[...] the purpose of abstraction is not to be vague, but to create a new semantic level in which one can be absolutely precise.
-- *Edsger W. Dijkstra*, “The Humble Programmer” (1972)
3.1 Thread description

• A process or thread (more about the distinction later) is represented by a special data structure, the thread control block (TCB), that contains all relevant information about the thread, e.g.:
  • Thread characteristics:
    • Thread ID, name of program
  • State information:
    • Instruction counter, stack pointer, register contents
  • Management data:
    • Priority, rights, statistics

• In larger systems thousands of threads are possible. That requires efficient management (i.e. suitable data structures).

• Depending on type and usage of OS different solutions are available.
Management of thread control blocks

a) Single scalars

b) static long array

c) Variably long linked list
d) tree

![Tree diagram]

1 2 3 4 5 6 7 8 9
Attribute i

1 2 3 4 5 6 7 8 9
Attribute j

e) inverted table
Management of thread control blocks

To increase efficiency:

Forming subsets with regard to important attribute values (e.g. thread state, priority)
Static and dynamic systems

- **Static Operating Systems**
  All threads are known in advance and statically defined.
  - Threads are defined "at the desk". The TCBs are declared as program variables.
  - Threads are used for a specific application.
  - The TCBs are generated by a configuration program once.

- **Dynamic Operating Systems**
  The threads are created and deleted by kernel operations.
  
  ```
  create_thread (id, initial values)
  // create thread control block
  // initialization of thread
  delete_thread (id, final values)
  // return of final values
  // deletion of control block
  ```
Threads and Address Spaces

- A (logical) address space of a thread is the universe of its valid addresses, which it can access.
- Modern processors enable not only relative addressing (basis register), but also provide a memory management unit (MMU) for address translation.
- That allows to have an arbitrary number of logical address spaces that automatically can be mapped to the physical address space.
- That also leads to mutual protection of address spaces.
- Address spaces are independent (orthogonal) to threads.
- Each thread needs an address space at any time but several relations are possible:
  - A thread owns exactly one private address space (Unix process).
  - Several threads share an address space (Threads).
  - A thread switches from one address space to another.
Concerning the terminology care must be taken in the relevant literature:

- A process (*task*) is mostly considered as a Unix-type process with a private address space.
- Most operating systems (including current UNIX variants) offer the possibility to run several processes in a shared address space.
- They are called *lightweight processes* or *threads*.
- Today's Unix variants (e.g. Linux, Solaris, ...) offer the original Unix processes (tasks), that may consist of many threads.
- A Unix process is therefore an address space, that contains at least one *thread*.
- For Windows the same holds.
- A group of threads in a shared address space is sometimes also called *team* (System V) or *actor* (Chorus).
- **In this lecture course we use the term "thread".**
## Overview of terms used

<table>
<thead>
<tr>
<th>Operating system</th>
<th>Unit of execution</th>
<th>Superior unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach</td>
<td>thread</td>
<td>task</td>
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<tr>
<td>Chorus</td>
<td>thread</td>
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<td>Mayflower</td>
<td>lightweight process</td>
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</tr>
<tr>
<td>NT</td>
<td>thread</td>
<td>process</td>
</tr>
</tbody>
</table>
3.2 Thread switch

Thread switching

- Thread switch means that the processor stops the execution of the current thread and continues with the execution of another thread.
- Thread switch is the transition from one instruction sequence to another one.

![Diagram showing thread switch]
Switching by jumping

- In the most simple case the switch can be programmed statically and directly in the threads.
- It means we insert a jump instruction that jumps into another thread.
- To continue the work at the very point where the thread was left, we have to memorize the position where we have to return.
- A switching point therefore consists of at least
  - continuation address (where did we interrupt the work)
  - jump instruction (where do we want to continue)
Switching by jumping

In program:

\[
\begin{align*}
P1 & : \\
L11: & \quad \downarrow \\
\quad \downarrow & \\
\quad \downarrow & \\
\quad \downarrow & \\
jmp L21 & \\
L12: & \quad \downarrow \\
\quad \downarrow & \\
\quad \downarrow & \\
\quad \downarrow & \\
jmp L22 & \\
\end{align*}
\]

in execution:

\[
\begin{align*}
P2 & : \\
\quad \downarrow & \\
L21: & \quad \downarrow \\
\quad \downarrow & \\
\quad \downarrow & \\
jmp L11 & \\
\quad \downarrow & \\
L22: & \quad \downarrow \\
\quad \downarrow & \\
\quad \downarrow & \\
\quad \downarrow & \\
jmp L12 & \\
\end{align*}
\]

- For certain application areas (real-time systems) the time needed to switch from one thread to another is an important quality measure.
- The thread switch should be realized efficiently.
- The jump is the "minimal solution".

