ECE445M/ECE380L.12 Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 5:

Semaphores, Deadlocks, Debugging, Testing

Graduate Projects Ideas

Due mid Feb

1. Extend the OS with more features
   - Efficient with 20 to 50 threads, multiple periodic/edge-triggered interrupts
   - Multiple cores (real-time scheduling algorithms & implementation)
   - Multiple Mailboxes, FIFOs, advanced communication primitives
   - Path expressions, bankers algorithm,
   - Semaphores with timeout, priority inheritance/ceiling (algorithms & implementation)
2. Make your Lab3 OS portable and port to another platform
   - First implement Lab3 on another architecture (each students does their own)
   - Rewrite OS into two parts: common OS.c (maximize), separate CPU.c per architecture (minimize)
3. Design and test a DMA-base drivers for peripherals
   - eDisk driver, compare and contrast your Lab5 to FAT (one person project)
   - Camera, e.g. LM3S811 http://www.ece.utexas.edu/~valvano/arm/Camera_811.zip (one person project)
4. Advanced robot control algorithms on top of OS
   - Reinforcement learning, Kalmann filter based control
   - Computer vision object/lane detection/recognition and lane keeping (self-driving car)
5. Write your own memory management
   - Advanced heap, e.g. using Knuth's Buddy Allocation (one-person project)
   - Use of Memory Protection Unit (MPU) on LaunchPad
   - Virtual memory, paging on a different platform (two or more students)
6. Networking, Internet-of-Things (IoT)
   - Port a lightweight TCP/IP stack onto board (e.g. lwIP using external WiFi module via UART)
   - Robots communicate with each other/base station, control robot remotely (vehicle-to-vehicle / vehicle-to-)
7. Use of Launchpad/OS in other applications
   - Energy harvesting OS with checkpointing for frequent power loss
   - OS safety/security mechanisms

Level of complexity depends on size of group

Semaphores

Edsger Dijkstra,
UT Austin CS 1984-2000

- *P*() or *wait*()
  - Dutch word *proberen*, to test
  - *probeer te verlagen*, try to decrease
  - `OS_Wait` `OSSemPend`
- *V*() or *signal*()
  - Dutch word *verhogen*, to increase
  - `OS_Signal` `OSSemPost`

Reference Book, Chapter 4

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Semaphore Meaning

- Counting semaphore
  - Number of elements stored in FIFO
  - Space left in the FIFO
  - Number of printers available
- Binary semaphore (= mutex = flag)
  - Free (1), busy (0)
  - Event occurred (1), not occurred (0)

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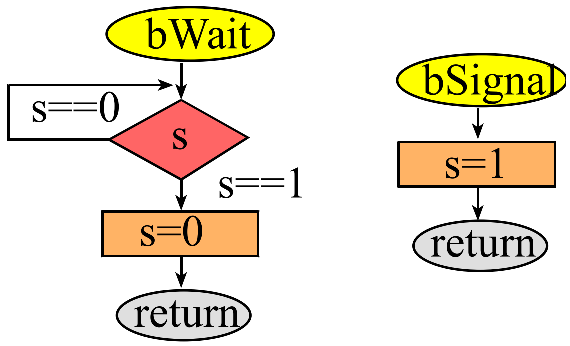
Spin-Lock Binary Semaphore



Mutual exclusion

bWait(&s);

// access LCD

bSignal(&s);

How do we use this to solve critical sections?

Why is this a good solution for critical sections?

What does the semaphore mean?

What would be a better name for *s*?

What about atomic?

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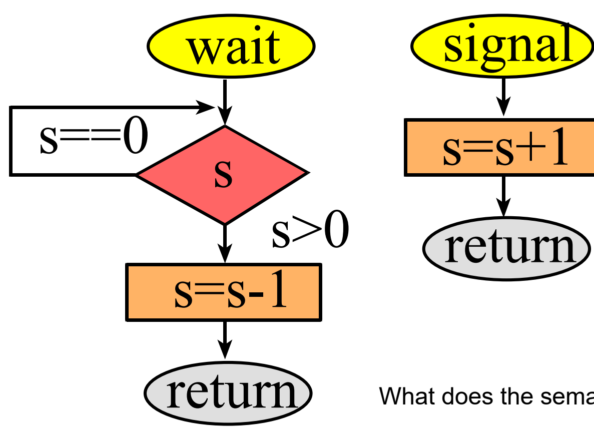
Spin-Lock Counting Semaphore



What does the semaphore mean?

What about atomic?

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Spin-Lock Semaphores

```
OS_Wait ;R0 points to counter
   LDREX    R1, [R0]  ; counter
   SUBS     R1, #1    ; counter -1,
   ITT      PL        ; ok if >= 0
   STREXPL  R2,R1,[R0]  ; try update
   CMPPL    R2, #0    ; succeed?
   BNE      OS_Wait   ; no, try again
   BX       LR

OS_Signal ; R0 points to counter
   LDREX    R1, [R0]   ; counter
   ADD      R1, #1     ; counter + 1
   STREX    R2,R1,[R0]  ; try update
   CMP      R2, #0     ; succeed?
   BNE      OS_Signal ;no, try again
   BX       LR
```

```
void OS_Wait(long *s) {
  DisableInterrupts();
  while((*s) <= 0){
    EnableInterrupts();
    DisableInterrupts();
  }
  (*s) = (*s) - 1;
  EnableInterrupts();
}

void OS_Signal(long *s) {
  long status;
  status = StartCritical();
  (*s) = (*s) + 1;
  EndCritical(status);
}
```

Program 4.11

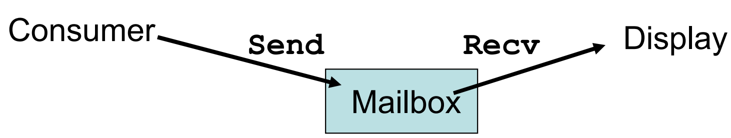
LDREX
STREX

Cortex-M3/M4F Instruction Set, pg. 50

Mailbox

MailBox_Send(…)
- **bWait(&BoxFree)**
- **Put data into Mailbox**
- **bSignal(&DataValid)**

MailBox_Recv(…)
- **bWait(&DataValid)**
- **Retrieve data from Mailbox**
- **bSignal(&BoxFree)**



What do the semaphores mean? What are the initial values?

What if we remove **bWait(&BoxFree)** and **bSignal(&BoxFree)**?

FIFO, Queue, or Pipe

FIFO_Put
Wait(&DataRoomLeft)
Disable Interrupts
Enter data into Fifo
Enable Interrupts
Signal(&DataAvailable)

FIFO_Get
Wait(&DataAvailable)
Disable Interrupts
Remove data from Fifo
Enable Interrupts
Signal(&DataRoomLeft)

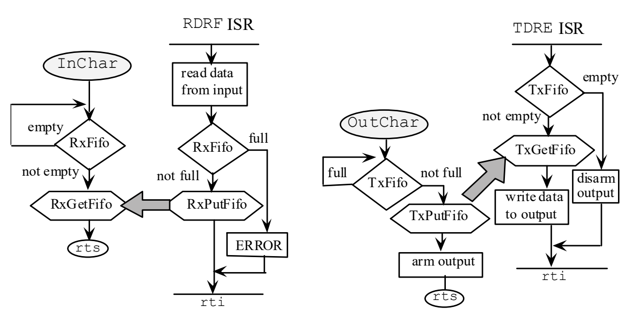
FIFO_Put
Wait(&DataRoomLeft)
bWait(&Mutex)
Enter data into Fifo
bSignal(&Mutex)
Signal(&DataAvailable)

FIFO_Get
Wait(&DataAvailable)
bWait(&Mutex)
Remove data from Fifo
bSignal(&Mutex)
Signal(&DataRoomLeft)

What do the semaphores mean?
What if the FIFO never fills?

