 0);
```

Example: Readers & Writers

```
monitor readerWriter_1 {
  int numberOfReaders = 0;
  int numberOfWriters = 0;
  boolean busy = FALSE;
public:
  startRead() {
    while(numberOfWriters != 0) ;
    numberOfReaders++;
  };
  finishRead() {
    numberOfReaders-;
  };
```

```
  startWrite() {
    numberOfWriters++;
    while(
          busy ||
         (numberOfReaders > 0)
          ) ;
    busy = TRUE;
  };
  finishWrite() {
    numberOfWriters--;
    busy = FALSE;
  };
};
```

Example: Readers & Writers

- **Deadlock can happen**

```
monitor readerWriter_1 {
  int numberOfReaders = 0;
  int numberOfWriters = 0;
  boolean busy = FALSE;
public:
  startRead() {
    while(numberOfWriters != 0) ;
    numberOfReaders++;
  };
  finishRead() {
    numberOfReaders--;
  };
  startWrite() {
    numberOfWriters++;
    while(
          busy ||
         (numberOfReaders > 0)
          ) ;
    busy = TRUE;
  };
  finishWrite() {
    numberOfWriters--;
    busy = FALSE;
  };
};
```

Sometimes Need to Suspend

- Process obtains monitor, but detects a condition for which it needs to wait
- Want special mechanism to suspend until condition is met, then resume
  - Process that makes condition true must exit monitor
  - Suspended process then resumes
- *Condition Variable*

Condition Variables

- Essentially an event (as defined previously)
- Occurs <u>only</u> inside a monitor
- Operations to manipulate condition variable
    - `wait`: Suspend invoking process until another executes a signal
    - `signal`: Resume one process if any are suspended, otherwise do nothing
    - `queue`: Return TRUE if there is at least one process suspended on the condition variable

Active vs Passive `signal`

- Hoare semantics: same as active semaphore
  - p_0 executes signal while p_1 is waiting ⇒ p_0 yields the monitor to p_1
  - The signal is only TRUE the instant it happens
- Brinch Hansen (“Mesa”) semantics: same as passive semaphore
  - p_0 executes signal while p_1 is waiting ⇒ p_0 continues to execute, then when p_0 exits the monitor p_1 can receive the signal
  - Used in the Xerox Mesa implementation

Hoare vs Mesa Semantics

- Hoare semantics:

```
. . .
if(resourceNotAvailable()) resourceCondition.wait();
/* now available … continue … */
. . .
```

- Mesa semantics:

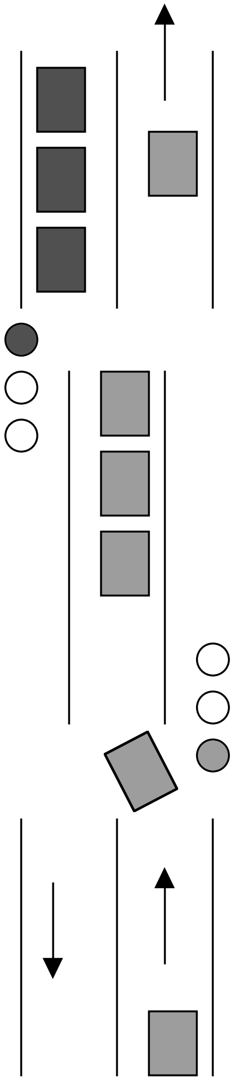
```
. . .
while(resourceNotAvailable()) resourceCondition.wait();
/* now available … continue … */
. . .
```

2nd Try at Readers & Writers

```
monitor readerWriter_2 {
  int numberOfReaders = 0;
  boolean busy = FALSE;
  condition okToRead, okToWrite;
public:
  startRead() {
    if(busy || (okToWrite.queue())
      okToRead.wait();
    numberOfReaders++;
    okToRead.signal();
  };
  finishRead() {
    numberOfReaders--;
    if(numberOfReaders == 0)
      okToWrite.signal();
  };
  startWrite() {
    if((numberOfReaders != 0)
      || busy)
         okToWrite.wait();
    busy = TRUE;
  };
  finishWrite() {
    busy = FALSE;
    if(okToRead.queue())
      okToRead.signal()
    else
      okToWrite.signal()
  };
};
```

Example: Synchronizing Traffic

- One-way tunnel
- Can only use tunnel if no oncoming traffic
- OK to use tunnel if traffic is already flowing the right way



Example: Synchronizing Traffic