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Switching more general

- Switching by direct jump is very inflexible and applicable only in very special cases.

- In general the thread switch will be more costly since
  - we do not know, from where we return to the interrupted thread (memorizing the continuation address),
  - the next thread, to which we switch, is not always the same (selection of next thread),
  - the processor contains essential parts of the thread description that must not get lost (register reload).
Before switching to the new thread, we store the address of the next instruction to be executed in a dedicated variable ni (next instruction) of thread control block.

```
SWITCH

t_run.ni := L // store address L in variable ni (next instruction)
    // in TCB of running thread t_run
jmp (t_next.ni)
L:             
```

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Switching with variable continuation addresses

thread $T_1$

$\ni_1$

thread $T_2$

$\ni_2$ := $L_{21}$

$L_{21}$:

thread $T_3$

$\ni_2$ := $L_{22}$

$L_{22}$:

$\ni_3$
Selection of next thread

- Up to now we assumed that we know the next thread to which we want to switch.
- However, in most cases this target thread is not constant but will be determined at the very time of switching:
- Criteria for selection:
  - number of thread (cyclic switching)
  - order of arrival
  - priority (urgency)
    - constant
    - dynamic
- The selection of next thread influences the distribution of the processor's computing capacity to the threads.
Selection of next thread

- Let $TSelect()$ be a function that selects the next thread according to some criteria.

```
SWITCH
  t_next := TSelect()  // select next thread to run
  t_run.ni := L         // store address L in variable ni (next instruction)
  jmp (t_next.ni)       // in TCB of running thread t_run
L:
```
Selection of next threads

- The selection problem can be solved such that the threads are already totally ordered with regard to the execution order.
- The first thread ($t_{\text{next}}$) in this sequence is selected.
- New arriving threads will be inserted into that sequence according to the chosen order.
Selection of next threads

- When using priorities, the order can be organized in two dimensions

Groups of equal priority
Processor registers

- Threads use arithmetic registers of the processor to store intermediate results.
- If we simply jump to a next thread, their content will be lost (overwritten).
- The "switch by jump" solution can only be used when
  - the contents of the registers will no longer be needed and
  - the new thread does not expect valid register contents.
Thread context

- Besides the instruction pointer the processor keeps much more thread specific information in its registers:
  - Contents of arithmetic registers, index registers, processor state etc., that represent the state of the execution of the program, i.e. of the thread.
  - Contents of address registers, segment tables, interrupt masks, access control information etc. that make up the thread’s execution environment.

- Altogether, i.e. the complete thread specific information stored in the processor is called thread context.

- This thread context has to be saved as part of switching and restored when the thread is resumed.

- Data that is constant and available in the TCB, does not need to be saved.
Context switch

- Context switch is the most time consuming part of thread switch.
- To speed it up, the processor hardware can give some support:
  - by special instructions that allow storing the complete set of registers to the memory in one instruction (and also restoring).
  - by providing several sets of registers (e.g. 8) on the processor, such that at thread switch only the register needs to be saved that indicates the number of the currently valid valid register set.
- Thread switch can be comparably fast, if only the arithmetic registers need to saved and reloaded while the addressing environment remains constant (thread switch within an address space, lightweight threads, *threads*).
Switch (as open instruction sequence)

Switching now has the following form:

```
SWITCH
__↓__
save context of t_run
__↓__
select t_next
__↓__
save next instruction of t_run
__↓__
jump to t_next.ni
__↓__
t_run := t_next
__↓__
load context of t_run
```

This sequence can be inserted in the thread’s program at all places where a thread switch should to take place.
Switching as a subroutine

• If there are many places where switching takes place, it is worthwhile to organize switching as a subroutine.
• If all thread switches are carried out using the same switching subroutine, the saving of the continuation address (ni) and the jump to the next thread can be omitted.
• This is already done as part of the subroutine call and the return operation, respectively.
• This subroutine call is unusual insofar as one thread makes the call but another thread will return from that call.

```
SWITCH()
 save context of t_run
 select t_next
 t_run := t_next
 load context of t_run
 return
```