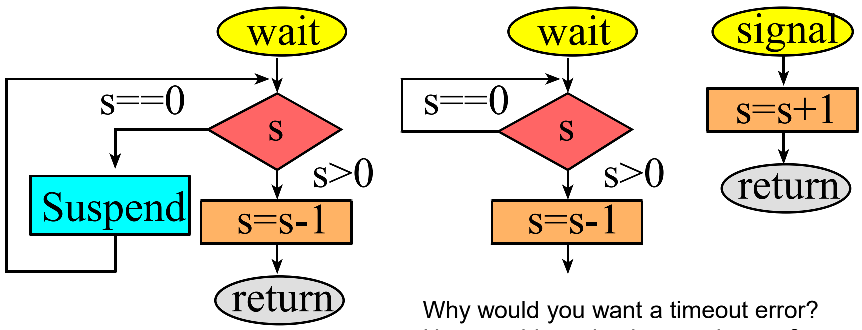
No Background Wait

- Redo Mailbox if `Send` in background
- Redo Fifo if `Put` in background (RX)
- Redo Fifo if `Get` in background (TX)



Cooperative Spin-Lock

Cooperative spin-lock **Regular spin-lock**



Why would you want a timeout error?
How would you implement timeout?

```
if(OS_Wait(&free,T100ms)){
  // use it
  OS_Signal(&free);
} else {
  // error
}
```

Could be implemented with a catch and throw

Cooperative Semaphores

```
void OS_Wait(long *s){
  DisableInterrupts();
  while((*s) <= 0){
    EnableInterrupts();
    OS_Suspend();
    DisableInterrupts();
  }
  (*s) = (*s) - 1;
  EnableInterrupts();
}

void OS_Signal(long *s){
  long status;
  status = StartCritical();
  (*s) = (*s) + 1;
  EndCritical(status);
}
```

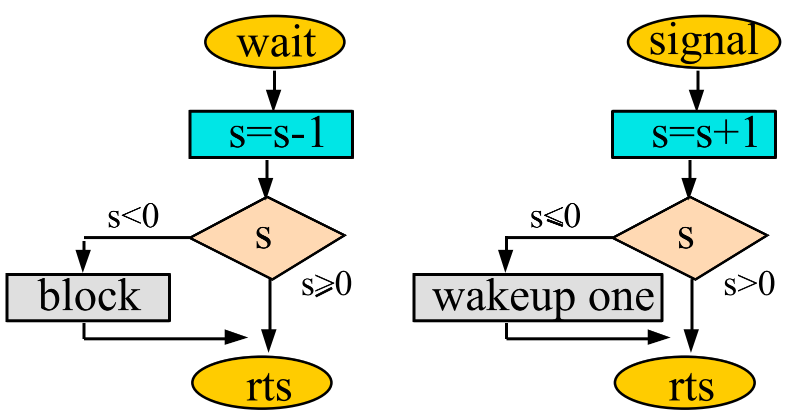
Let other thread run (→ OS_Suspend();)

Do an experiment of Lab 2 with and without cooperation

Blocking Semaphore (Lab 3)

- Recapture time lost in the spin-lock
  - No spin operation, wakeup only on signal
  - Eliminate wasted time running threads that are not doing work (e.g., waiting)
- Implement **bounded waiting**
  - Once thread calls **Wait** and is not serviced,
  - There are a finite number of threads that will go ahead

Blocking Semaphore



What does the semaphore mean?

What about atomic?

Blocking Semaphore (V1)

- All threads exist on circular TCB list (active and blocked)
  - Each semaphore simply has a **Value**
  - No blocked threads if semaphore **Value ≥ 0**
    - e.g., if **Value** is -2, then two threads are blocked
  - No information about which thread has waited longest
  - Add to TCB, a **BlockPt**, of type **Sema4Type**
    - initially, this pointer is **null**
    - **null** means this thread is active and ready to run
    - If blocked, this pointer contains the semaphore address
- New Scheduler
  - Find the next active thread from the TCB list
  - Only run threads with **BlockPt** equal to **null**

Blocking Semaphore (V1)

OS_Wait(Sema4Type *semaPt)

1) Disable interrupts, I=1

2) Decrement the semaphore counter, S=S-1

```
(semaPt->Value)--;
```

3) If the Value<0 then this thread will be blocked

specify this thread is blocked to this semaphore

```
RunPt->BlockPt = semaPt;
```

suspend thread;

4) Enable interrupts, I=0

Blocking Semaphore (V1)

OS_Signal(Sema4Type *semaPt)

1) Save I bit, then disable interrupts
2) Increment the semaphore Value, S=S+1
`(semaPt->Value)++;`
3) If `Value ≤ 0` then
 wake up one thread from the TCB linked list
 (no bounded waiting)
 search TCBs for thread with `BlockPt == semaPt`
 set the `BlockPt` of this TCB to null
 do not suspend the thread that called `OS_Signal`
4) Restore I bit

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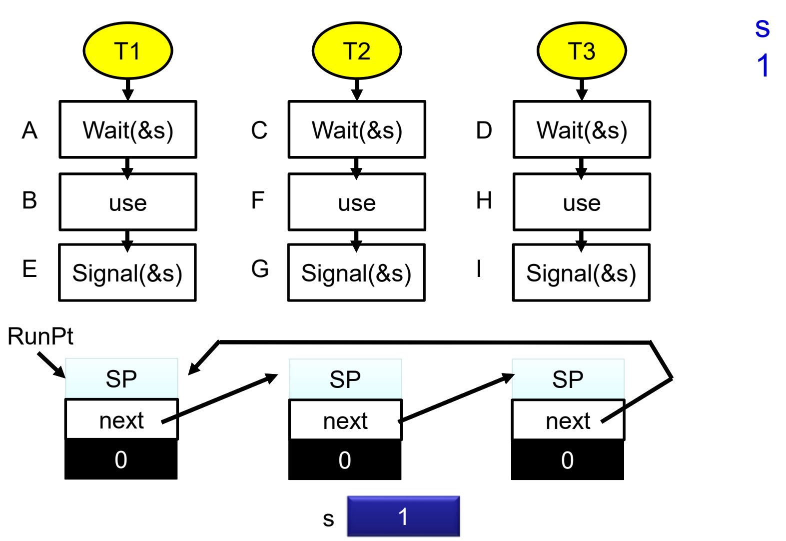
Mutex Example (V1)



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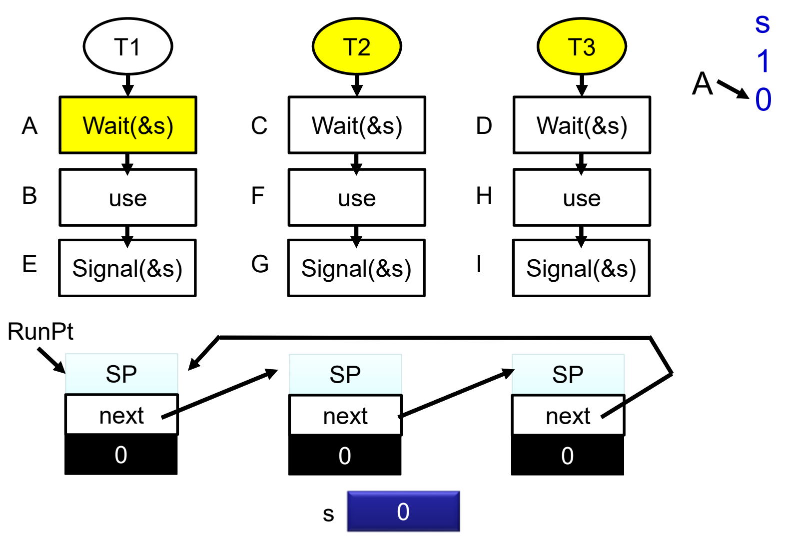
Mutex Example (V1)



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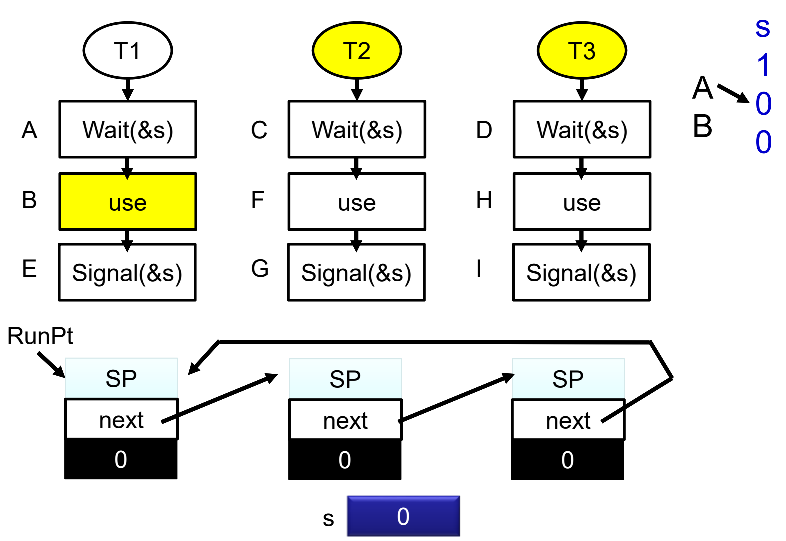
Mutex Example (V1)