```
monitor tunnel {
  int northbound = 0, southbound = 0;
  trafficSignal nbSignal = RED, sbSignal = GREEN;
  condition busy;
public:
  nbArrival() {
    if(southbound > 0) busy.wait();
    northbound++;
    nbSignal = GREEN; sbSignal = RED;
  };
  sbArrival() {
    if(northbound > 0) busy.wait();
    southbound++;
    nbSignal = RED; sbSignal = GREEN;
  };
  depart(Direction exit) (
    if(exit = NORTH {
      northbound--;
      if(northbound == 0) while(busy.queue()) busy.signal();
    else if(exit == SOUTH) {
      southbound--;
      if(southbound == 0) while(busy.queue()) busy.signal();
    }
  }
}
```

Dining Philosophers … again ...

```
#define  N  ___
enum status(EATING, HUNGRY, THINKING};
monitor diningPhilosophers {
  status state[N];
  condition self[N];
  test(int i) {
    if((state[(i-1) mod N] != EATING) &&
       (state[i] == HUNGRY) &&
       (state[(i+1) mod N] != EATING)) {
      state[i] = EATING;
      self[i].signal();
    }
  };
public:
  diningPhilosophers() { // Initilization
    for(int i = 0; i < N; i++) state[i] = THINKING;
  };
```

Dining Philosophers … again ...