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Thread Control: Cooperative Scheduling

Assumption: Given 2 CPU-bound threads T1 and T2, 1 CPU and no interference with peripherals. Any dispatching is done cooperatively via `switch()`
Simplified Calling of “Procedure” switch()

Thread Control

!!! A bit tricky !!!
Return to another caller
Simplified Calling of “Procedure” switch()
Thread Control

Simplified Calling of “Procedure” switch()

switch(T2)
call switch
switch
save context of T1
reload context of T2
return from switch

switch(T1)
call switch
save context of T1
reload context of T2
return from switch
Simplified Implementation of “Procedure” switch

procedure switch(NT:thread)
begin
 ...
 save context of CT
 ...
 load context of NT
 ...
 return to NT
end

Assumption: Both threads T1 and T2 already have called switch() many times before.

This Part of switch still runs under control of CT

This Part of switch already runs under control of NT
procedure switch(NT:thread)
begin
    ...
    save context of CT
    ...
    load context of NT
    ...
    return to NT
end

Assumption: Both threads T1 and T2 already have called switch() many times before.
Corollary: Each thread gets and gives up control within switch code at exactly the same point.
procedure switch(NT:thread) begin ... save context of CT ... ? ... load context of NT ... return to NT end

Assumption: Both threads T1 and T2 already have called switch() many times before.

Corollary: Each thread *gives up* and *gets* control within switch code at exactly the same point.

This Part of switch still runs under control of CT

This Part of switch already runs under control of NT

How to solve this problem?
procedure switch(NT:thread)
begin
...
save context of CT
CT.sp := SP, SP := NT.sp
load context of NT
...
return to NT
end

Assumption: Both threads T1 and T2 already have called switch() many times.

Corollary: Each thread gets and gives up control within switch code at exactly the same point.
Thread Control

Stack Contents during simplified switch

Stack Contents during simplified switch

Local Variables of T1

Local Variables of T1

Local Variables of T2

Local Variables of T2

Parameter T1

Return address to T2

T1 runs

SP

Local Variables of switch

Local Variables of switch

SP
Thread Control

Stack Contents during simplified switch

- Return address to T1
- Parameter T2
- Local Variables of T1
- Local Variables of T1

- Local Variables of switch
- Return address to T2
- Parameter T1
- Local Variables of T1
- Local Variables of T2
Thread Control

Stack Contents during simplified switch

SP →

Local Variables of switch

Local Variables of switch

Return address to T1

Parameter T2

Local Variables of T1

Local Variables of T1

Save Context of T1

→ SP

Local Variables of switch

Local Variables of switch

Return address to T2

Parameter T1

Local Variables of T2

Local Variables of T2
Stack Contents during simplified switch

Switch Stack Pointer

Save to CT tcb

Local Variables of switch
Local Variables of switch
Return address to T1
Parameter T2
Local Variables of T1
Local Variables of T1

Local Variables of switch
Local Variables of switch
Return address to T2
Parameter T1
Local Variables of T2
Local Variables of T2
Thread Control

Stack Contents during simplified switch

Switch Stack Pointer

Load from NT tcb

Local Variables of switch
Local Variables of switch
Return address to T1
Parameter T2
Local Variables of T1
Local Variables of T1

Local Variables of switch
Local Variables of switch
Return address to T2
Parameter T1
Local Variables of T2
Local Variables of T2

SP →

SP →
Thread Control

Stack Contents during simplified switch

SP  

Local Variables of switch
Local Variables of switch
Return address to T1
Parameter T2
Local Variables of T1
Local Variables of T1

SP

Restore Context of T2
Local Variables of switch
Local Variables of switch
Return address to T2
Parameter T1
Local Variables of T2
Local Variables of T2
Thread Control

Stack Contents during simplified switch

SP

Local Variables of switch
Local Variables of switch
Return address to T1
Parameter T2
Local Variables of T1
Local Variables of T1

Return from switch

Return address to T2
Parameter T1
Local Variables of T2
Local Variables of T2
Thread Control

Stack Contents during simplified switch

- Local Variables of switch
- Local Variables of T2
- Return address to T1
- Parameter T2
- Local Variables of T1

T2 runs

- Local Variables of T2
- Local Variables of T1

SP
Automatic switching

- In many cases it is not possible or not reasonable to explicitly insert switching points into the threads.
- More desirable is **automatic** switching.
- To that end we need a **clock (timer)**, i.e. a hardware device offering the following functions:
  - specifying a deadline (timer set)
  - interrupt on timeout
Automatic switching

• With automatic switching programs can remain unchanged.