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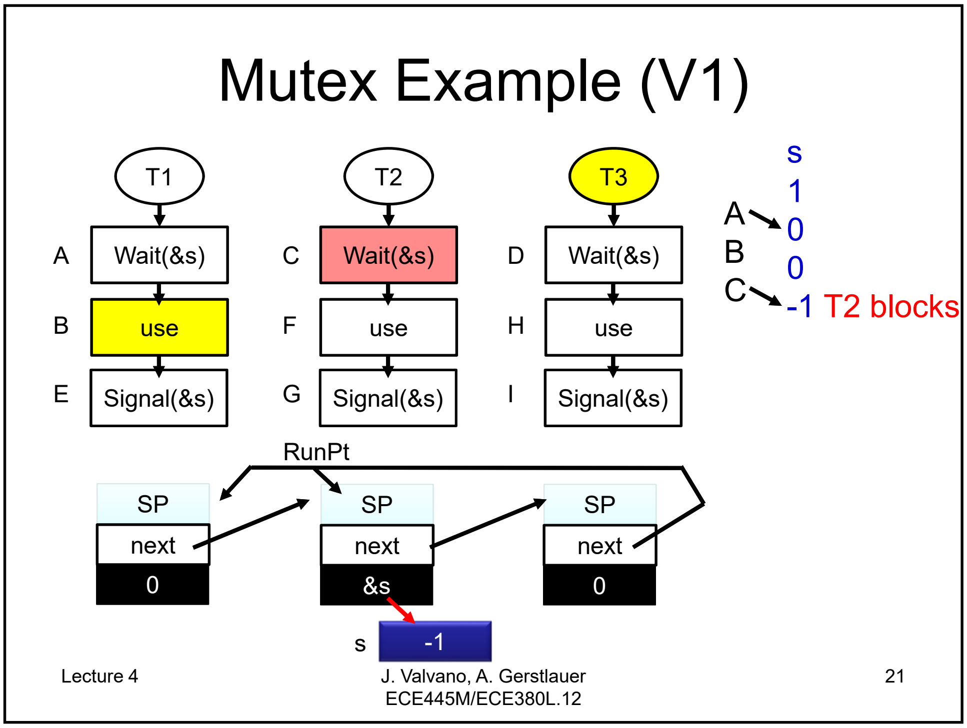
Mutex Example (V1)
T1
T2
T3
A
Wait(&s)
C
Wait(&s)
D
Wait(&s)
B
use
F
use
H
use
E
Signal(&s)
G
Signal(&s)
I
Signal(&s)
s
1
A 0
B 0
C -1 T2 blocks
RunPt
SP
next
0
SP
next
&s
SP
next
0
s -1
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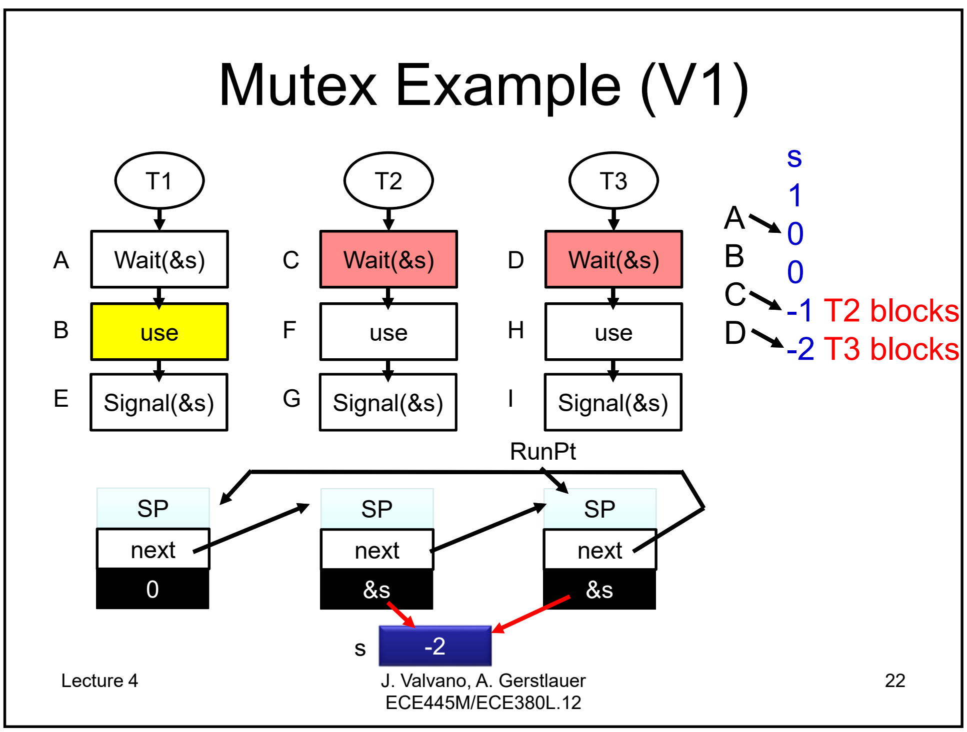
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T3
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Wait(&s)
C
Wait(&s)
D
Wait(&s)
B
use
F
use
H
use
E
Signal(&s)
G
Signal(&s)
I
Signal(&s)
s
1
A 0
B 0
C -1 T2 blocks
D -2 T3 blocks
RunPt
SP
next
0
SP
next
&s
SP
next
&s
s -2
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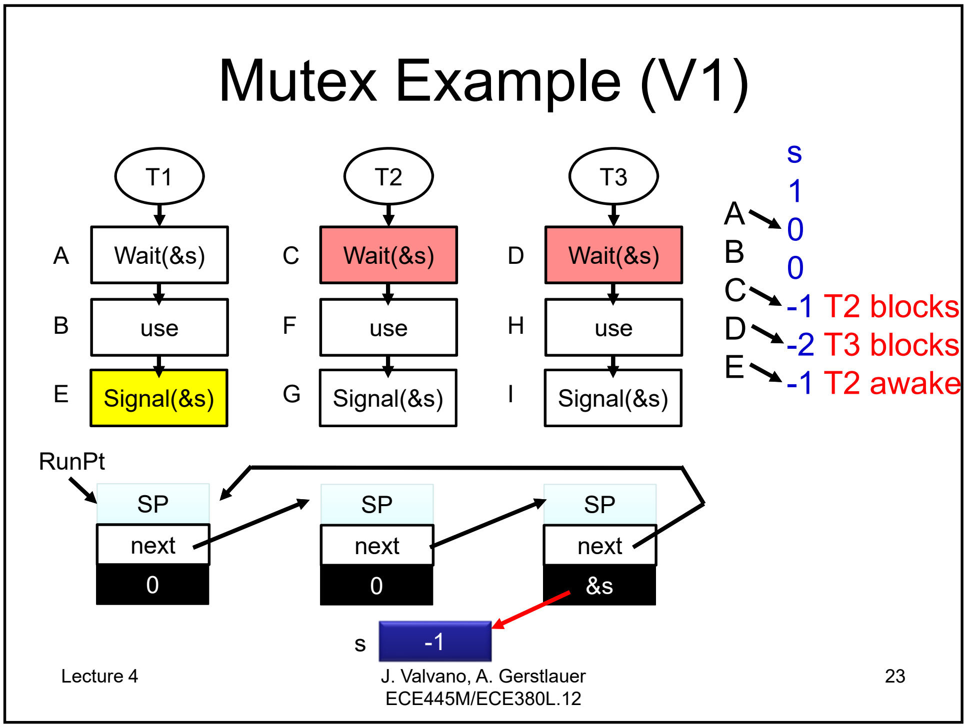
Mutex Example (V1)
T1
T2
T3
A Wait(&s)
B use
E Signal(&s)
C Wait(&s)
F use
G Signal(&s)
D Wait(&s)
H use
I Signal(&s)
s
1
A 0
B 0
C -1 T2 blocks
D -2 T3 blocks
E -1 T2 awake
RunPt
SP
next
0
SP
next
0
SP
next
&s
s -1
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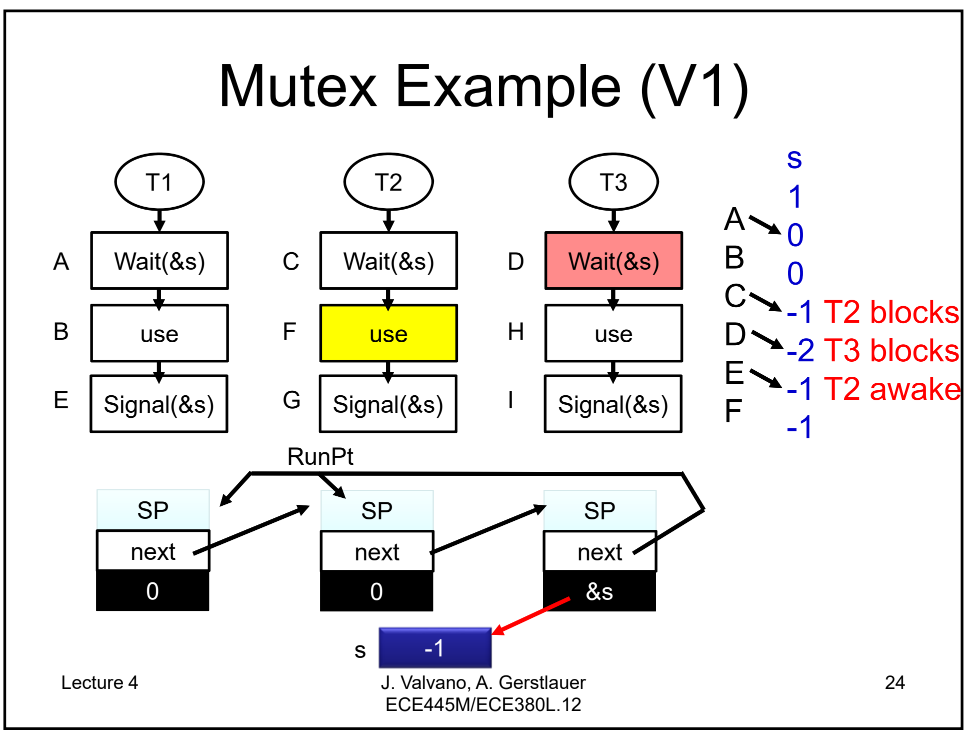
Mutex Example (V1)
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A Wait(&s)
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C Wait(&s)
F use
G Signal(&s)
D Wait(&s)
H use
I Signal(&s)
s
1
A 0
B 0
C -1 T2 blocks
D -2 T3 blocks
E -1 T2 awake
F -1
RunPt
SP
next
0
SP
next
0
SP
next
&s
s -1
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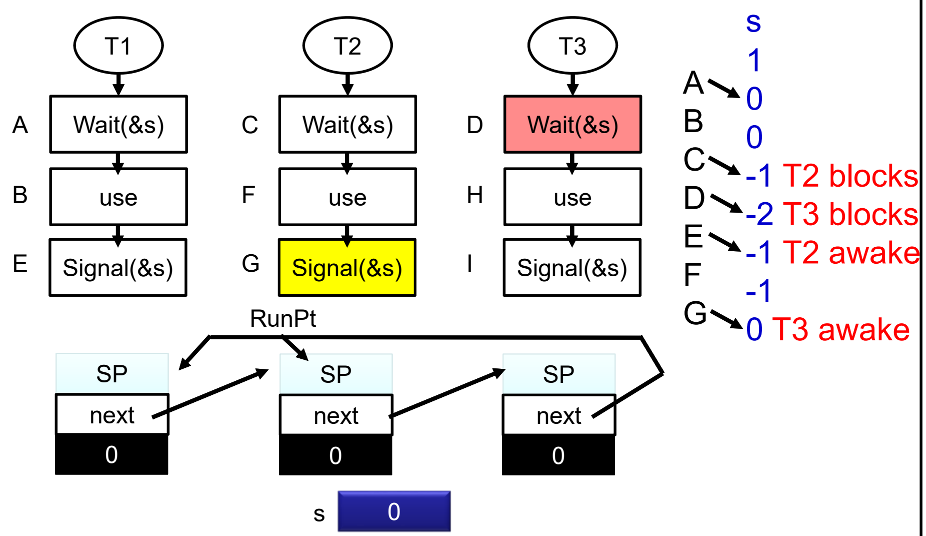
Mutex Example (V1)



