

EE445M/ECE380L.12

Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 5: Semaphores, Deadlocks, Debugging, Testing

Lecture 5

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Graduate Projects Ideas

1. Extend the OS with more features (do this if two students in group)
 - Efficient with 20 to 50 threads
 - Multiple cores (real-time scheduling algorithms & implementation)
 - Multiple Mailboxes, FIFOs
 - Multiple periodic/edge-triggered interrupts
 - 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-based eDisk driver for the LaunchPad board (one-person project)
 - Compare and contrast your Lab5 to FAT
4. Design and test a DMA-based camera driver for the LaunchPad board
 - See LM3S811 example http://www.ece.utexas.edu/~valvano/arm/Camera_811.zip (one person project)
 - Implement object/lane detection/recognition and lane keeping (self-driving car) (two or more students)
5. Write your own memory management
 - Heap, malloc and free (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

Due end of Feb

Level of complexity depends on size of group

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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

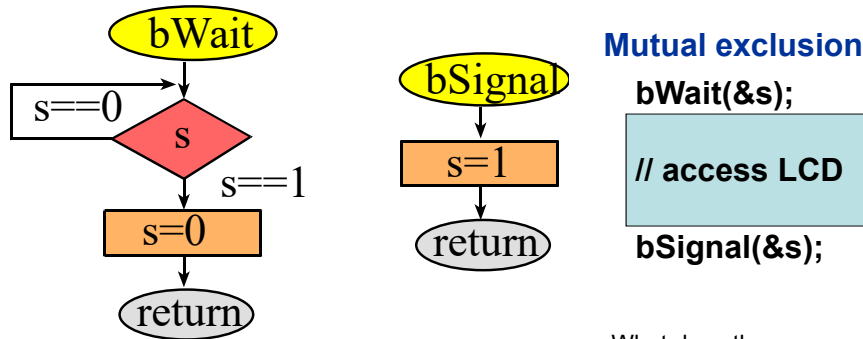
- Counting semaphore
 - Number of elements stored in FIFO
 - Space left in the FIFO
 - Number of printers available
- Binary semaphore (= mutex = flag)
 - Free (1), busy (0)
 - Event occurred (1), not occurred (0)

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Spin-Lock Binary Semaphore



How do we use this to solve critical sections?
 Why is this a good solution for critical sections?

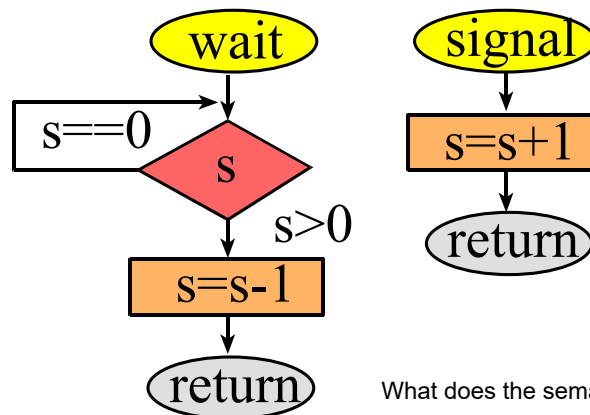
What does the semaphore mean?
 What would be a better name for s ?
 What about atomic?

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Spin-Lock Counting Semaphore



What does the semaphore mean?
 What about atomic?

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Spin-Lock Semaphores

<pre> OS_Wait ;R0 points to counter LDREX R1, [R0] ; counter SUBS R1, #1 ; counter -1, ITTT 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 </pre>	<pre> 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); } </pre>
--	--

LDREX
STREX

Program 4.11

Cortex-M3/M4F Instruction Set, pg. 50

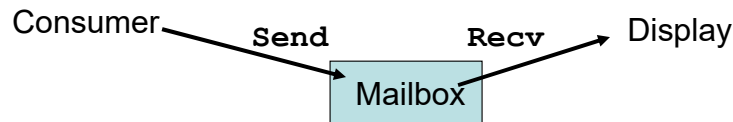
Mailbox

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)

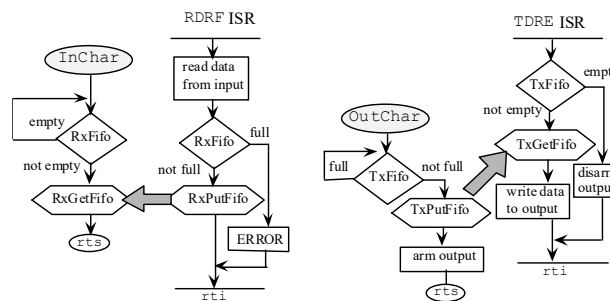
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What do the semaphores mean?
 What if the FIFO never fills?