• The thread switch is triggered "from outside" and can happen at any arbitrary point in time. (Interrupts may not be switched off.)
Conditioned switching

• In the course of a thread situations can arise where a continuation of the processing is temporarily not possible, e.g. if the thread has to wait for input data.
• Instead of wasting time, the processor can do some other work.
• This is called **conditioned switching**, since the fact that switching takes place or not depends on some condition.
• Such a condition can be represented by a simple binary variable.
Objective: Establishing Fair Scheduling

Assumption: No other thread switching events

Simplification: No detailed clock interrupt handling

---

Start of Time Slice of CT

Time Slice of Current Thread

End of Time Slice of CT

---

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Simplified Thread Switch

Current thread

Running in User Mode

Clock Interrupt

Interrupt

Green → Blue

Time
Simplified Thread Switch

Clock Interrupt

Hardware accepts Interrupt switching to Kernel Mode

Kernel Level

User Level

Current thread

green → blue

time
Simplified Thread Switch

Clock Interrupt Handling

Kernel Level

User Level

Time

Current thread

Clock Interrupt

green → blue
Simplified Thread Switch

- Clock Interrupt
- Clock Interrupt Handling
- Internal Call
- Thread Switch
- Current thread
- Kernel Level
- User Level

Green arrow pointing to blue.
Simplified Thread Switch

- Current thread
- Clock Interrupt
- Clock Interrupt Handling
- Internal Call
- Thread Switch
- Kernel Level
- User Level

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Simplified Thread Switch

Clock Interrupt

Old Current Thread

Thread Switch

Return from Internal call

Kernel Level

New Current Thread

User Level

Return from ?? to User Mode

Kernel Level

User Level

Return from ?? to User Mode

kernel_mode

user_mode

Kernel Level

User Level

Return from ?? to User Mode

Old Current Thread

Thread Switch

Return from Internal call

Kernel Level

User Level

Return from ?? to User Mode

kernel_mode

user_mode
Simplified Thread Switch

Clock Interrupt

Old Current Thread

Kernel Level

User Level

Thread Switch

Internal call

New Current Thread

Return from Internal call

Return from ??? to User Mode

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Simplified Thread Switch

- Clock Interrupt
- Clock Interrupt Handling
- Internal call
- Thread Switch

Kernel Level

User Level

Old Current Thread

New Current Thread

Return from Internal call

Return from ??? to User Mode

Green to Blue Transition

User Level

Kernel Level

Time
Simplified Thread Switch

Old Current Thread

Thread Switch

Clock

Intr Handling

Current Thread

green → blue
Simplified Thread Switch

- Old Current Thread
- Current Thread
- Clock Intr Handling
- Thread Switch
- Clock Interrupt
- time

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Simplified Thread Switch

Thread Switch
Clock Intr Handling
Old Current Thread

Current Thread

Clock Intr Handling

Clock Interrupt

time

blue → green
Simplified Thread Switch

- Thread Switch
- Clock Intr Handling
- Clock Interrupt
- Internal call

Old Current Thread

Current Thread
Simplified Thread Switch

- Thread Switch
- Old Current Thread
- Clock Intr Handling
- Current Thread
- Clock Intr Handling
- Clock Interrupt
- Internal call
- Thread Switch
- blue
- green

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Simplified Thread Switch

Old Current Thread

Current Thread

Clock Intr Handling

Thread Switch

Clock Intr Handling

Internal call

Thread Switch

Clock Intr Handling

clock Intr post

blue

green

time
Simplified Thread Switch

- Old Current Thread
- Current Thread
- New Current Thread
- Clock Intr Handling
- Clock Interrupt
- Internal call
- Return to User Mode

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Simplified Thread Switch

- Thread Switch
- Clock Intr Handling
- Clock Interrupt
- Internal call
- Clock Intr Handling
- Return to User Mode
- New Current Thread
- Old Current Thread
- Current Thread
- Clock Intr
- post
- time
Simplified Thread Switch