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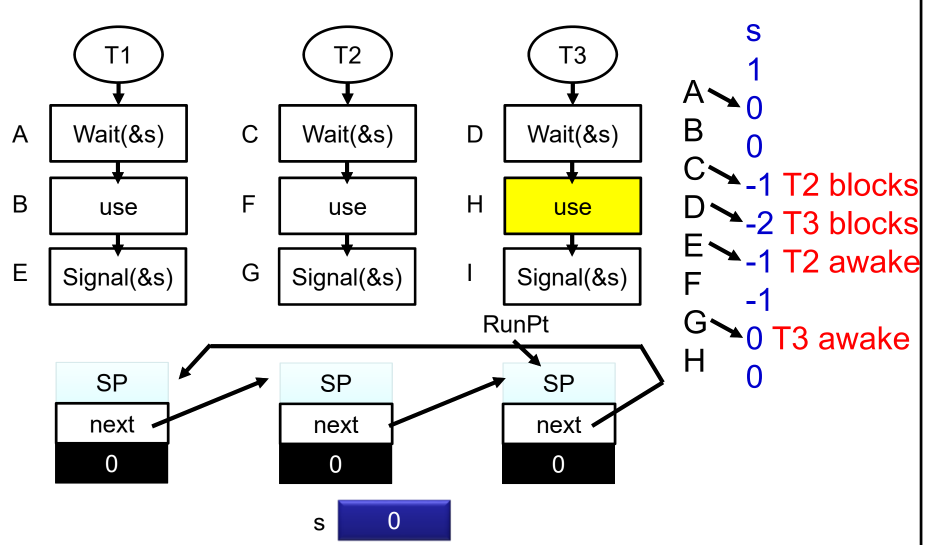
Mutex Example (V1)



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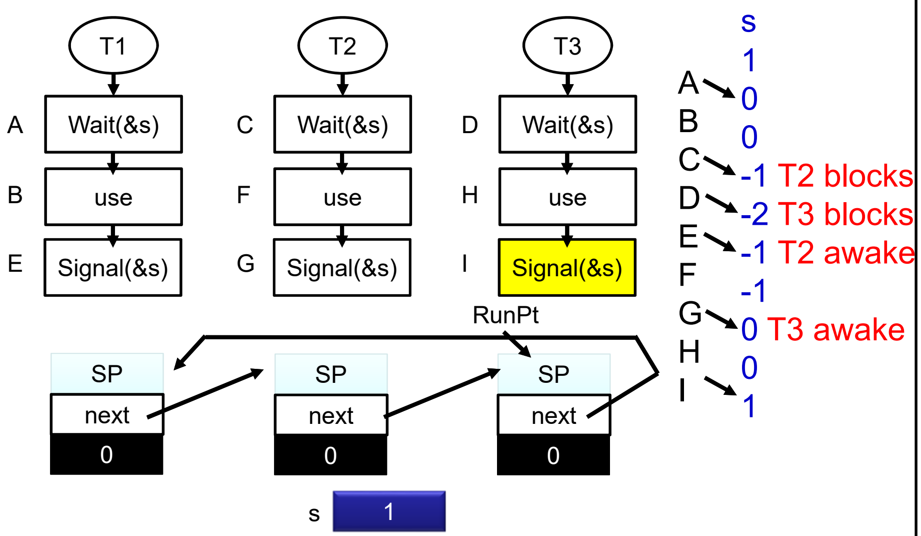
Mutex Example (V1)



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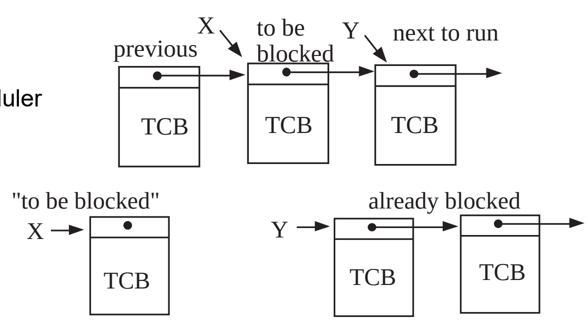
Blocking Semaphore (V2)

- Each semaphore has a blocked TCB linked list
  - contains the threads that are blocked
  - empty if semaphore **Value ≥ 0**
    - e.g., if **Value == -2**, then two threads are blocked
  - order on blocked list determine sequence of blocking
  - sequence of blocking determine which to wake up

How is the scheduler different?



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Blocking Semaphore (V2)

OS_Wait(Sema4Type *semaPt)

1) Save the I bit and disable interrupts
2) Decrement the semaphore counter, S=S-1
   `(semaPt->Value)--;`
3) If the `Value < 0` then this thread will be blocked
   set the status of this thread to blocked,
   specify this thread blocked on this semaphore,
   suspend thread
4) Restore the I bit

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Blocking Semaphore (V2)

OS_Signal (Sema4Type *semaPt)

1) Save I bit, then disable interrupts
2) Increment the semaphore counter, S=S+1
   `(semaPt->Value)++;`
3) If the `Value ≤ 0` then
   Wake up one thread from the TCB linked list
      Bounded waiting -> the one waiting the longest
      Priority -> the one with highest priority
   Move TCB of the "wakeup" thread
      from the blocked list to the active list
   What to do with the thread that called OS_Signal?
      Round robin -> do not suspend
      Priority -> suspend if wakeup thread is higher priority
4) Restore I bit