```
test(int i) {
    if((state[(i-1) mod N] != EATING) &&
       (state[i] == HUNGRY) &&
       (state[(i+1) mod N] != EATING)) {
      state[i] = EATING;
      self[i].signal();
    };
  };
public:
  diningPhilosophers() {...};
  pickUpForks(int i) {
    state[i] = HUNGRY;
    test(i);
    if(state[i] != EATING) self[i].wait();
  };
  putDownForks(int i) {
    state[i] = THINKING;
    test((i-1) mod N);
    test((i+1) mod N);
  };
}
```

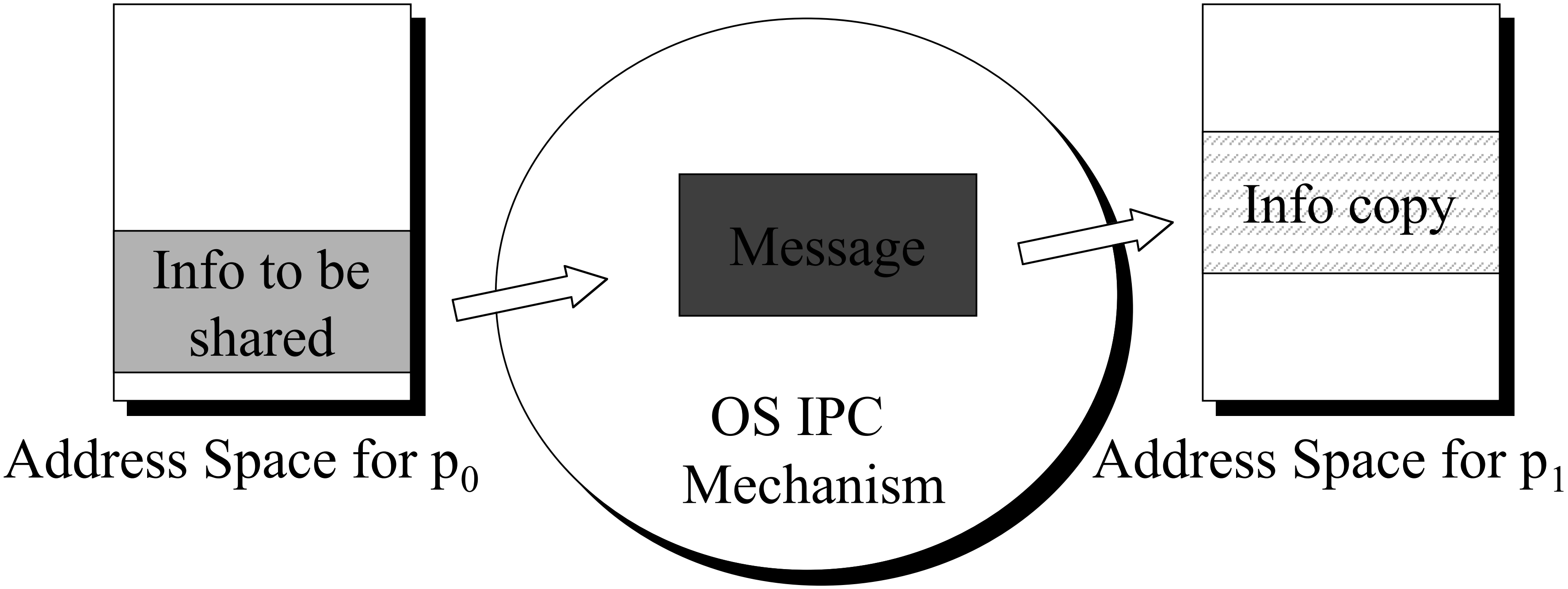
Experience with Monitors

- Danger of deadlock with nested calls
- Monitors were implemented in Mesa
  - Used Brinch Hansen semantics
  - Nested monitor calls are, in fact, a problem
  - Difficult to get the right behavior with these semantics
  - Needed timeouts, aborts, etc.
- See paper by Lampson & Redell

Interprocess Communication (IPC)

- Signals, semaphores, etc. do not pass information from one process to another
- Monitors support information sharing, but only through shared memory in the monitor
- There may be no shared memory
  - OS does not support it
  - Processes are on different machines on a network
- Can use *messages* to pass info while synchronizing

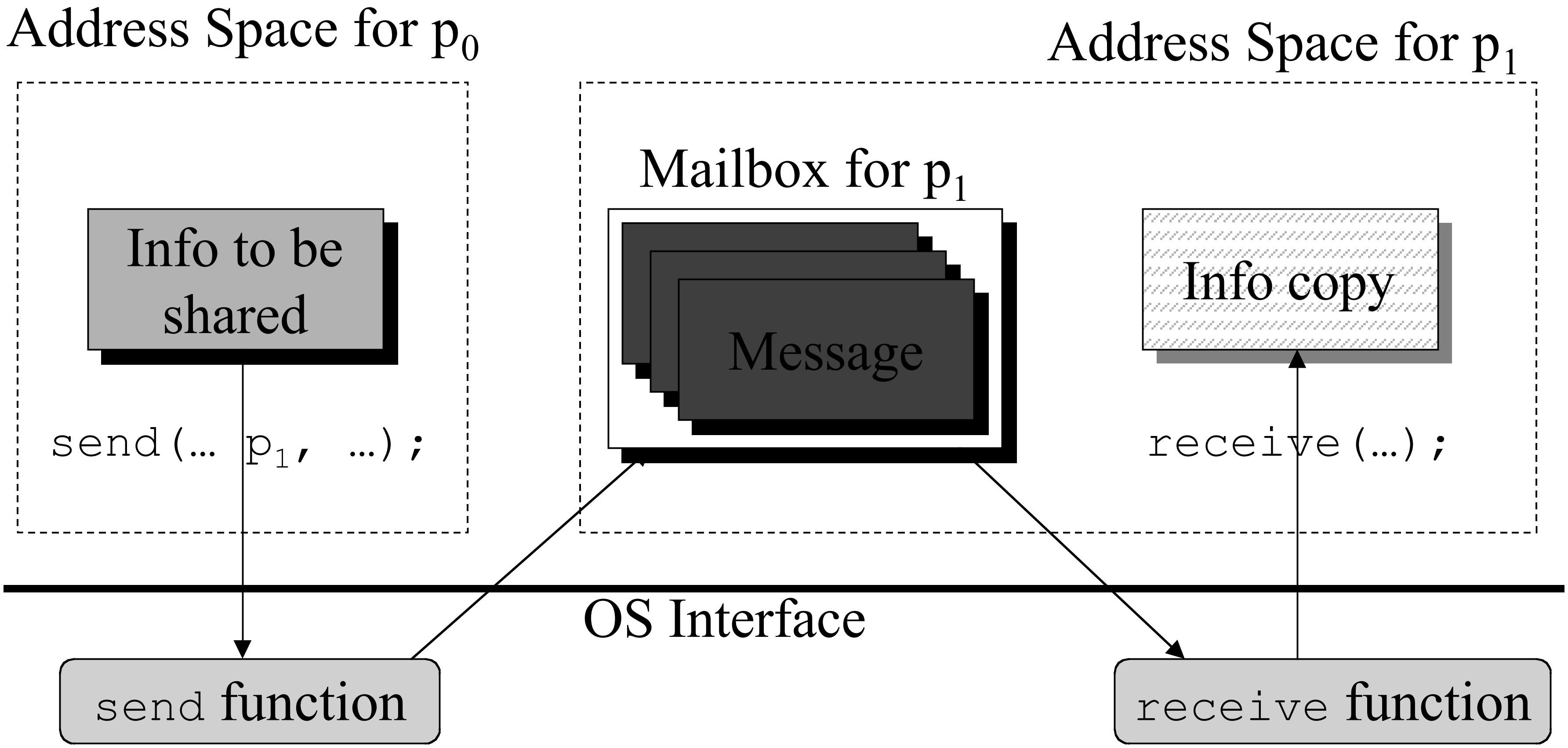
IPC Mechanisms



- Must bypass memory protection mechanism for local copies
- Must be able to use a network for remote copies