Old Current Thread

Clock Intr Handling

Thread Switch

New Current Thread

Return to User Mode

click Intr post

time
Simplified Thread Switch

- Clock Intr Handling
- Thread Switch
- Return to User Mode
- New Current Thread
- Time

Old Current Thread

New Current Thread

Thread Switch

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Simplified Thread Switch

Old Current Thread

Thread Switch

Clock Intr Handling

Return to User Mode

New Current Thread

Thread Switch

clock Intr post

Old Current Thread
Simplified Thread Switch
Simplified Thread Switch

Old Current Thread

- Clock
- Intr Handling
- Post

New Current Thread

Return to User Mode

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Thread Switch

Assumption:

Hardware automatically pushes SP, IP and Flags of Current Thread T1 onto its Kernel Stack within TCB1!
Thread Switch

Note: Kernel Stack of T1 (CT) is empty!

Current Thread T1 is running.
Thread Switch

Current Thread T1 is running. Clock Interrupt saving context of T1 and ...

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Thread Switch

Current Thread T1 is running. Clock Interrupt saving context of T1 and loading context of Clock IH.
Thread Switch

Current Thread T1 is running. Clock Interrupt saving context of T1 and loading Context of Clock IH. CIH states End of Time Slice of T1 calling Thread Switch(T2).
Thread Switch

Current Thread T1 is running. Clock Interrupt saving context of T1 and loading Context of Clock IH. CIH states End of Time Slice of T1 calling Thread Switch(T2).
Save Kernel SP(TCB T1) and ...
Current Thread T1 is running. Clock Interrupt saving context of T1 and loading Context of Clock IH. CIH states End of Time Slice of T1 calling Thread Switch(T2). Save Kernel SP(TCB T1) and ...
Thread Switch

Current Thread T1 is running. Clock Interrupt saving context of T1 and loading Context of Clock IH. CIH states End of Time Slice of T1 calling Thread Switch(T2). Save Kernel SP(TCB T1) and load Kernel SP(TCB T2).
Thread Switch

Current Thread T1 is running. Clock Interrupt saving context of T1 and loading Context of Clock IH. CIH states End of Time Slice of T1 calling Thread Switch(T2). Save Kernel SP(TCB T1) and load Kernel SP(TCB T2). Next Steps? Complete it!
Example: Simple Thread Switch on ARM

; save process state onto stack
STMFD SP!, {r14} ; link register for interrupt
STMFD SP!, {r0-r14}^ ; user registers
MRS r2, spsr ; saved CPU state into R2
STMFD SP!, {r2} ; and then to stack
STR SP, [r0] ; pcb->cpu_state = SP

; switch to other process
LDR SP, [r1] ; SP = next_pcb->cpu_state

; restore context
LDMFD SP!, {r2} ; CPU state to R2
MSR spsr, r2 ; and then into saved state
LDMFD SP!, {r0-r14}^ ; user registers
LDMFD SP!, {pc} ; link register for return
; from interrupt
3.3 Switching Prevention

• When using automatic switching, which is triggered by an external signal, we have no control of place and time of switching.

• It can happen that switching is triggered at exactly the time when a (voluntary) switching is just taking place. This can lead to unwanted behavior and errors.

• During switching we must make sure that no additional switching is triggered.

• Generally, it can result in errors, when a kernel operation is interrupted by another kernel operation, since kernel operations often work on shared data structures.

• If switching can take place at any point of time, then an arbitrary interleaving of threads and also kernel operations is possible.
Problems due to interleaved execution

- In kernel operations there are places, where depending on a condition some action is performed.
- It cannot be excluded that between the evaluation of the condition and the following action a thread switch takes place and before returning to this thread another threads changes the condition (Example: allocation of resources).

The action is based on wrong assumptions can result in faulty behavior.
Kernel as critical section

- Critical sections are safe if such an interleaving can be excluded.
- When a thread is within a critical section, no other thread is allowed to enter a critical section that is in conflict.
- This is called **mutual exclusion**.
- In OS kernels all possible places of conflict need to be identified and protected accordingly.
- Because in the kernel a large number of those critical sections can be found, we can do it the simple way and regard the entire kernel as a critical section.
- As a consequence we put the whole kernel under mutual exclusion.
- It must be made sure that kernel operations can not be executed in an interleaved fashion but are executed until completion.
Realization of kernel exclusion

- If the processor does not provide an interrupt mechanism, no interrupt can occur.
- If the processor does provide an interrupt mechanism, we may disable interrupts for the duration of the kernel operation.
- By doing so, we have reduced the second case to the first case.
- But this is possible only with uniprocessor machines.