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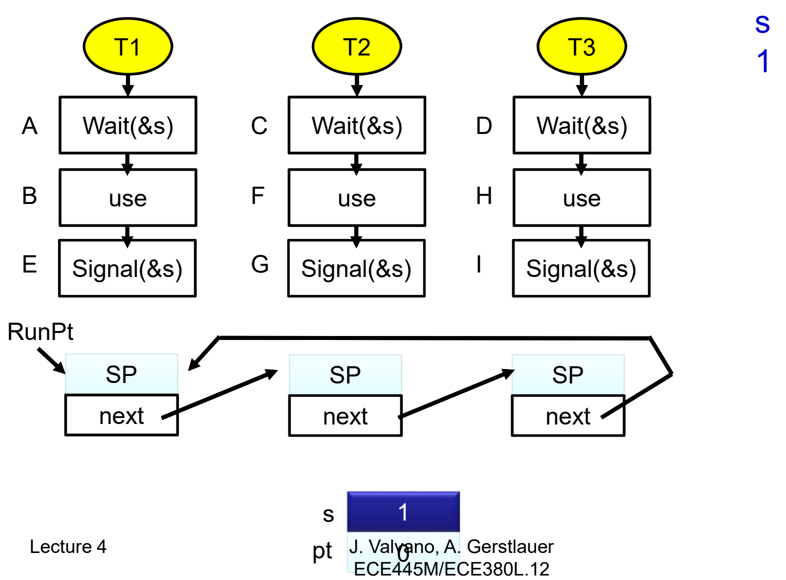
Mutex Example (V2)



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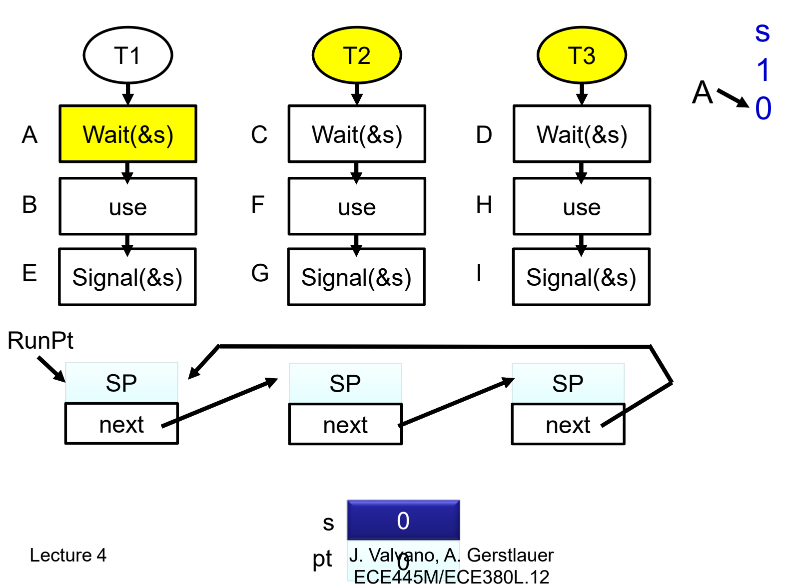
Mutex Example (V2)



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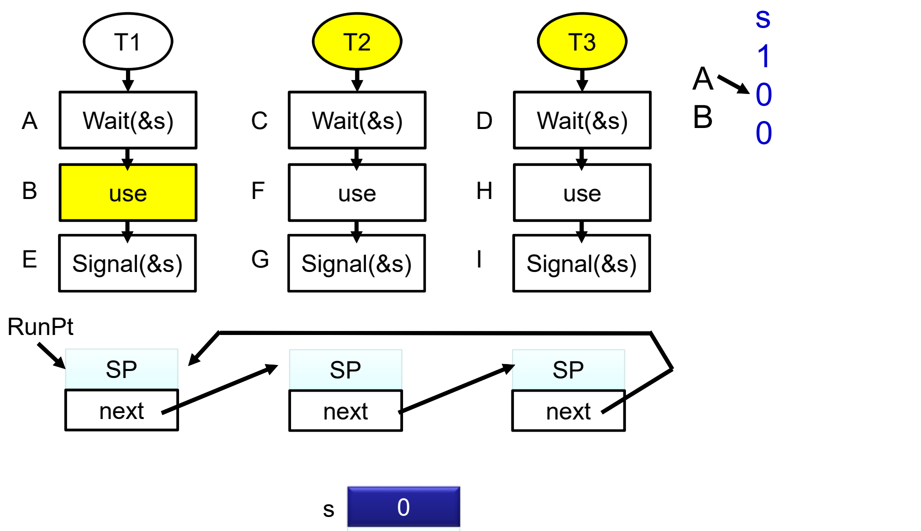
Mutex Example (V2)



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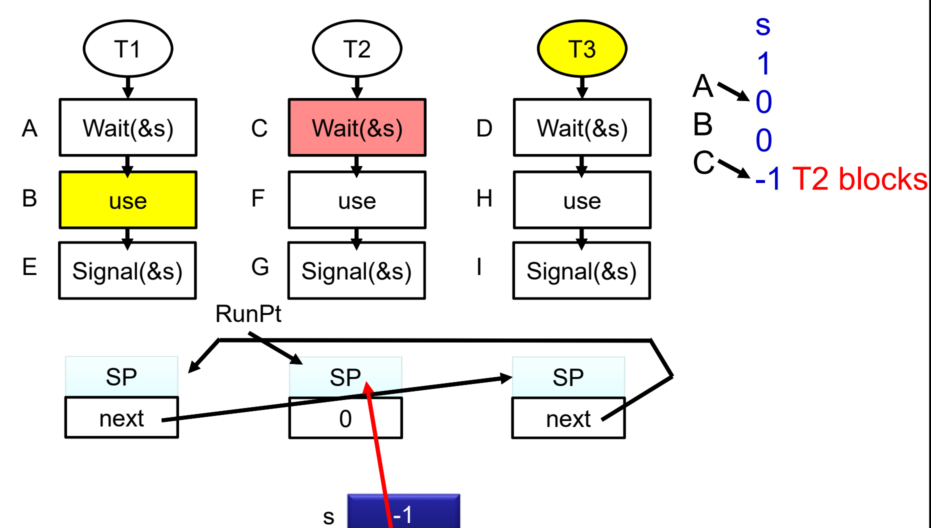
Mutex Example (V2)