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No Background Wait

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



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Cooperative Spin-Lock

Cooperative spin-lock

Could be implemented with a catch and throw

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
}
    
```

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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

Do an experiment of Lab 2 with and without cooperation

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Blocking Semaphore (Lab 3)

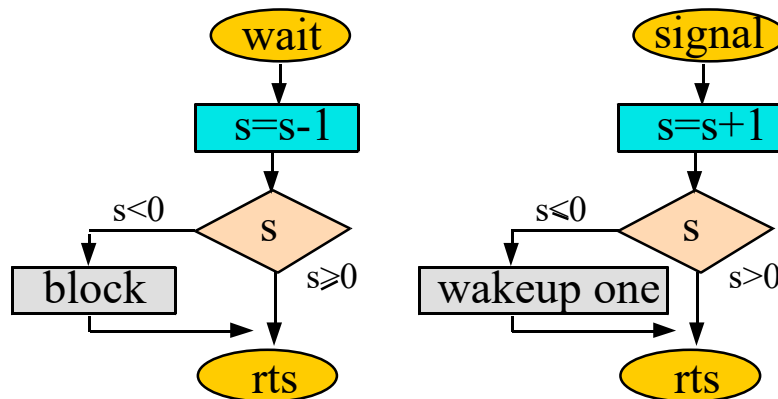