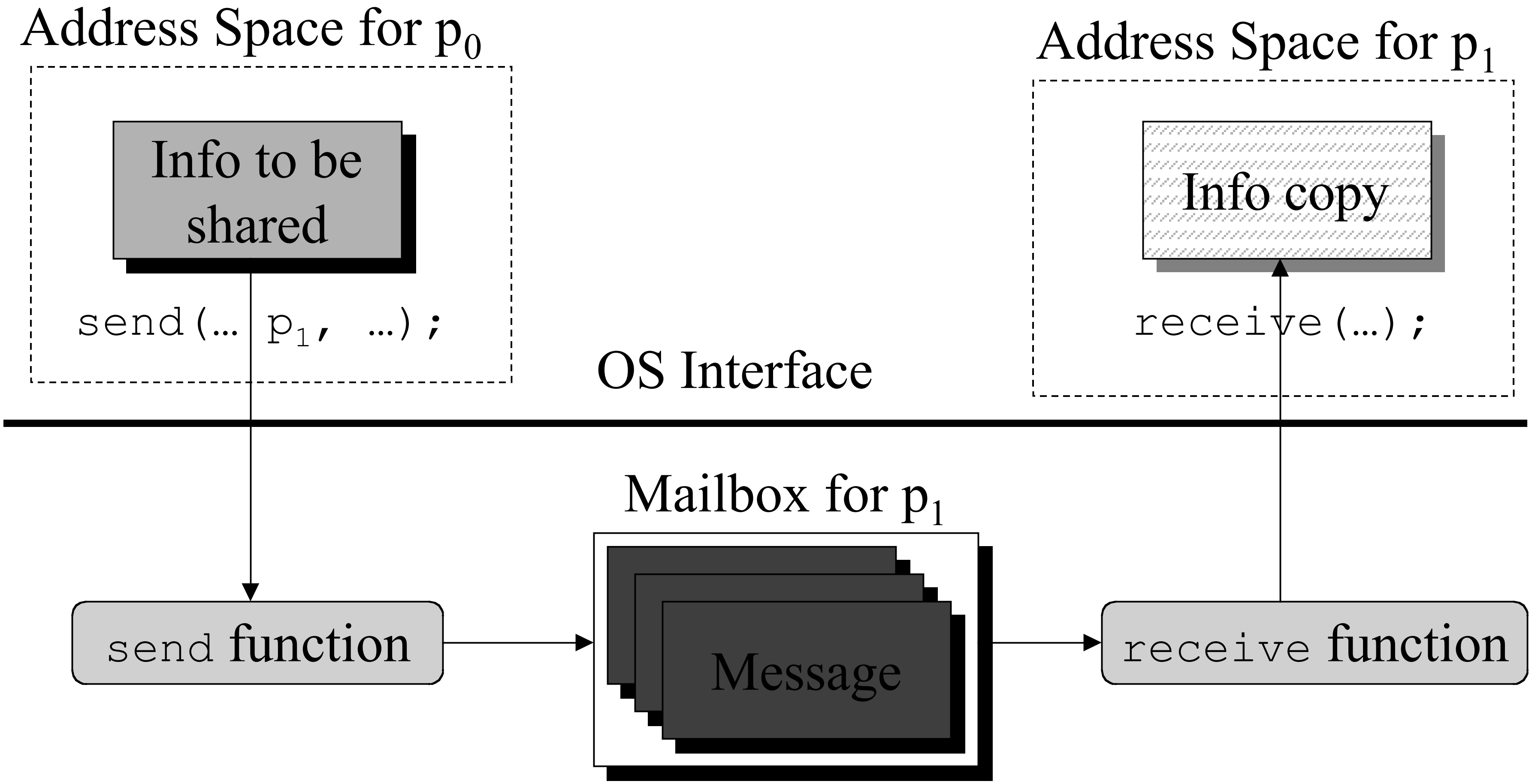
Refined IPC Mechanism

- Spontaneous changes to p_1's address space
- Avoid through the use of mailboxes



Refined IPC Mechanism

- OS manages the mailbox space
- More secure message system



Message Protocols

- Sender transmits a set of bits to receiver
  - How does the sender know when the receiver is ready (or when the receiver obtained the info)?
  - How does the receiver know how to interpret the info?
  - Need a *protocol* for communication
    - Standard "envelope" for containing the info
    - Standard header
- A message system specifies the protocols

Transmit Operations

- Asynchronous `send`:
  - Delivers message to receiver's mailbox
  - Continues execution
  - No feedback on when (or if) info was delivered
- Synchronous `send`:
  - Goal is to block sender until message is received by a process
    - Variant sometimes used in networks: Until the message is in the mailbox

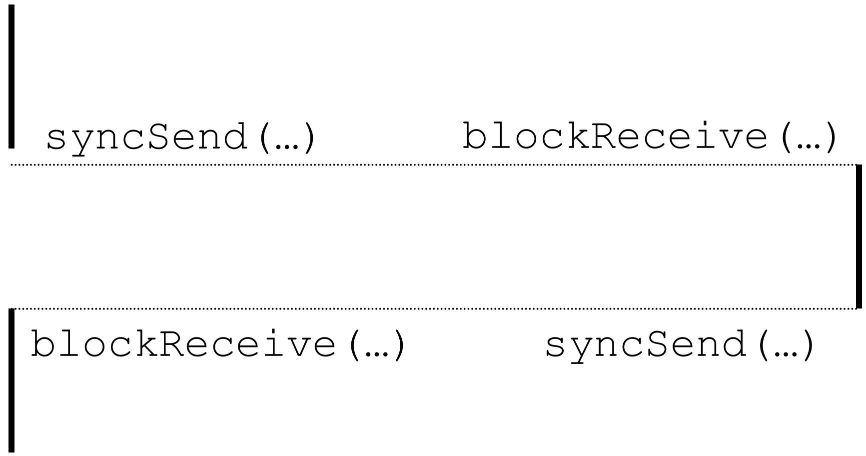
Receive Operation

- Blocking `receive`:
  - Return the first message in the mailbox
  - If there is no message in mailbox, block the receiver until one arrives
- Nonblocking `receive`:
  - Return the first message in the mailbox
  - If there is no message in mailbox, return with an indication to that effect

Synchronized IPC

Code for p_1 | **Code for p_2**