In multiprocessor systems we may - even with interrupts disabled - experience a simultaneous execution of different kernel operations that access memory in an interleaved fashion.

- In this case we must enforce mutual exclusion for kernel operations explicitly by a central kernel lock.
- This is, however, no appropriate solution for many-core systems, since it would lead to a situation where parallel threads have to line up at the entry of the kernel.
Kernel exclusion

• The realization of kernel exclusion obviously depends on
  • interrupts being possible or not
  • multiple processors or not

• Therefore we distinguish four cases:
  • Case 1: single processor system without interrupts
  • Case 2: single processor system with interrupts
  • Case 3: multiprocessor system without interrupts
  • Case 4: multiprocessor system with interrupts

• Case 1 does not need any precautionary measures since there is no reason to leave a kernel operation before completion.
Case 2: single processor system with interrupts

- The kernel operation is bracketed by an *disable interrupt* and an *enable interrupt*.
Using an atomic test-and-set instruction, we can come up with a simple solution:

- If the kernel lock is busy, we repeatedly check its value in a mini loop.
- This is called **busy waiting**.
- Such a lock is called a **spin lock**.
- Busy waiting means some waste of compute capacity that can be tolerated since kernel operation are usually short.

```
reset kernel_lock
kernel_lock set ?
set kernel_lock
```

**Case 3: Multiprocessor system without interrupts**
Case 4: Multiprocessor system with interrupts

- Here both techniques kernel lock and disabling interrupts must be employed.
- So we want to discuss the following three solutions:

(a) yes
   \[\text{kernel\_lock set?}\]
   \[\text{set kernel\_lock}\]
   \[\text{disable interrupt}\]
   \[\text{kernel operation}\]
   \[\text{enable interrupt}\]
   \[\text{reset kernel\_lock}\]

(b) yes
   \[\text{kernel\_lock set?}\]
   \[\text{set kernel\_lock}\]
   \[\text{disable interrupt}\]
   \[\text{kernel operation}\]
   \[\text{enable interrupt}\]
   \[\text{reset kernel\_lock}\]

(c) yes
   \[\text{kernel\_lock set?}\]
   \[\text{set kernel\_lock}\]
   \[\text{disable interrupt}\]
   \[\text{kernel operation}\]
   \[\text{reset kernel\_lock}\]
   \[\text{enable interrupt}\]
Discussion of solutions

• **Solution A:**
Here we have to consider that interrupt handling is also a kernel operation that also needs the kernel lock. If there is right after setting the kernel lock an interrupt, the interrupt processing would try to acquire the kernel lock in vain. The thread would be stuck at that point.

• **Solution B**
An operation that acquires the kernel lock and disables the interrupts in one atomic operation would be ideal. Unfortunately, this is not offered by today's processors.

• **Solution C**
Thus, we first have to disable the interrupts and then acquire the kernel lock. Solution C is the correct one.
3.4 Thread states

- We used the conditioned switch to release the processor, when the current thread could not continue execution for some reason.
- In this case we switch to another thread. This new thread, however, may also be blocked, e.g. because it waits for the completion of an I/O operation. If we switch to such a thread, the processor would be again immediately released.
- This way, we could try one thread after another until we finally may detect a thread that is ready to resume execution.
- To speed up the search for a ready thread, we combine threads according to their state (resumable, not resumable) to thread subsets.
- If we also consider the currently running thread, we can distinguish three different states:
  - State running: threads that are currently executed on the processor
  - State ready: threads that are ready to be executed but have to wait for the processor to become free.
  - State waiting: threads that are blocked since they wait for some (external) event
Thread states and their transitions

- Ready
- Running
- Active
- Waiting (Blocked)
- RELINQUISH
- ASSIGN
- DEBLOCK
- BLOCK
State change operations

For all state changes, the corresponding kernel operations are available:

- **Relinquish**
  Voluntary switching to another thread. The currently running thread remains executable, i.e. its state changes to "ready".

- **Assign**
  Taking the next thread from the ready set to resume its operation on the processor.

- **Block**
  Leave the processor since some condition does not hold (conditioned switch). Execution must not resumed until condition is met. Thread switches to state "waiting" or "blocked".