- Recapture time lost in the spin-lock
 - No spin operation, wakeup only on signal
 - Eliminate wasted time running threads that are not doing work (e.g., waiting)
- Implement **bounded waiting**
 - Once thread calls **Wait** and is not serviced,
 - There are a finite number of threads that will go ahead

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Blocking Semaphore



What does the semaphore mean?
What about atomic?

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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**

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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

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Blocking Semaphore (V1)

OS_Signal(Sema4Type *semaPt)

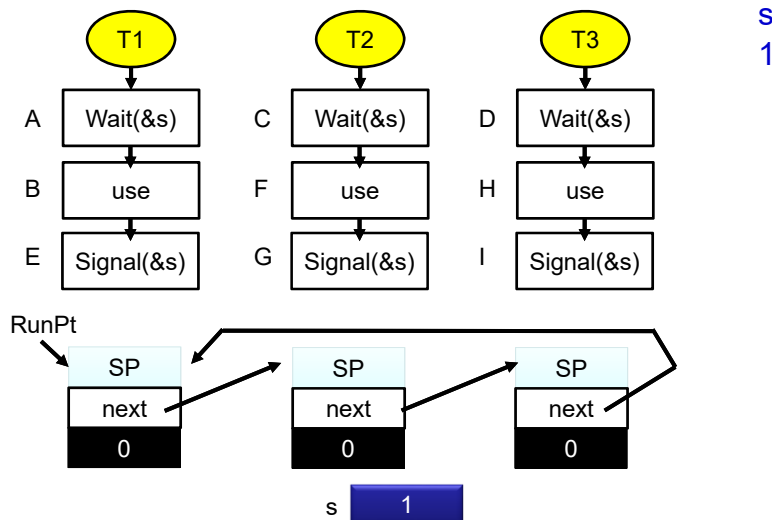
- 1) Save I bit, then disable interrupts
- 2) Increment the semaphore Value, $S=S+1$
`(semaPt->Value) ++;`
- 3) If $Value \leq 0$ then
 - wake up one thread from the TCB linked list
(no bounded waiting)
 - search TCBs for thread with `BlockPt == semaPt`
 - set the `BlockPt` of this TCB to null
 - do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

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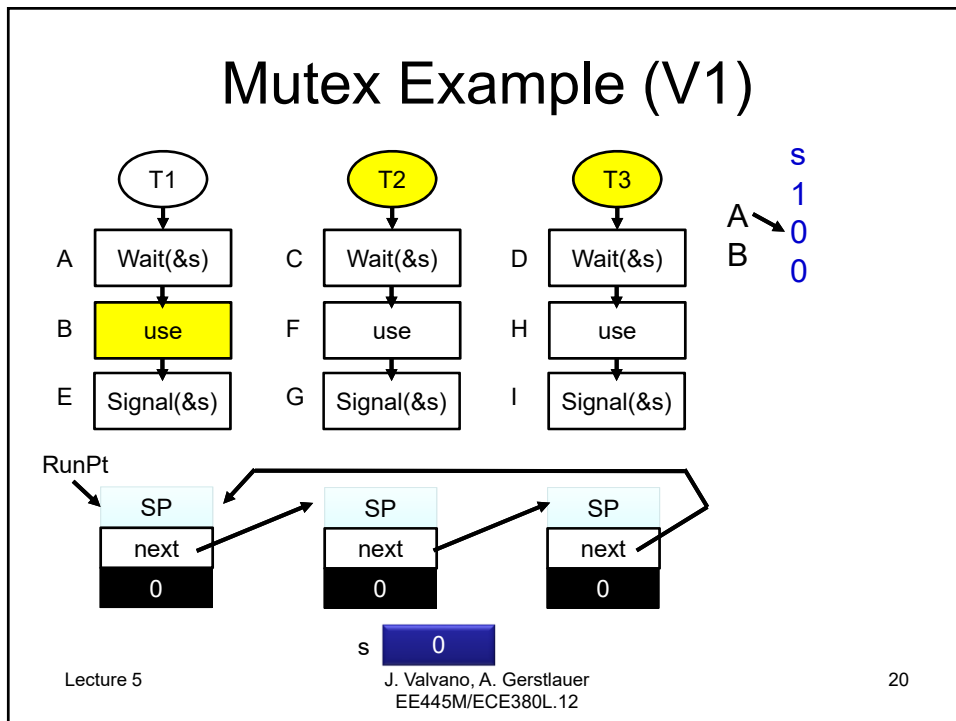