```
/* signal p2 */                             /* wait for signal from p1 */
syncSend(message1, p2);        ────────▶    blockReceive(msgBuff, &from);
<waiting …>;                                <process message>;
/* wait for signal from p2 */               /* signal p1 */
blockReceive(msgBuff, &from);  ◀──          syncSend(message2, p1);
```



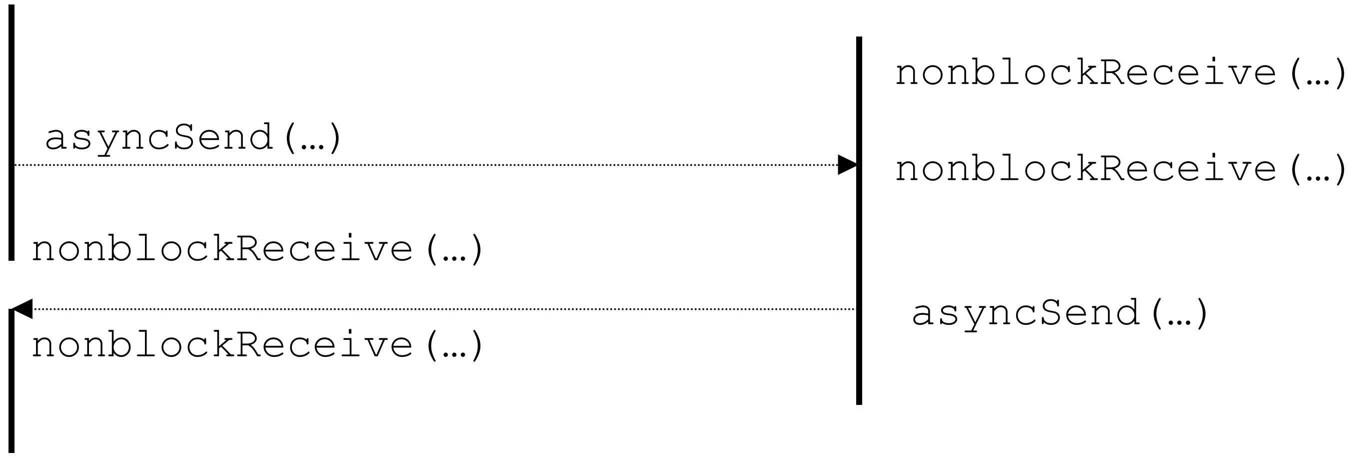
Asynchronous IPC

Code for p_1