- **Deblock**
  If the event happened for which the blocked thread waited it changes its state from waiting to ready and is inserted into the set of ready threads.
State change operations

- When executing the state transitions we have to distinguish:
  - the state change operation themselves,
  - other actions that may be necessary related to the state change.

- The pure state change operations depend on how we implement the thread states. Example: stch_deblock ("stch" for "state change")
  - Thread state as attribute in the TCB
    
    ```
    TCB
    | | | waiting |
    stch_deblock
    TCB
    | | | ready |
    ```

  - Thread state as membership in list
    
    ```
    SWT = sequence of waiting threads
    SRT = sequence of ready threads
    stch_deblock
    ```
Thread switch as kernel operation

• Besides the state change as an operation at the TCB data structure we also perform the switch operation itself.

• “Relinquish” as a kernel operation may look like this:

```
RELINQUISH
  stch_relinquish(t_run)  // state change of running thread from running to ready
  switch(t_run, t_next)  // switch threads, i.e. save and load thread context
  stch_assign(t_run)    // state change of new running thread from ready to running
```
Dynamic System

- In dynamic systems the set of threads is variable.

- For dynamic systems, we need the following operations
  - Activate / Deactivate
    - A thread may be defined (there exists a TCB), even code and data segment may be available, but the thread "rests", i.e. it is not active.
    - We distinguish between active and inactive threads.
    - Transition between these states are possible by means of the operations activate and deactivate.
  - Create / Delete
    - In a second step we have to assume that threads are not yet available at system start and need to be created (and deleted) explicitly.
    - For that we provide the operations create and delete.
Complete state diagram
Thread states in Unix

- **User Running**
  - return to user
  - system call, interrupt

- **Kernel Running**
  - preempt
  - return
  - interrupt, interrupt return
  - sleep
  - exit

- **Preempted**
  - return to user

- **Created**
  - fork
  - not enough memory (swapping system only)

- **Ready to Run in Memory**
  - reschedule thread
  - swap in
  - swap out

- **Asleep in Memory**
  - sleep
  - reschedule thread

- **Sleep, Swapped**
  - sleep
  - swap out

- **Zombie**
  - exit
  - swap in

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Windows thread states

- **Waiting**
  - Wait complete
  - Kernel stack outswapped
  - Wait on object
  - Transition

- **Transition**
  - Kernel stack inswapped
  - Preempt
  - Select

- **Ready**
  - Start
  - Preempt
  - Preempt

- **Standby**
  - Preempt
  - Select
  - Reinitialize

- **Running**
  - Context switch
  - Execution completes

- **Terminated**
Process states IBM VM/CMS
Process states Siemens BS 2000


3.5 Preemptions and Idling

- Up to now, a thread remains being executed until
  - it voluntarily gives up the execution (relinquish),
  - it is forced to give up execution by a clock interrupt,
  - it cannot continue due to some condition it is waiting for.

- In many application areas not all activities (and the threads as their representatives) are of equal importance or urgency which leads to the concept of priorities.

- When using priorities, we want to make sure that at any time the thread with the highest priority is being executed.

- The consequence is that we do not wait until one of the above situations for thread switch occurs but immediately switch if a thread with a higher priority shows up, i.e. enters the ready queue.

- We say, the current thread is being **preempted** by the thread with the higher priority.
Check for preemption

- The priority rule requires that no ready thread may possess a higher priority than a running one.
- If we assume that this condition currently holds and the priorities are constant a violation of that rule can only happen when a new thread enters the ready queue.
- According to our state diagram there are exactly three transitions into the ready state.
  - relinquish
  - deblock
  - activate

Within these operations we have to check whether the thread performing the transition has a higher priority than the currently running ones.

If this is the case we switch to the more urgent one.

```latex
\begin{align*}
\text{check_preemption}(t) & \quad \text{N} \\
& \quad \text{N} \\
\text{t\_run.prio < t.prio} & \\
\text{stch_relinquish}(t\_run) & \\
\text{switch}(t\_run, p) & \\
\text{stch_assign}(t\_run) & \\
\end{align*}
```
Idle problem