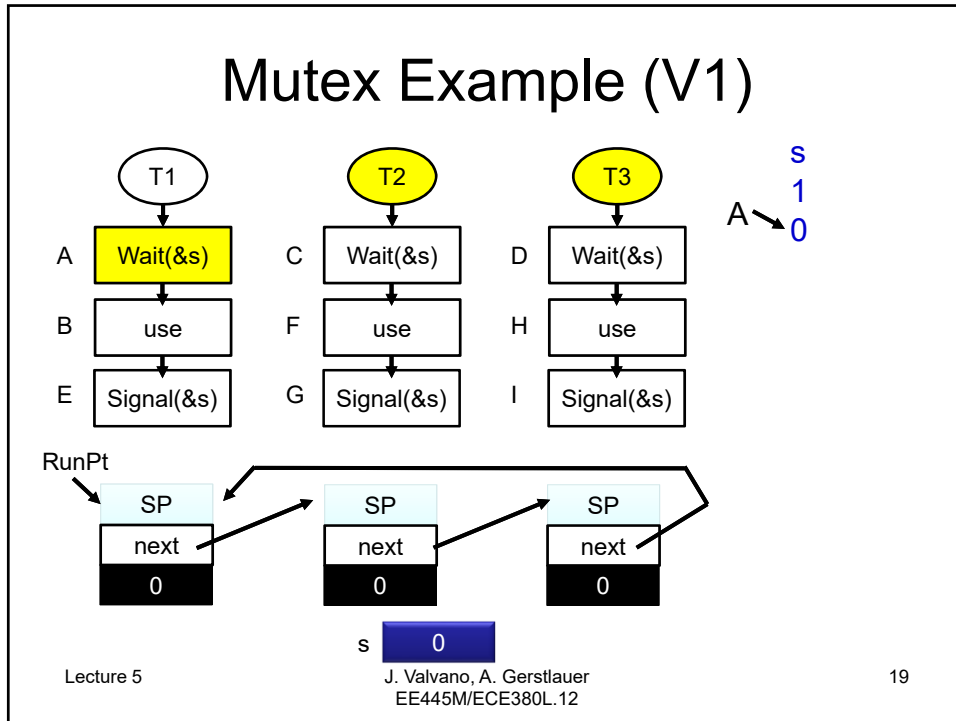
Mutex Example (V1)

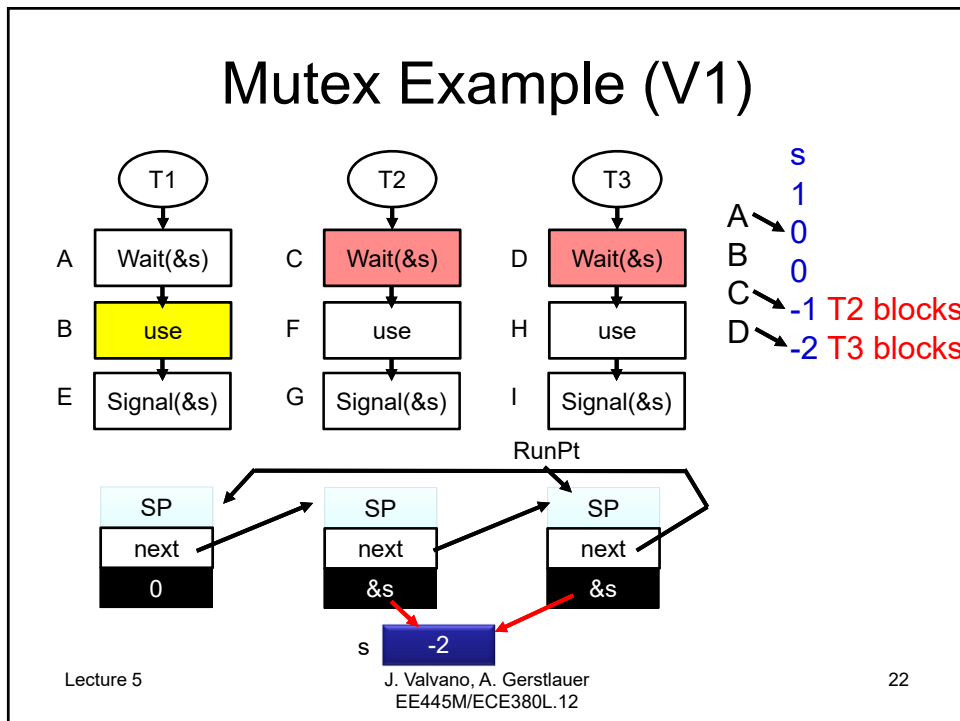
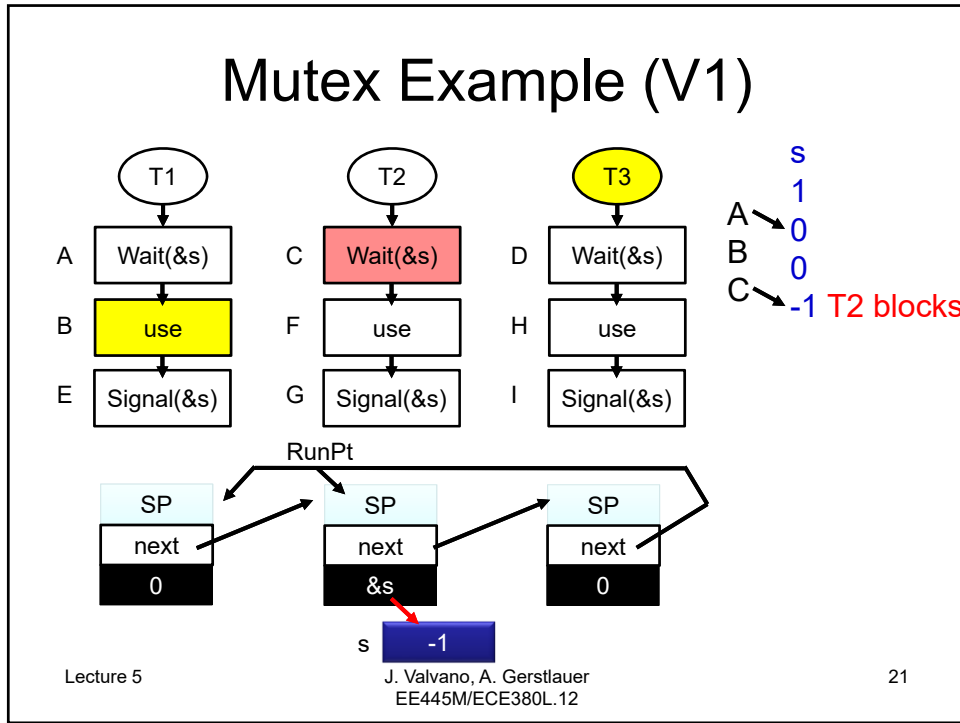


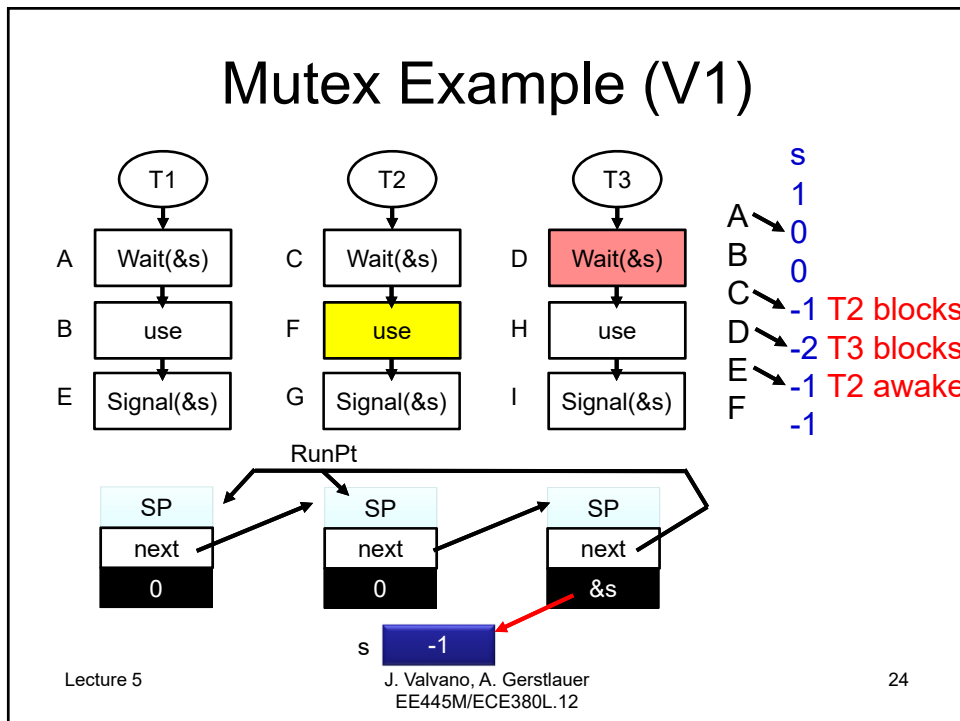
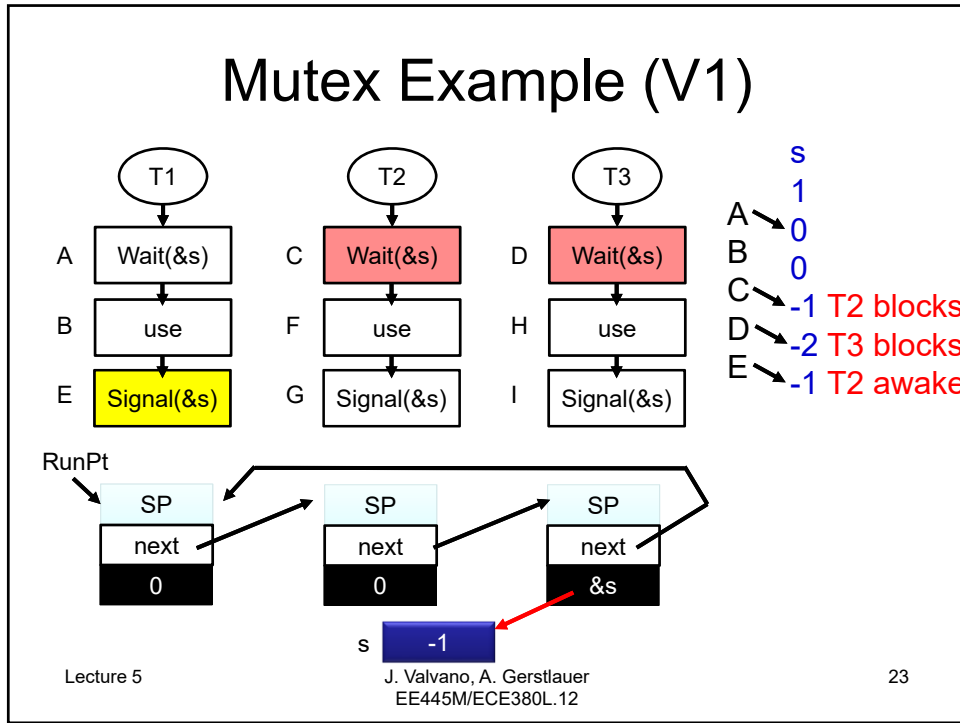
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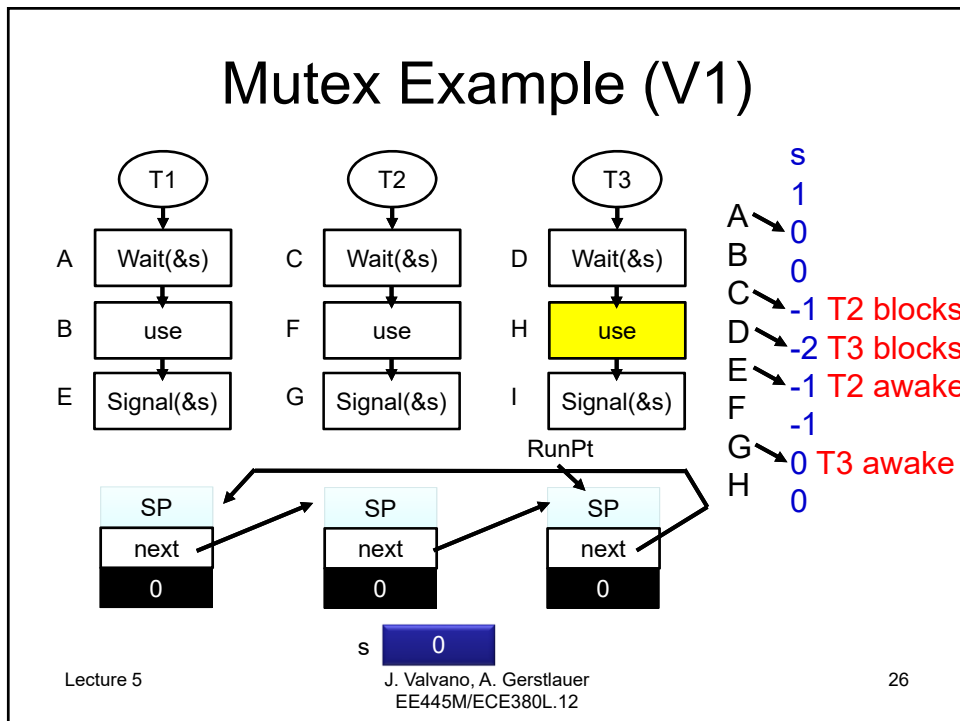
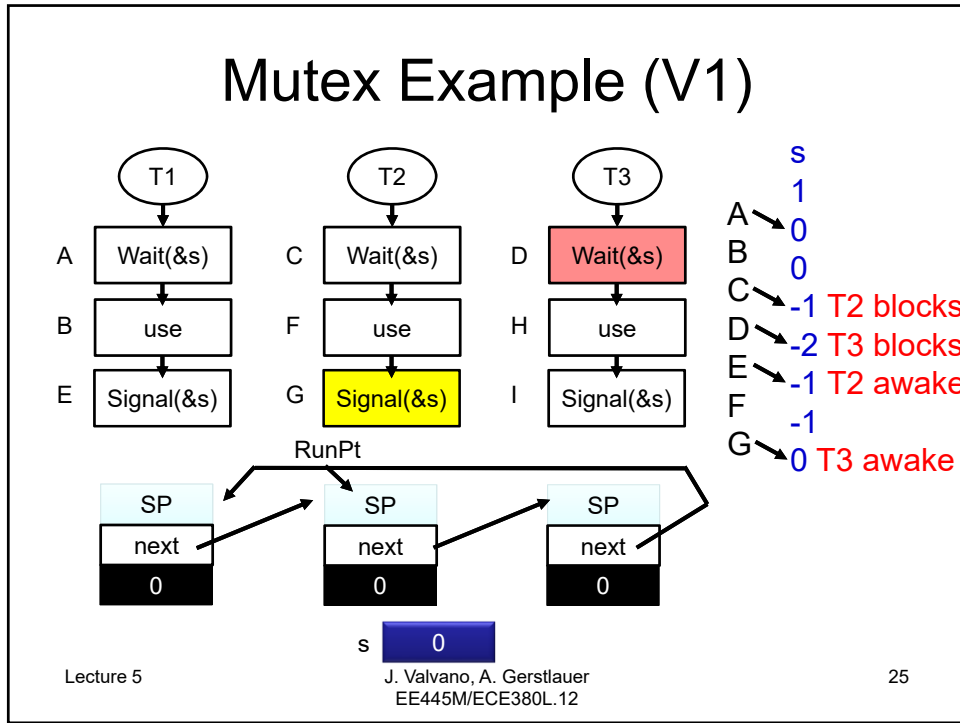
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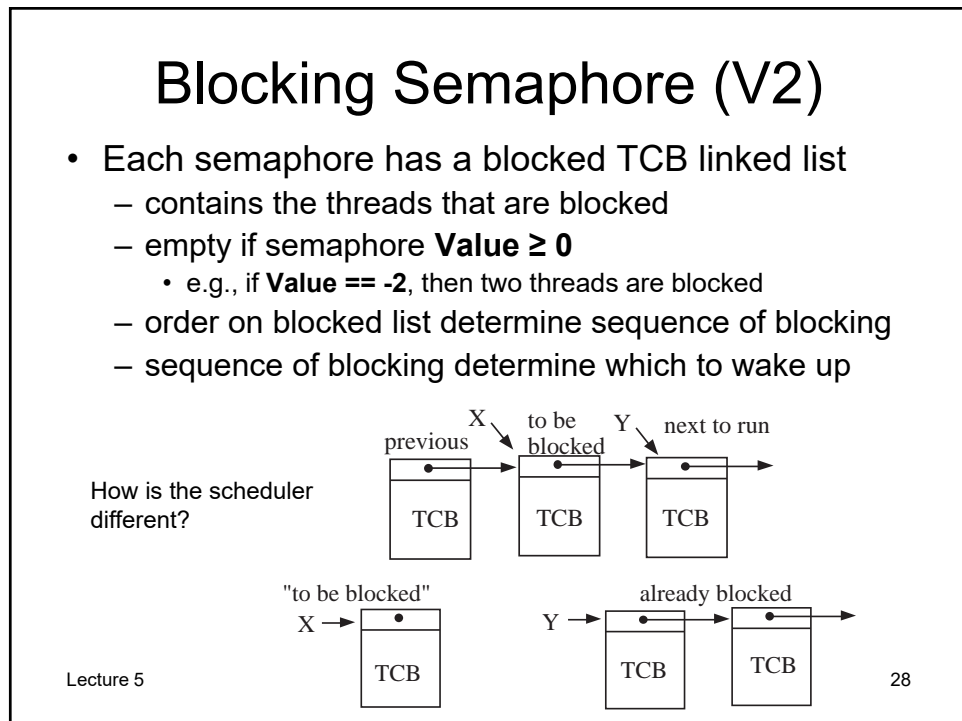
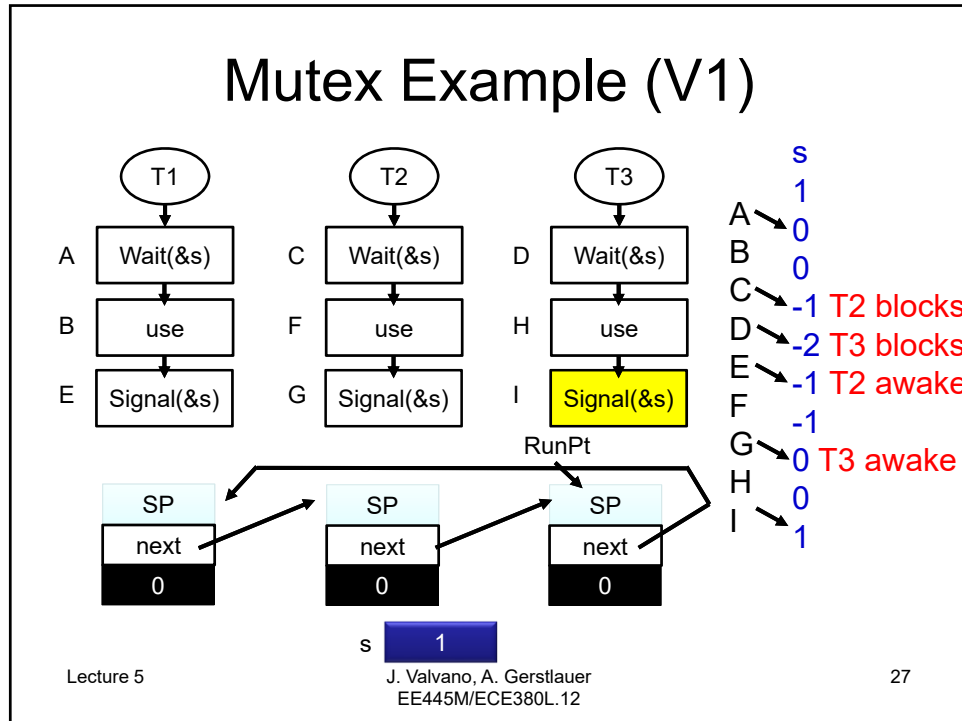
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Blocking Semaphore (V2)

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)