```
/* signal p2 */
asyncSend(message1, p2);
<other processing>;
/* wait for signal from p2 */
while(!nbReceive(&msg, &from));
```

Code for p_2

```
/* test for signal from p1 */
if(nbReceive(&msg, &from)) {
  <process message>;
  asyncSend(message2, p1);
}else<
  <other processing>;
}
```



`nonblockReceive(…)`

`asyncSend(…)`

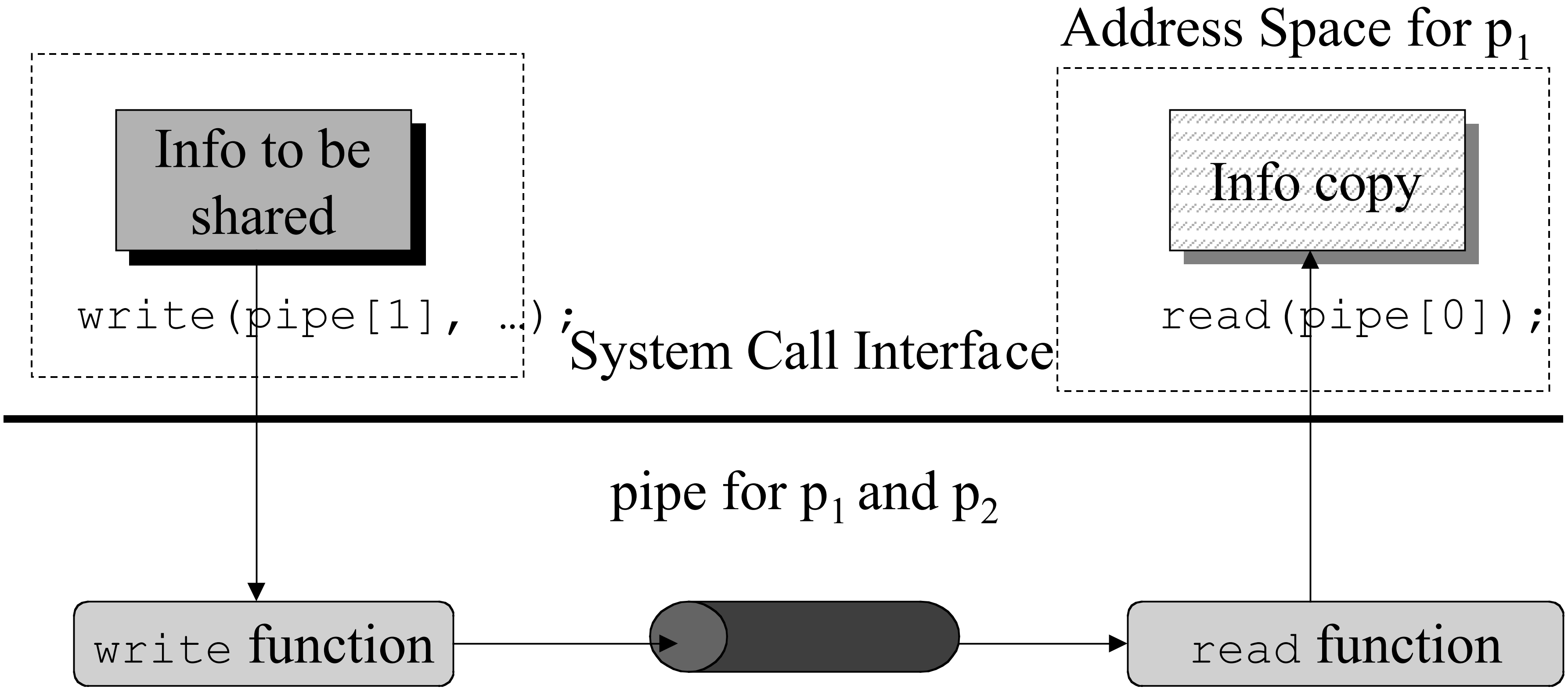
`nonblockReceive(…)`

`nonblockReceive(…)`

`asyncSend(…)`

`nonblockReceive(…)`

UNIX Pipes



Address Space for p_1

Info to be shared

`write(pipe[1], …);`

System Call Interface

Info copy

`read(pipe[0]);`

pipe for p_1 and p_2

`write` function

`read` function

UNIX Pipes (cont)

- The pipe interface is intended to look like a file interface
  - Analog of open is to create the pipe
  - File `read`/`write` system calls are used to send/receive information on the pipe
- What is going on here?
  - Kernel creates a buffer when pipe is created
  - Processes can read/write into/out of their address spaces from/to the buffer
  - Processes just need a handle to the buffer

UNIX Pipes (cont)

- File handles are copied on fork
- … so are pipe handles