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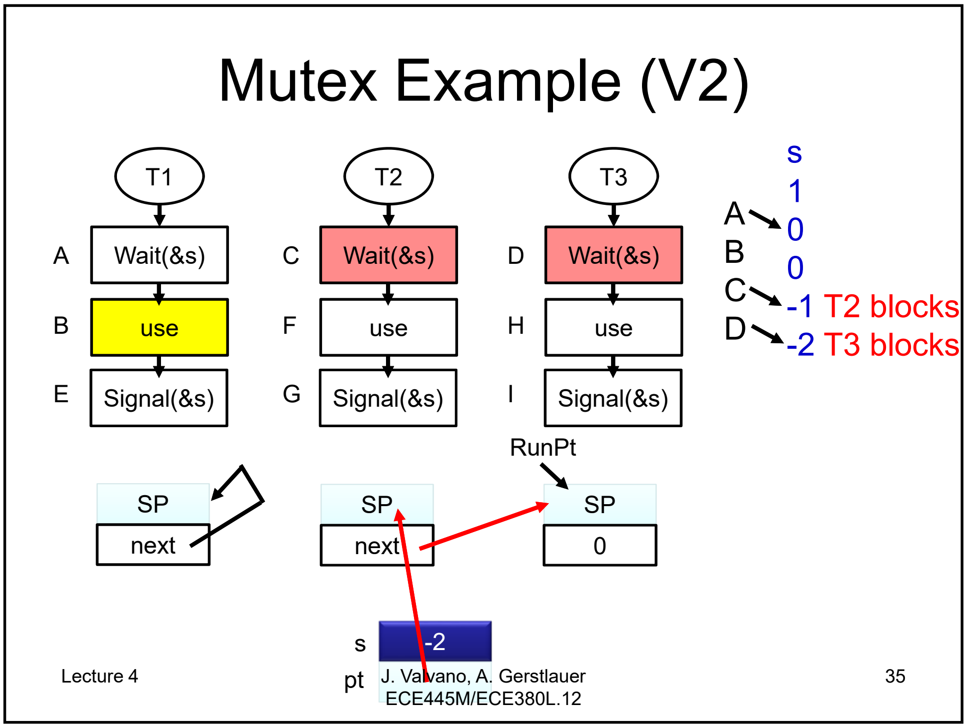
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T2
T3
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B
use
E
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C
Wait(&s)
F
use
G
Signal(&s)
D
Wait(&s)
H
use
I
Signal(&s)
s
1
A 0
B 0
C -1 T2 blocks
D -2 T3 blocks
RunPt
SP
next
SP
next
SP
0
s -2
pt
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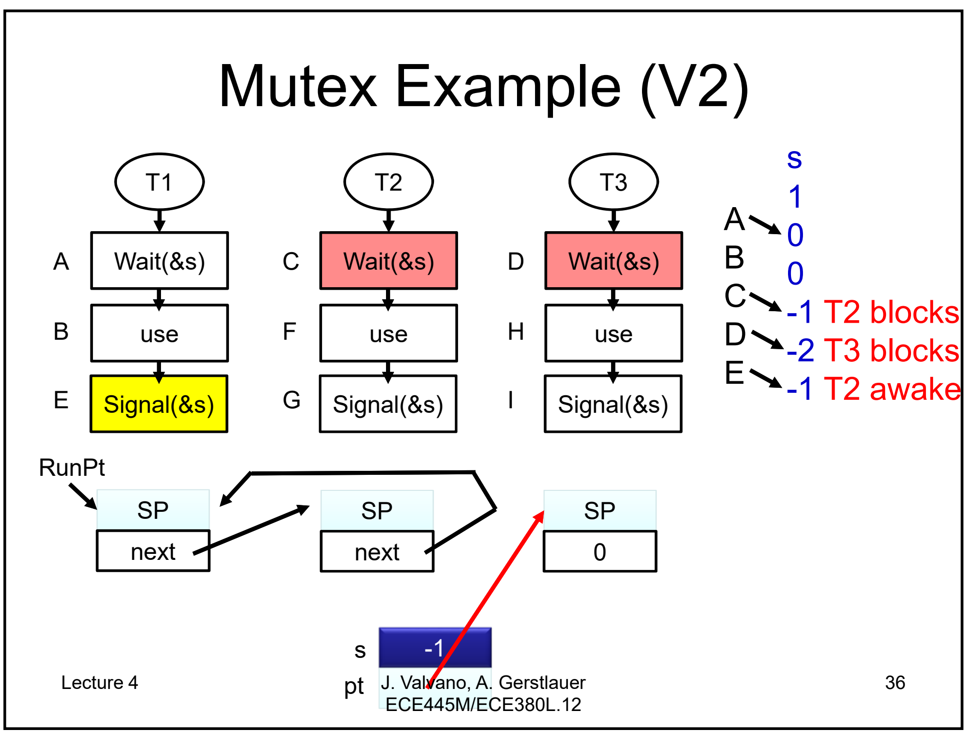
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H
use
I
Signal(&s)
s
1
A 0
B 0
C -1 T2 blocks
D -2 T3 blocks
E -1 T2 awake
RunPt
SP
next
SP
next
SP
0
s -1
pt
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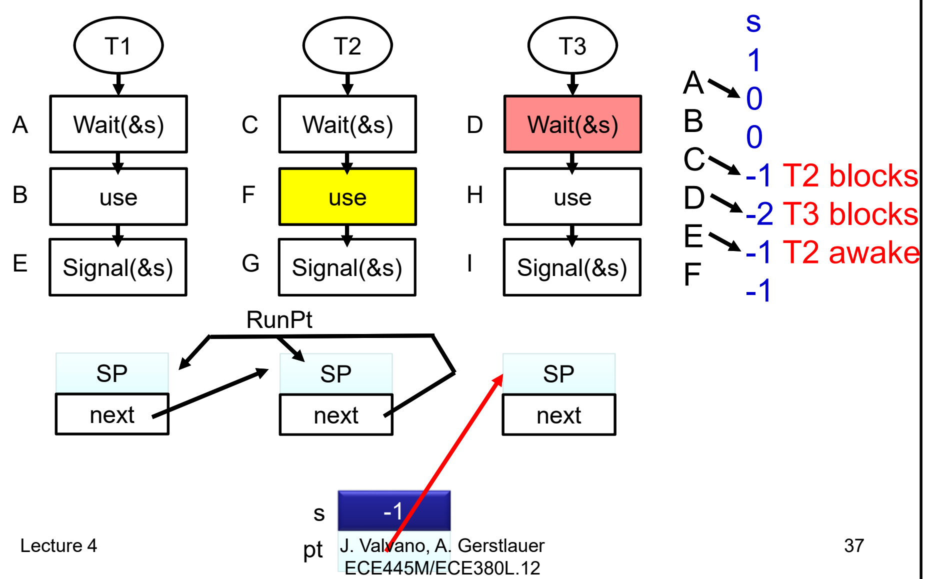
Mutex Example (V2)



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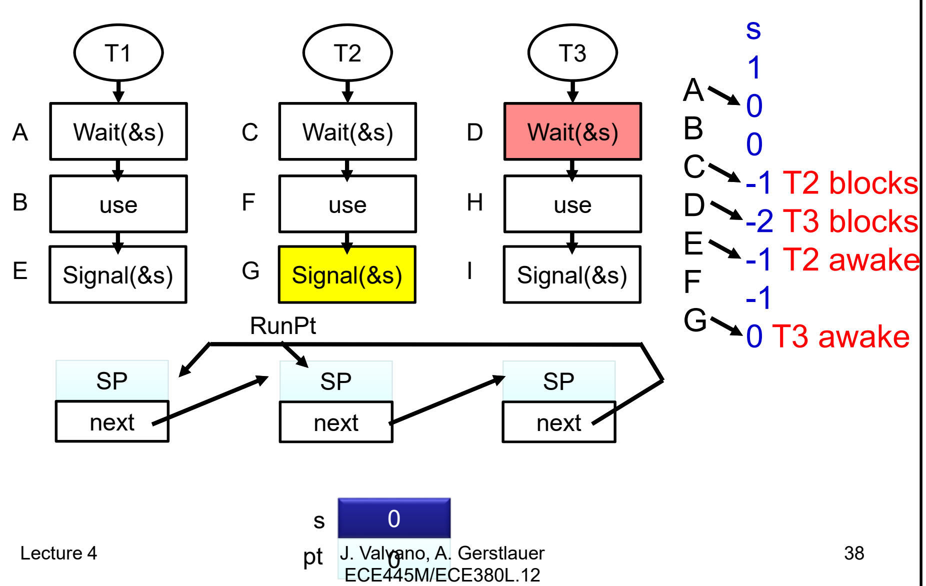
Mutex Example (V2)



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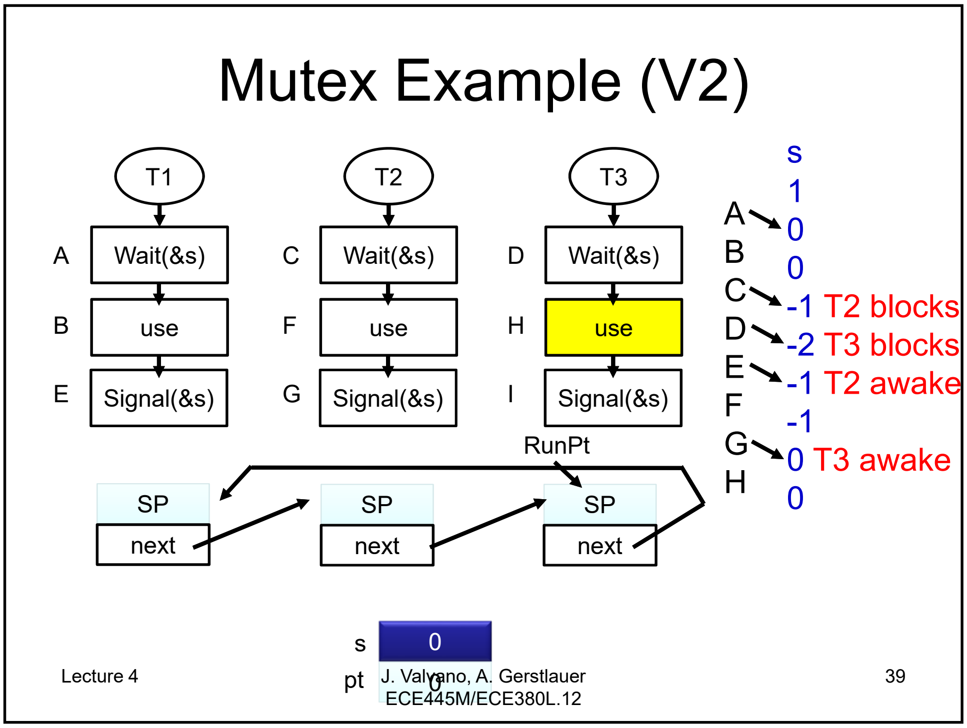
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G 0 T3 awake
H 0
s 0
pt
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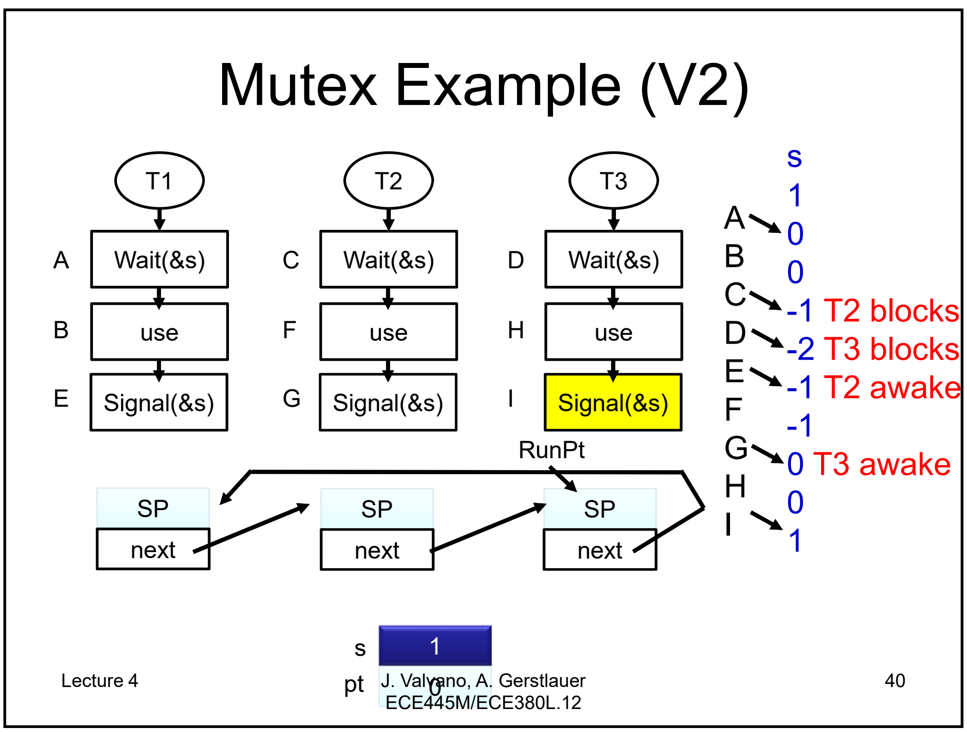
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Wait(&s)
H
use
I
Signal(&s)
RunPt
SP
next
SP
next
SP
next
s
1
A 0
B 0
C -1 T2 blocks
D -2 T3 blocks
E -1 T2 awake
F -1
G 0 T3 awake
H 0
I 1
s 1
pt
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Semaphore Applications