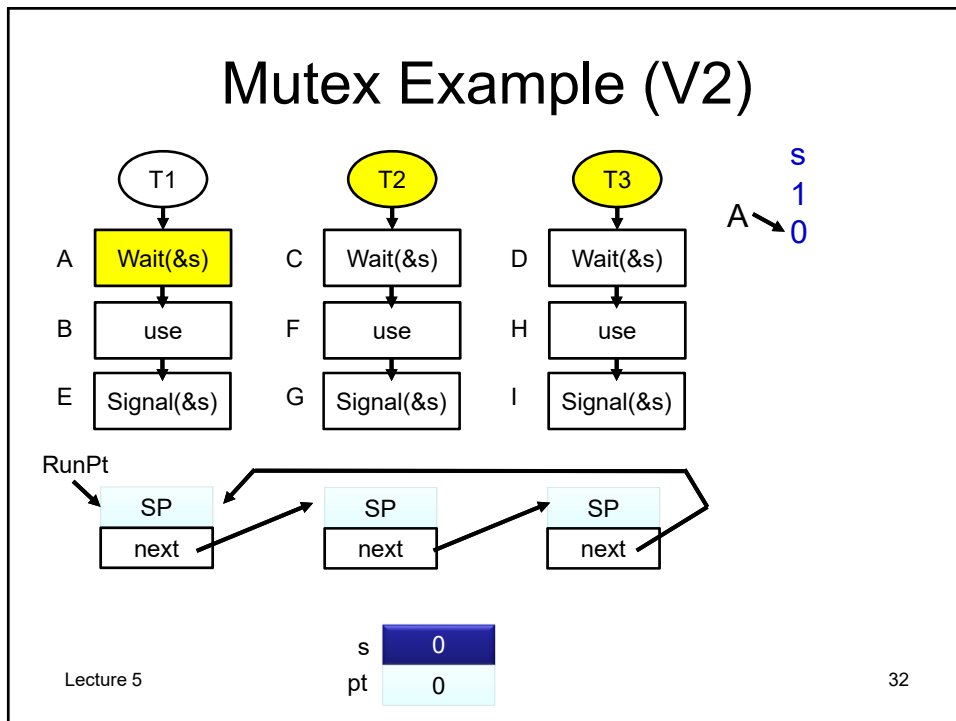
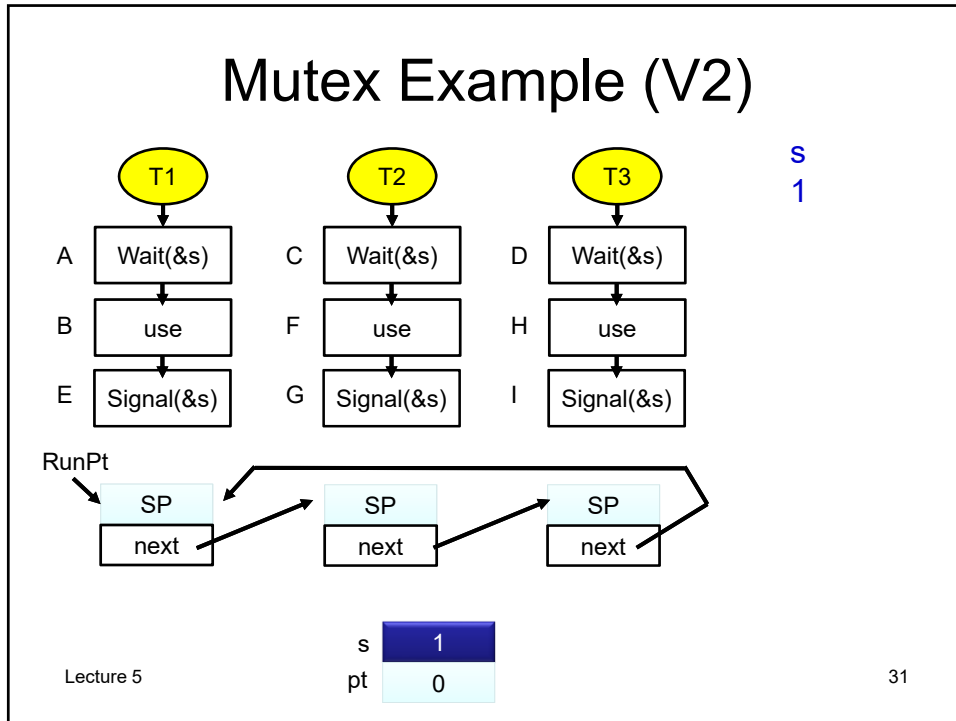
OS_Signal (Sema4Type *semaPt)

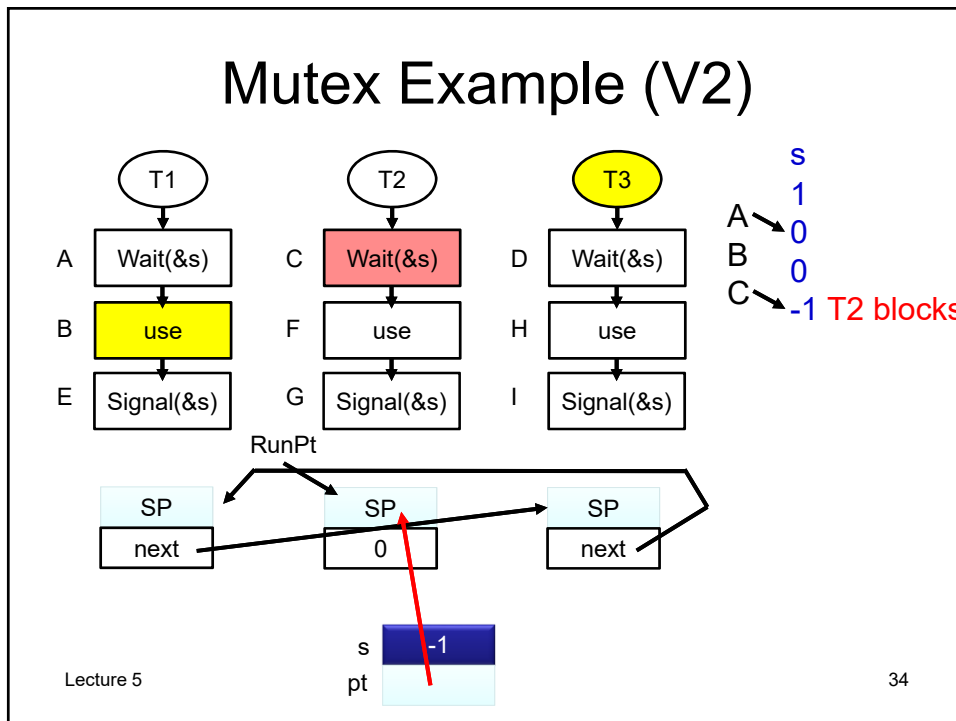
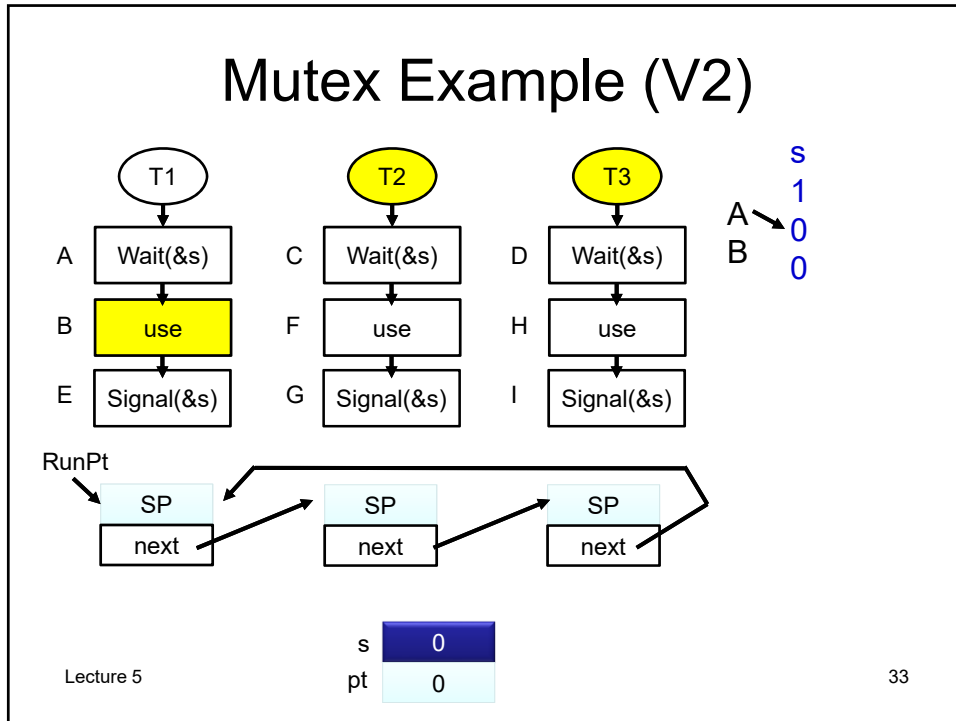
- 1) Save I bit, then disable interrupts
- 2) Increment the semaphore counter, $S=S+1$
`(semaPt->Value)++;`
- 3) If the `value ≤ 0` then
 - Wake up one thread from the TCB linked list**
 - Bounded waiting -> the one waiting the longest
 - Priority -> the one with highest priority
 - Move TCB of the "wakeup" 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

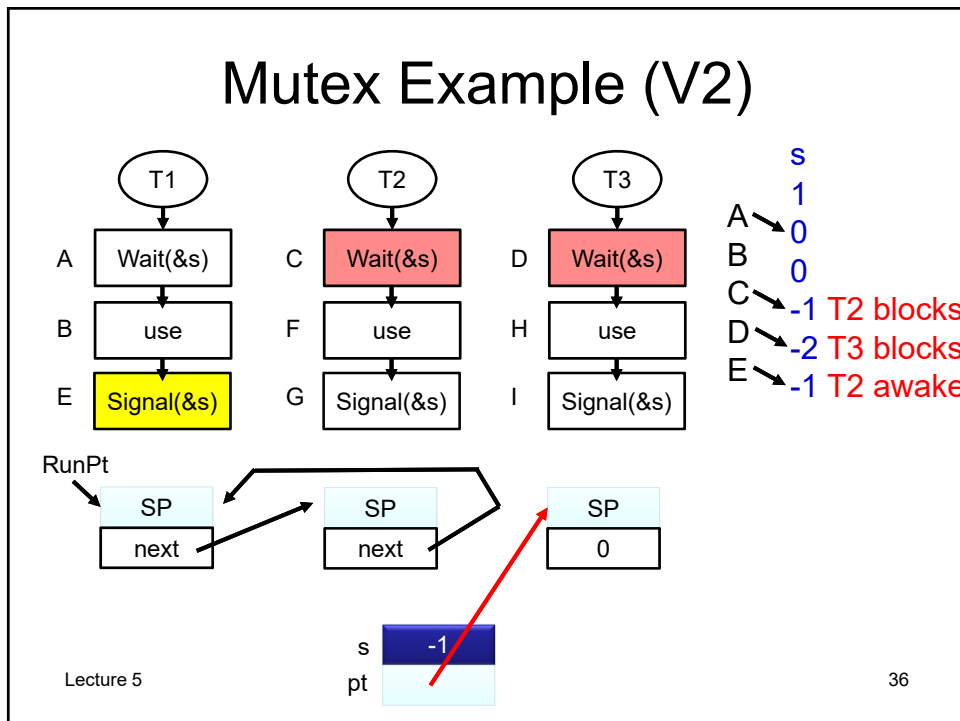
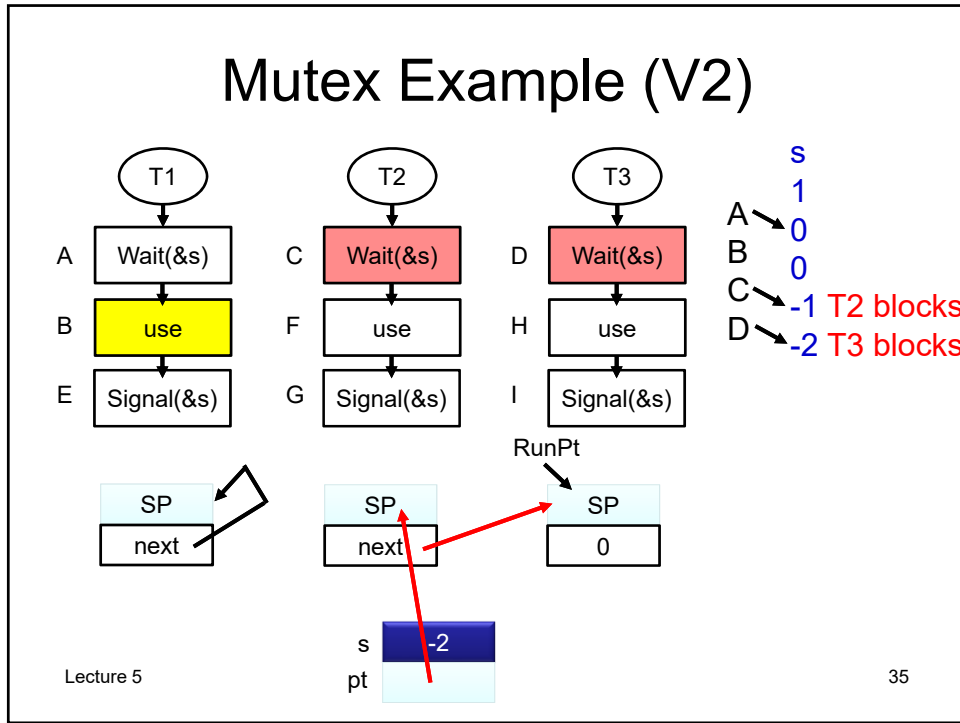