```
int pipeID[2];
. . .
pipe(pipeID);
. . .
if(fork() == 0) { /* the child */
  . . .
  read(pipeID[0], childBuf, len);
  <process the message>;
  . . .
} else { /* the parent */
  . . .
  write(pipeID[1], msgToChild, len);
  . . .
}
```

UNIX Pipes (con)

- The normal `write` is an asynchronous op (that notifies of write errors)
- The normal `read` is a blocking read
- The `read` operation can be nonblocking

```
#include   <sys/ioctl.h>
. . .
int pipeID[2];
. . .
pipe(pipeID);
ioctl(pipeID[0], FIONBIO, &on);
. . .
read(pipeID[0], buffer, len);
if(errno != EWOULDBLOCK) {
  /* no data */
} else { /* have data */
```

Explicit Event Ordering

- Alternative technique of growing importance in network systems
- Rely on knowing the relative order of occurrence of every event
  - (occurrence of y in p_j) < (occurrence of x in p_i)
  - Then can synchronize by explicitly specifying each relation (when it is important)

`advance(eventCount)`: Announces the occurrence of an event related to `eventCount`, causing it to be incremented by 1

`await(eventCount, v)`: Causes process to block as long as `eventCount < v`.

Bounded Buffer

```
producer() {
  int i = 1;
  while(TRUE) {
    await(out, i-N);
    produce(buffer[(i-1)mod N]);
    advance(in);
    i++;
  }
}
```

```
consumer() {
  int i = 1;
  while(TRUE) {
    await(in, i);
    consume(buffer[(i-1)mod N]);
    advance(out);
    i++;
  }
}
```

```
eventcount in = 0; out = 0;
fork(producer, 0);
fork(consumer, 0);
```

More on EventCounts

- Notice that `advance` and `await` need not be uninterruptible
- There is no requirement for shared memory
- For full use of this mechanism, actually need to extend it a bit with a sequencer
- Underlying theory is also used to implement “virtual global clocks” in a network
- Emerging as a preferred synchronization mechanism on networks