- Sequential execution
  - **Run-A** then **Run-B** then **Run-C**
- Rendezvous
- Event trigger
  - **Event-A** and **Event-B**
  - **Event-A** or **Event-B**
- Fork and join
- Readers-Writers Problem

Look at old exams

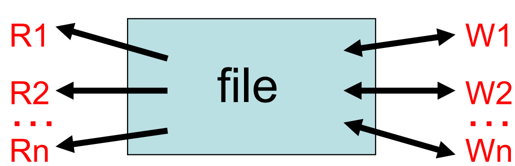
Readers-Writers Problem

Reader Threads

1) Execute **ROpen(file)**
2) Read information from **file**
3) Execute **RClose(file)**

Writer Threads

1) Execute **WOpen(file)**
2) Read information from **file**
3) Write information to **file**
4) Execute **WClose(file)**



Readers-Writers Problem

ReadCount=0: number of Readers that are open
mutex=1: semaphore controlling access to **ReadCount**
wrt=1: semaphore is true if a writer is allowed access

ROpen
```
wait(&mutex);
ReadCount++;
if(ReadCount==1) wait(&wrt)
signal(&mutex);
```

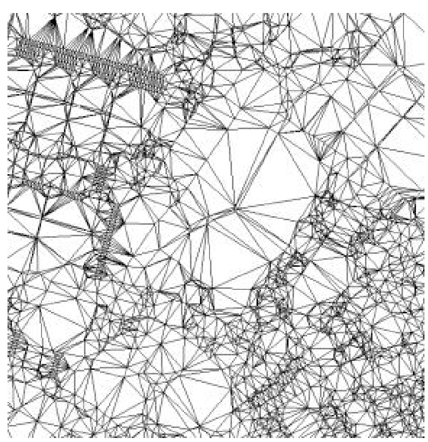
WOpen
```
wait(&wrt);
```

RClose
```
wait(&mutex);
ReadCount--;
if(ReadCount==0) signal(&wrt)
signal(&mutex);
```

WClose
```
signal(&wrt);
```


Deadlock

- Conditions
  - Mutual exclusion
  - Hold and wait
  - No preemption of resources
  - Circular waiting

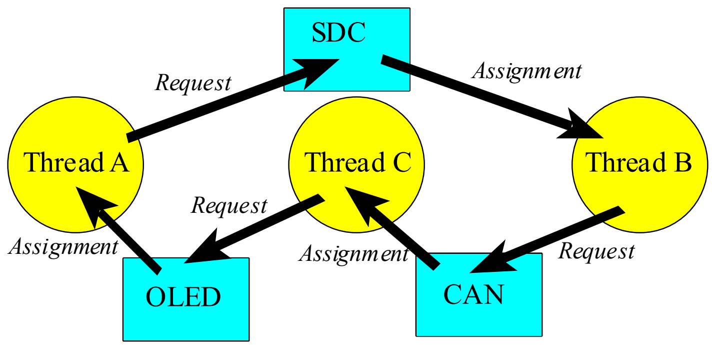


Where is the deadlock?

Resource Allocation Graph

Thread A	Thread B	Thread C

wait(&bOLED); //1
wait(&bSDC); //4
use OLED and SDC
signal(&bSDC);
signal(&bOLED);
	wait(&bSDC); //2
	wait(&bCAN); //5
	use CAN and SDC
	signal(&bCAN);
	signal(&bSDC);
		wait(&bCAN); //3
		wait(&bOLED); //6
		use CAN and OLED
		signal(&bOLED);
		signal(&bCAN);



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Deadlock Prevention

- No mutual exclusion
- No hold and wait
  - Ask for all at same time
  - Release all, then ask again for all
- No circular waiting
  - Number all resources
  - Ask for resources in a specific order

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Prevention

- No hold and wait

Thread A	Thread B	Thread C

wait(&bOLED,&bSDC);
use OLED and SDC
signal(&bOLED,&bSDC);
	wait(&bSDC,&bCAN);
	use CAN and SDC
	signal(&bSDC,&bCAN);
		wait(&bCAN,&bOLED);
		use CAN and OLED
		signal(&bCAN,&bOLED);

- No circular wait

Thread A	Thread B	Thread C

wait(&bOLED);
wait(&bSDC);
use OLED and SDC
signal(&bSDC);
signal(&bOLED);
	wait(&bSDC);
	wait(&bCAN);
	use CAN and SDC
	signal(&bCAN);
	signal(&bSDC);
		wait(&bOLED);
		wait(&bCAN);
		use CAN and OLED
		signal(&bOLED);
		signal(&bCAN);

Deadlock Avoidance

- Is there a safe sequence?
- Tell OS current and future needs
  - Request a resource
  - Specify future requests while holding
  - Yes, if there is one safe sequence
- OS can say no, even if available
  - Google search on Banker's Algorithm

Deadlock Detection

- Add timeouts to semaphore waits
- Detect cycles in resource allocation graph
- Kill threads and recover resources
  - Abort them all, and restart
  - Abort them one at a time until it runs

Advanced Topics (Grad Students)

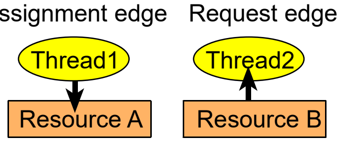
- Bounded waiting
- Time-out
- Deadlock avoidance
  - Banker's algorithm
- Deadlock detection
  - Wait-for-graph
  - Resource allocation graph

Two names for the same thing

Works for single instance resources

- Two types of boxes
  Threads, resources
- Two types of arrows
  Assignment, request

Assignment edge Request edge



Thread 1 captures Resource A

Thread 2 blocked on Resource B

Testing (1)

- How long do you test?
  - *n* = number of times T1 interrupts T2
  - *m* = total number of assembly instructions in T2
  - Run test until *n* greatly exceeds *m*
- Think of this corresponding probability question
  - *m* different cards in a deck
  - Select one card at random, with replacement
  - What is the probability after *n* selections (with replacement) that a particular card was never selected?
  - Similarly, what is the probability that all cards were selected at least once?

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Testing (2)

Entered 486,736,253 times

```
Rx_Fifo_Get
 0 24996444 0x000009B4 4601   MOV   r1,r0          ;int RxFifo_Get(rxDataType *datapt){
 1 47909851 0x000009B6 481D   LDR   r0,[pc,#116]   ;  if(RxPutPt == RxGetPt ){
 2 12498221 0x000009B8 6800   LDR   r0,[r0,#0x00]
 3 71517599 0x000009BA 4A1B   LDR   r2,[pc,#108]
 4 14581259 0x000009BC 6812   LDR   r2,[r2,#0x00]
 5 11109532 0x000009BE 4290   CMP   r0,r2
 6 10415182 0x000009C0 D101   BNE   0x000009C6
 7 12498220 0x000009C2 2000   MOVS  r0,#0x00       ;    return(RXFIFOFAIL);
 8  4860416 0x000009C4 4770   BX    lr             ;  }
 9   694345 0x000009C6 4818   LDR   r0,[pc,#96]    ;  *datapt = *(RxGetPt++);
10  4860416 0x000009C8 6800   LDR   r0,[r0,#0x00]
11  1388690 0x000009CA 7800   LDRB  r0,[r0,#0x00]
12   694345 0x000009CC 7008   STRB  r0,[r1,#0x00]
13  4166071 0x000009CE 4816   LDR   r0,[pc,#88]
14  1388690 0x000009D0 6800   LDR   r0,[r0,#0x00]
15  2777381 0x000009D2 1C40   ADDS  r0,r0,#1
16  1388691 0x000009D4 4A14   LDR   r2,[pc,#80]
17        0 0x000009D6 6010   STR   r0,[r2,#0x00]
18  1388692 0x000009D8 4610   MOV   r0,r2
19  1388690 0x000009DA 6802   LDR   r2,[r0,#0x00]
20  2777380 0x000009DC 4811   LDR   r0,[pc,#68]
21  1388690 0x000009DE 4282   CMP   r2,r0          ;  if(RxGetPt==&RxFifo[RXFIFOSIZE]
22        0 0x000009E0 D102   BNE   0x000009EA
23        0 0x000009E2 3820   SUBS  r0,r0,#0x20    ;    RxGetPt = &RxFifo[0];
24  1388691 0x000009E4 4A10   LDR   r2,[pc,#64]
25  1388690 0x000009E6 6010   STR   r0,[r2,#0x00]
26  2083035 0x000009E8 2001   MOVS r0,#0x01
27        0 0x000009EA E7EA   B     0x000009C4     ;  return(RXFIFOSUCCESS);}
```