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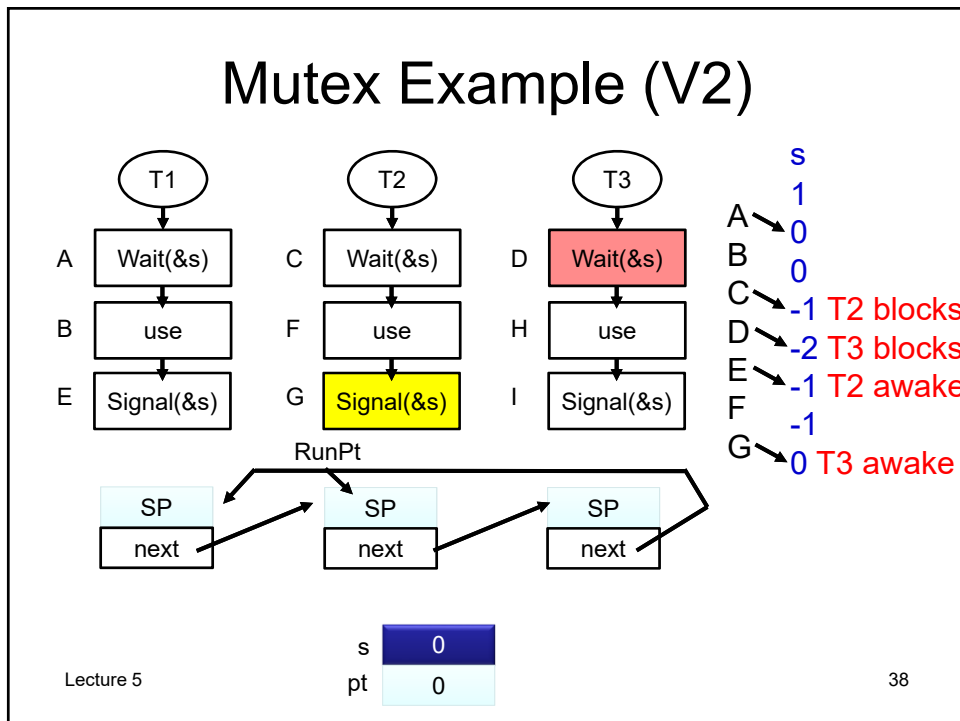
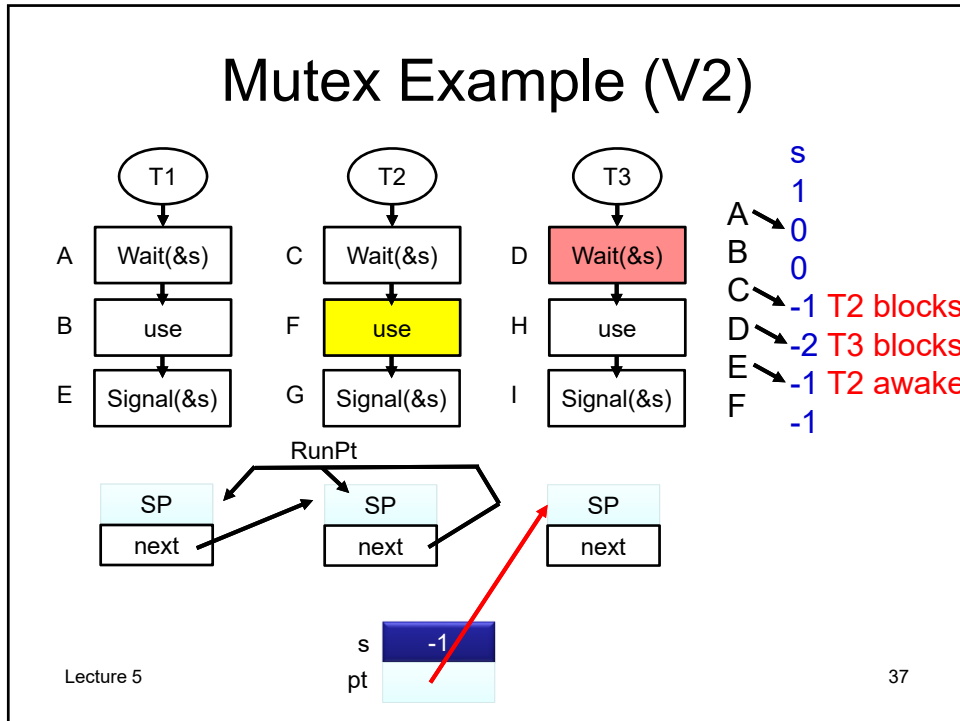
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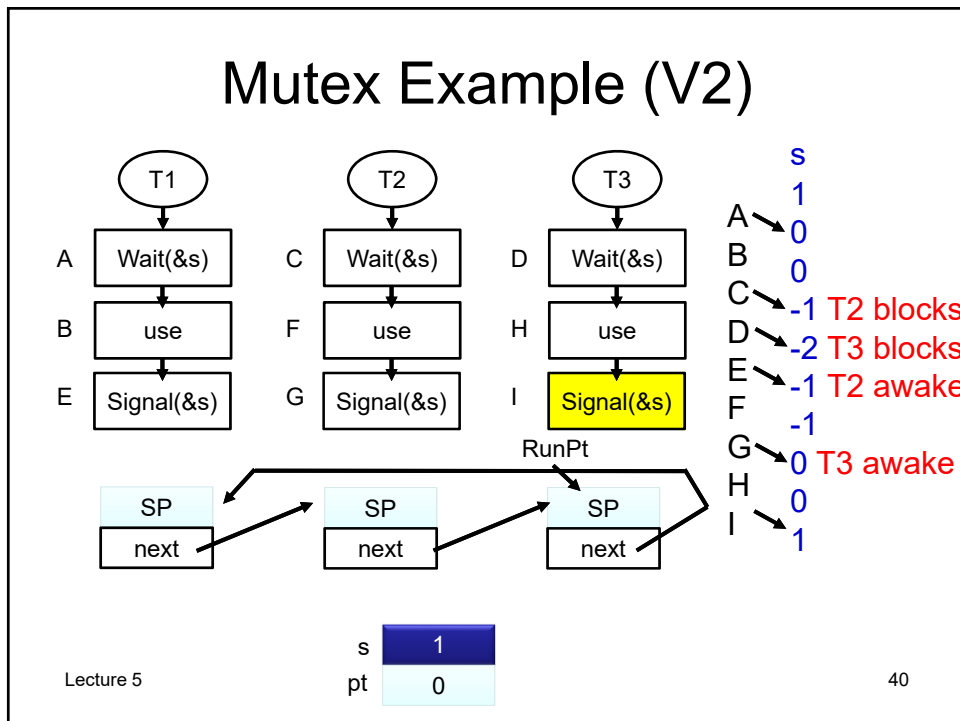
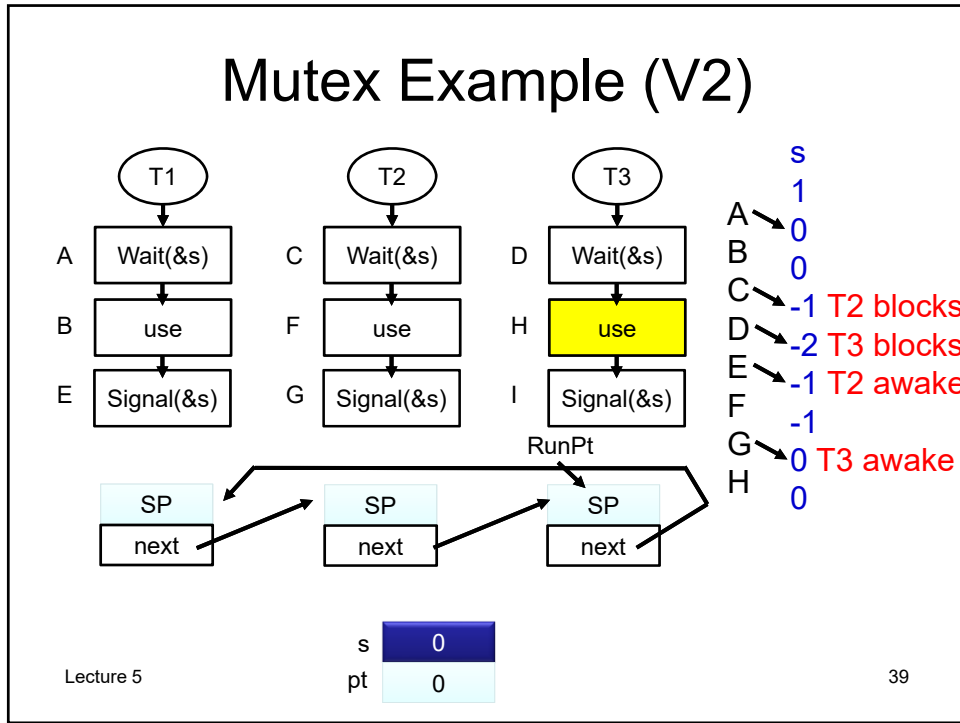
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Semaphore Applications

- 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

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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)**



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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);
```