- In operating with waiting states it may happen that all threads are blocked since they are waiting for something. In this case the processor has nothing to do.
- To handle this situation in an elegant and consistent way we simply introduce an **idle thread**.
- It must have the following properties:
  - must not stop (cyclic thread, endless loop),
  - lowest priority (to be preempted by any real thread),
  - must be preemptable at any time.
- **Examples**
  - Empty loop while true do; (usually wastes energy)
  - Dynamic Stop If available: Special machine instruction that does not access memory but reacts to external signals (such as halt or entering C-states on x86, dynamically disables parts of processor)
  - Insertion of useful housekeeping tasks: Checks, reorganizations (e.g. garbage collection)
3.6 Initialization

- How can we switch to a thread for the first time?
- Each "entrance" to a thread takes place via the procedure "switch".
Initialization problem

• The thread starts and ends in the "kernel of the kernel", in the procedure "switch".

```
t_run := t_next
load context of t_run
(program of t_run)
save context of t_run
select t_next
```

prologue: switch part 2

epilogue: switch part 1
Initialization problem

- We have to initialize the thread (thread control block, stack) such that it looks as if it is just “in the middle” of the procedure switch.
- The switch, however, may be entered depending on the structure of the kernel after some other procedure calls.
Thread initialization (Example)

Thread program

5000

Kernel op. 1

6000

Kernel op. 2

6200

switch

6300

Thread control block (TCB)

Instr. counter

: 6300

Stack base

1000

Stack end

2000

Stack pointer

1003

stack

1000 5000

1001 6000

1002 6200

1003 :

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First entrance to a thread

From somewhere

Switch

Thread program

Kernel interface

Prepared during initialization
3.7 Kernel operation for thread management

- Thread management
- Thread interaction
- Thread state change operations
- Data structure operations
- Kernel memory management

(for dynamic Systems)

addressed in lecture
Example: Kernel operations for thread management I

```
kernle module thread management;
export <thread operations>;
import <state change operations>;
procedure CREATE_THREAD(P: thread);
    begin
        { create TCB for thread P;}
        STCH_CREATE(T)
    end;
procedure DELETE_THREAD(P: thread);
    begin
        STCH_DELETE(T);
        { delete TCB of thread P;}
    end;
procedure SET_ATTRIBUTE(P: thread; A: attribute; V: value);
    begin
        P.A := V
    end;
procedure READ ATTRIBUTE(P: thread; A: attribute; V: value);
    begin
        V := P.A
    end;
```
procedure RELINQUISH_THREAD(T: thread);
  begin
    STCH_RELINQUISH(T);
    SWITCH(P,T_NEXT);
    STCH_ASSIGN(T_RUN)
  end;
procedure BLOCK_THREAD(WT: sequence of thread; T: thread);
begin
  if T = T_RUN then
  begin
    begin
      STCH_BLOCK(WT,T);
      SWITCH(T,T_NEXT);
      STCH_ASSIGN(T_RUN)
    end
  end;
procedure DEBLOCK_THREAD(WT: sequence of thread; T: thread);
begin
  STCH_DEBLOCK(WT,T);
  { check for preemption}
end;
procedure ACTIVATE_THREAD(T: thread);
begin
{ initialize TCB and stack;}
STCH_ACTIVATE(T);
{ check for preemption}
end;

procedure DEACTIVATE_THREAD(T: thread);
begin
if T /= T_RUN
then begin
  case T.STATE
  waiting: STCH_DEBLOCK(waiting queue of T,T);
  ready:
    end;
  { delete objects created by thread T}
  { finish all activities of T}
  STCH_DEACTIVATE(T);
  end
else begin
  STCH_RELINQUISH(T);
  { delete objects created by thread T}
  { finish all activities of T}
  STCH_DEACTIVATE(T);
  SWITCH(T,T_NEXT);
  STCH_ASSIGN(T_RUN) // !!!!
  end
end
end thread management.

Example: Kernel operations for thread management III
3.8 Threads in Programming Languages

• Many modern programming languages contain a thread concept to formulate concurrent activities within programs (e.g. Java Threads).

• Or there are programming libraries, that extend a programming language by a thread concept.

• What is the relation of these threads to OS threads?
• How does the OS support those threads?
Threads in OS and Programming Languages

Classic multiprogramming:
Independent threads in private address spaces.

Threads in a programming language without OS support:
For the OS these threads are not visible.
The whole program is one thread to the OS.
Programming language threads are mapped 1:1 to OS-threads.

The programming language does not support threads.

The parallel program consists of OS-threads, that share an address space (e.g. Pthreads)
Threads in OS and Programming Languages

User-level threads are mapped m:n to OS-threads.
Further References