FIFO_4C123

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Performance Measures

- Maximum time running with I=1
- Percentage of time it runs with I=1
- Latency $t_{action} - t_{trigger}$
- Time jitter δt on periodic tasks

$$T_i - \delta t < t_n - t_{n-1} < T_i + \delta t \qquad \text{for all } n$$

- CPU utilization
  - Percentage time running idle task
- Context switch overhead
  - Time to switch tasks

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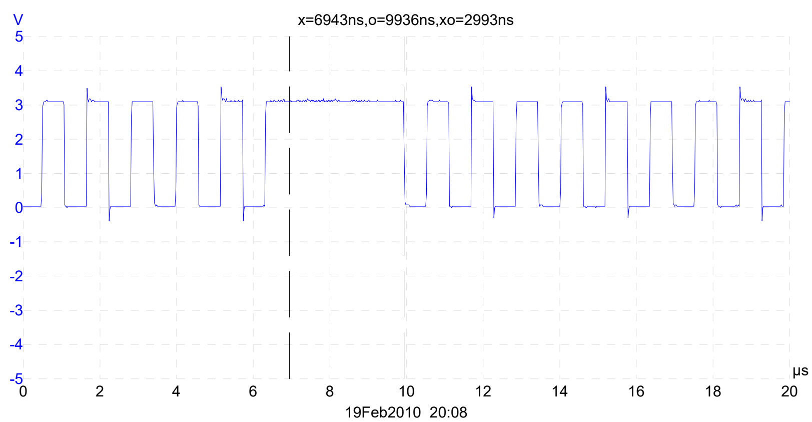
Context Switch Time

- Just like the Lab 1 measurement



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Running with I = 1

```
#define  OSCRITICAL_ENTER() { sr = StartCritical(); }
#define  OSCRITICAL_EXIT()  { EndCritical(sr); }
```

- Record time *t1* when I=1

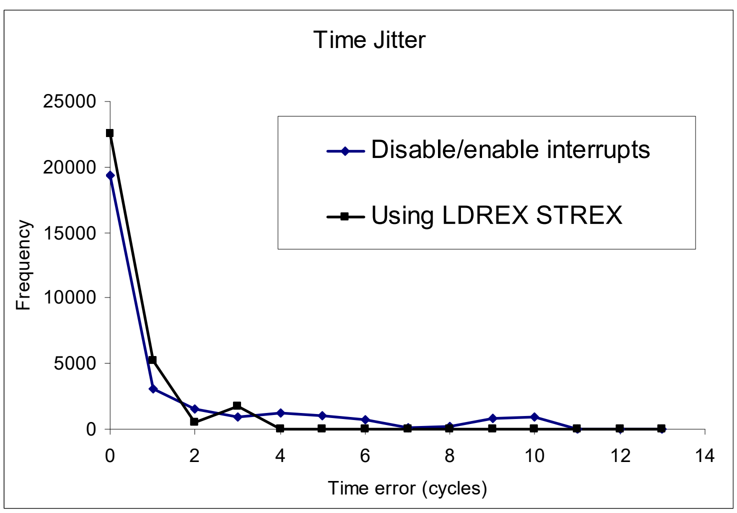
```
#define  OSCRITICAL_ENTER() {sr = StartCritical(); t1=OS_Time(); }
```

- Record time *t2* when I=0 again
- Measure difference

```
#define  OSCRITICAL_EXIT()  {dt=OS_TimeDifference(OS_Time(),t1);
EndCritical(sr); }
```

- Record maximum and total

Time Jitter

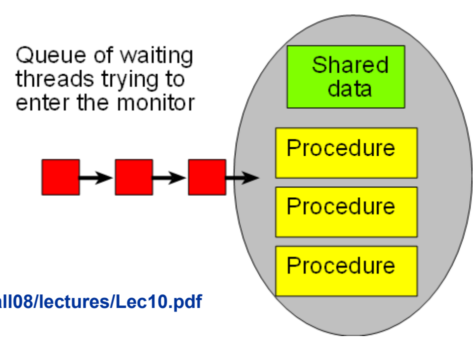


Semaphore Drawbacks

- Shared global variables
  - Can be accessed from anywhere
- No connection between the semaphore and the data being controlled by the semaphore
  - Used both for critical sections (mutual exclusion) and coordination (scheduling)
- No control or guarantee of proper usage

Monitors

- Proper use is enforced
- Synchronization attached to the data
- Removes hold and wait
- Threads enter
  - One active at a time



http://lass.cs.umass.edu/~shenoy/courses/fall08/lectures/Lec10.pdf

Monitors

- Lock
  - Only one thread active at a time
  - Must have lock to access condition variables
- One or more condition variables
  - If cannot complete, leave data consistent
  - Threads can sleep inside by releasing lock
  - Wait (acquire or sleep)
  - Signal (if any waiting, wakeup else NOP)
  - Broadcast

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FIFO Monitor

Put(item):	Get():
1) lock->Acquire(); 2) put item on queue; 3) conditionVar->Signal(); 4) lock->Release();	1) lock->Acquire(); 2) while queue is empty conditionVar->Wait(lock); 3) remove item from queue; 4) lock->Release(); 5) return item;

http://lass.cs.umass.edu/~shenoy/courses/fall08/lectures/Lec10.pdf

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Hoare vs. Mesa Monitor

- Signal() switches immediately vs. later

Hoare wait:	Mesa wait:

if(FIFO empty)
  wait(condition)
	while(FIFO empty)
	  wait(condition)

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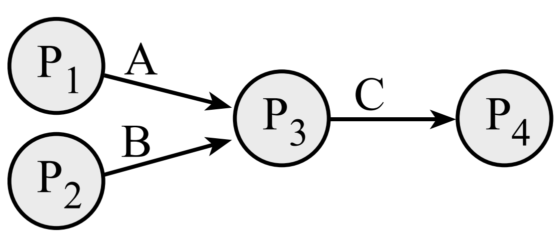
Kahn Process Network (KPN)

- Parallel programming model
  - Blocking read
  - Non-blocking writes (never full)
  - Tokens are data (no time stamp)



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Kahn Process Network (KPN)

- Deterministic
  - Same inputs result in same outputs
  - Independent of scheduler
- Non-blocking writes (never full)
- Monotonic
  - Needs only partial inputs to proceed
  - Works in continuous time

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Kahn Process Network (KPN)

```
void Process3(void){
long inA, inB, out;
  while(1){
    while(AFifo_Get(&inA)){};
    while(BFifo_Get(&inB)){};
    out = compute(inA,inB);
    CFifo_Put(out);
  }
}
```

```
void Process3(void){
long inA, inB, out;
  while(1){
    if(AFifo_Size()==0){
      while(BFifo_Get(&inB)){};
      while(AFifo_Get(&inA)){};
    } else{
      while(AFifo_Get(&inA)){};
      while(BFifo_Get(&inB)){};
    }
    out = compute(inA,inB);
    CFifo_Put(out);
  }
}
```

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Kahn Process Network (KPN)

- Strictly bounded?
  - Prove it never fills (undecidable!)
  - Dependent on scheduler
- Termination
  - All processed blocked on input
- Scheduler
  - Needs only partial inputs to proceed
  - Works in real time

KPN Boundedness

- Try to find a mathematical proof
- Experimentally adjust FIFO size
  - Needs a realistic test environment
  - Profile/histogram DataAvailable for each FIFO
  - Leave the profile in delivered machine
- Dynamically adjust size with malloc/free
- Use blocking write (not a KPN anymore)
- Discard the data

Summary

- Use the logic analyzer
  - Visualize what is running
- Learn how to use the debugger
  - Breakpoint inside ISR
    - Does not seem to single step into ISR
- What to do after a thread calls Kill?