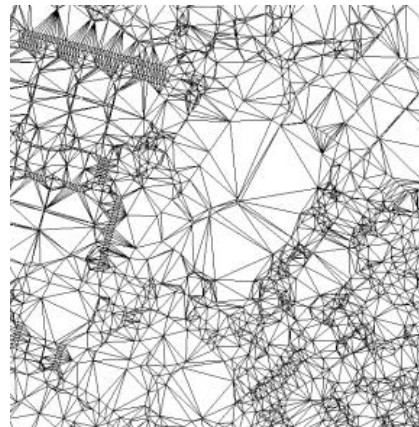
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Deadlock

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



Where is the deadlock?

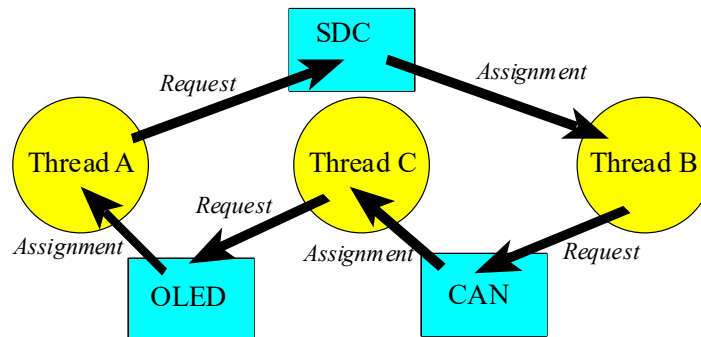
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Resource Allocation Graph

Thread A	Thread B	Thread C
<code>wait(&bOLED); //1</code>	<code>wait(&bSDC); //2</code>	<code>wait(&bCAN); //3</code>
<code>wait(&bSDC); //4</code>	<code>wait(&bCAN); //5</code>	<code>wait(&bOLED); //6</code>
<code>use OLED and SDC</code>	<code>use CAN and SDC</code>	<code>use CAN and OLED</code>
<code>signal(&bSDC);</code>	<code>signal(&bCAN);</code>	<code>signal(&bOLED);</code>
<code>signal(&bOLED);</code>	<code>signal(&bSDC);</code>	<code>signal(&bCAN);</code>



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Deadlock Prevention

- No mutual exclusion
 - 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);

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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

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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

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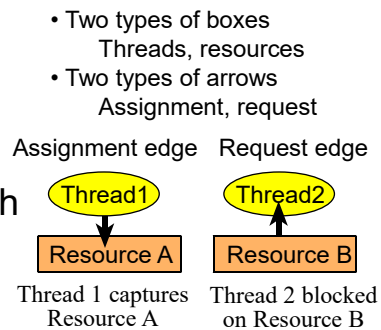
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Advanced Topics (Grad Students)

- 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



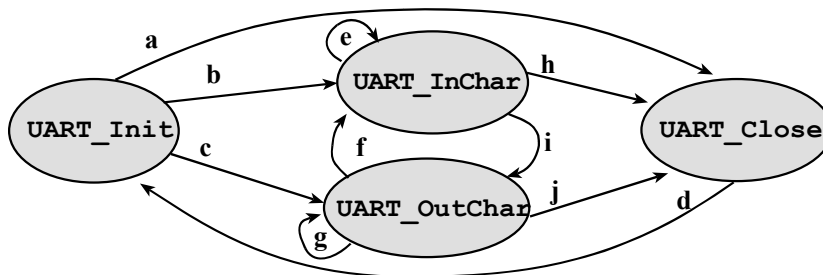
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Path Expressions (1)

- Specify and enforce correct calling order
 - A group of related functions/tasks (task graph)
 - E.g. I/O, initialize before use



Book Section 5.7

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Path Expressions (2)

Each arrow is
a '1' in matrix

```

int State=3; // start in the Closed state
int const Path[4][4]={ /* Init  InChar  OutChar  Close */
/*      column  0      1      2      3 */
/* Init   row 0*/ {  0  ,  1  ,  1  ,  1  },
/* InChar row 1*/ {  0  ,  1  ,  1  ,  1  },
/* OutChar row 2*/ {  0  ,  1  ,  1  ,  1  },
/* Close  row 3*/ {  1  ,  0  ,  0  ,  0  }};
void UART_Init(void){
  if(Path[State][0]==0) OS_Kill(); // kill if illegal
  State = 0;                       // perform valid Init
  // xxxx regular stuff xxxx
}
char UART_InChar(void){
  if(Path[State][1]==0) OS_Kill(); // kill if illegal
  State = 1;                       // perform valid InChar
  // xxxx regular stuff xxxx
}

```

Final exam 2004, Q9

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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 *dataptr){
1 47909851 0x000009B6 481D LDR    r0,[pc,#116] ; if(RxFutPt == 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 MOVNS r0,#0x00    ; return(RXFIPOFAIL);
8 4860416 0x000009C4 4770 BX     lr          ; }
9 694345 0x000009C6 4818 LDR    r0,[pc,#96] ; *dataptr = *(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 MOVNS r0,#0x01
27 0 0x000009EA E7EA B     0x000009C4 ; return(RXFIPOSUCCESS);}

```

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

$$T_i - \delta t < t_n - t_{n-1} < T_i + \delta t \quad \text{for all } n$$
- CPU utilization
 - Percentage time running idle task
- Context switch overhead
 - Time to switch tasks

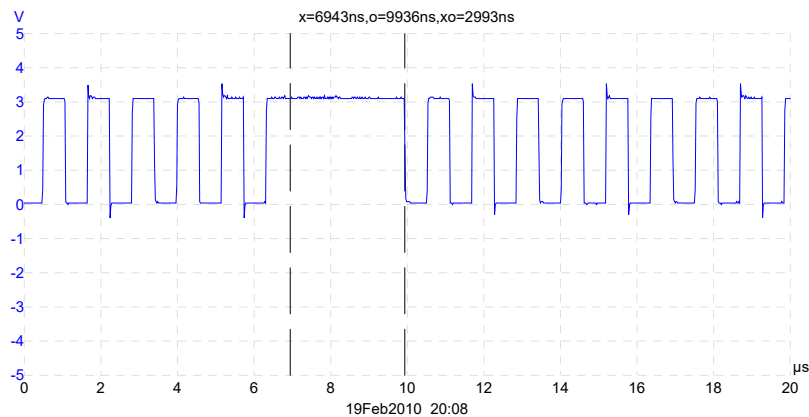
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Context Switch Time

- 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); }
```

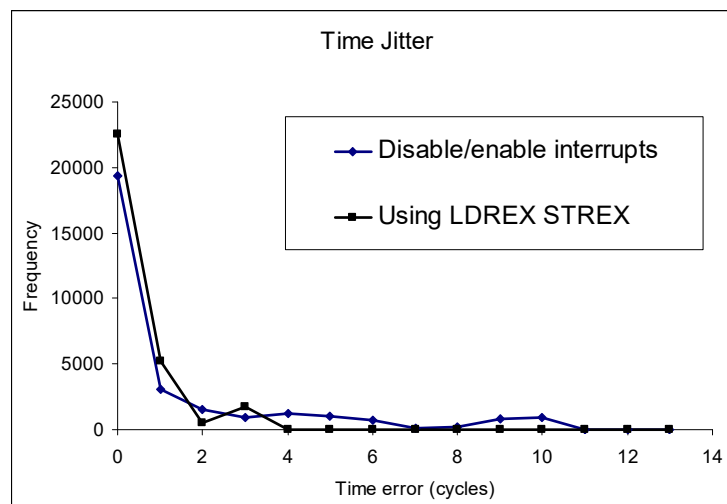
- Record maximum and total

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Time Jitter



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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

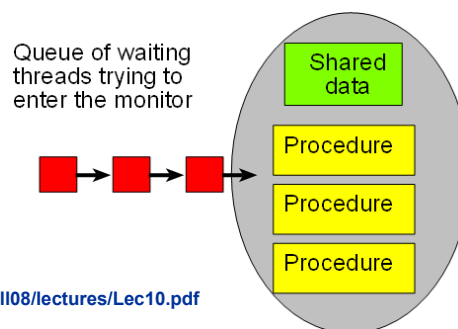
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Monitors

- 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>

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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):

- 1) lock->Acquire();
- 2) put item on queue;
- 3) conditionVar->Signal();
- 4) lock->Release();

Get():

- 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:
if(FIFO empty)
wait(condition)

Mesa wait:
while(FIFO empty)
wait(condition)

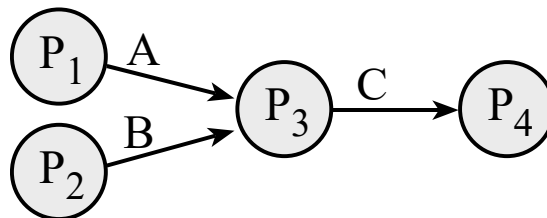
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Kahn Process Network (KPN)

- 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

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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

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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?