Concurrent Systems

Nebenläufige Systeme

III. Processes

Wolfgang Schröder-Preikschat

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Agenda

Preface

Fundamentals
  Program
  Process

Characteristics
  Physical
  Logical

Summary
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  Program
  Process

Characteristics
  Physical
  Logical

Summary
discussion on abstract concepts as to multiplexing machines:

**program**
- concretized form of an algorithm
- static sequence of actions to be conducted by a processor
- of sequential or non-sequential structure

**process**
- a program in execution
- dynamic sequence of actions conducted by a processor
- of parallel, concurrent, simultaneous, or interacting nature
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  ■ appearance of a process as kernel thread and/or user thread
  ■ sequencing of processes, process states, and state transitions
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**a bridging** of concurrency/simultaneity concepts and mechanisms
- on the one hand, program as the means of specifying a process
- on the other hand, process as medium to reflect simultaneous flows
Process – The Course of Being Done

acc. [9], cf. p. 33

Operating systems bring programs to execution by creation, releasing, controlling and timing of processes.
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In computer sciences, a process is unimaginable without a program:
- as coded representation of an algorithm, the program specifies a process,
- thereby, the program manifests and dictates a specific process,
- if so, it even causes, controls, or terminates other processes\(^1\).

\(^1\)Provided that the operating system offers all necessary commands.
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- a program (also) describes the kind of flow (Ger. \textit{Ablauf}) of a process
  - sequential
    - a sequence of temporally non-overlapping actions
    - proceeds deterministically, the result is determinate
  - parallel
    - non-sequential

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  - parallel: non-sequential

- in both kinds does the program flow consist of actions (p. 7 ff.)

Consider: Program Flow and Level of Abstraction

One and the same program flow may be sequential on one level of abstraction and parallel on another. [8, 10]

---

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Summary
Program I

Definition
For a certain machine concretised form of an algorithm.
Program I

Problem-Oriented Language Level

Definition

For a certain machine concretised form of an algorithm.

virtual machine C
- after editing and
- before compilation

```c
#include <stdint.h>

void inc64(int64_t *i) {
    (*i)++;
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- **virtual machine ASM (x86)**
  - after compilation
  - before assembly

```asm
inc64:
    movl 4(%esp), %eax
    addl $1, (%eax)
    adcl $0, 4(%eax)
    ret
```

---

\(^2\)gcc -O4 -m32 -static -fomit-frame-pointer -S, also below
Program I  
Problem-Oriented/Assembly Language Level

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- one action (line 4)

- virtual machine ASM (x86)
  - after compilation\(^2\) and
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- three actions (lines 7–9)

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Definition (Action)

The execution of an instruction of a (virtual/real) machine.

\(^2\text{gcc -O4 -m32 -static -fomit-frame-pointer -S, also below}\)
address space and virtual machine SMC\(^3\)

- text segment
- Linux

<table>
<thead>
<tr>
<th>Line</th>
<th>Address</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0x080482f0</td>
<td>mov 0x4(%esp),%eax</td>
</tr>
<tr>
<td>2</td>
<td>0x080482f4</td>
<td>add $0x1,%eax</td>
</tr>
<tr>
<td>3</td>
<td>0x080482f7</td>
<td>adc $0x0,0x4(%eax)</td>
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<tr>
<td>4</td>
<td>0x080482fb</td>
<td>ret</td>
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</table>

\(^3\)symbolic machine code: x86 + Linux.
Program II

address space and virtual machine SMC\(^3\)
- text segment
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Linux

1. 0x080482f0: mov 0x4(%esp),%eax
2. 0x080482f4: add $0x1,(%eax)
3. 0x080482f7: adc $0x0,0x4(%eax)
4. 0x080482fb: ret

real machine
- after linking/binding and
- before loading

real machine
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- executable

same number of actions (lines 1–3, resp.), but different forms of representation

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real machine
- after loading
- executable

1. 8b 44 24 04
2. 83 00 01
3. 83 50 04 00
4. c3

same number of actions (lines 1–3, resp.), but different forms of representation

Hint (ret or c3, resp.)

The action for a subroutine return corresponds to the action of the corresponding subroutine call (\texttt{gdb, disas /rm main}):

1. \(0x080481c9:\) c7 04 24 b0 37 0d 08 movl $0x80d37b0,(%esp)
2. \(0x080481d0:\) e8 1b 01 00 00 call 0x80482f0 <inc64>

\(^3\)\textit{symbolic machine code}: x86 + Linux.
Definition

A program $P$ specifying actions that allow for parallel flows in $P$ itself.
Non-Sequential Program I

Definition

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an excerpt of $P$ using the example of POSIX Threads [4]:

```c
// Example code

pthread_t tid;

if (!pthread_create(&tid, NULL, thread, NULL)) {
    /* ... */
    pthread_join(tid, NULL);
}
```

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Fundamentals – Program
Non-Sequential Program I

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}
```

the parallel flow allowed in $P$ itself:

```c
void *thread(void *null) {
    /* ... */
    pthread_exit(NULL);
}
```
Non-Sequential Program II

despite actions of parallelism, **sequential flows** of the same program:

```c
pid_t pid;

if (!(pid = fork())) {
    /* ... */
    exit(0);
}
wait(NULL);
```

- **fork** duplicates the address space $A$ of $P$, creates $A'$ as a copy of $A$
- within $A$ as source address space arises thereby no parallel flow, however
- independent of the degree of parallelism within $P$, **fork** sets it to 1 for $A'$
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  - multiprocessing (Ger. *Simultanbetrieb*) of sequential programs requires the operating system in the shape of a non-sequential program
  - serviceable characteristic is multithreading **within** the operating system
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concept “operating system” is epitome of “non-sequential program”

4The exception (strictly cooperative systems) proves the rule.

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Multiprocessing of Sequential Programs

address space A

directions

fork()

wait(NULL)
Multiprocessing of Sequential Programs

address space A

parent
fork()
wait(NULL)

address space A'

child

duplicate

/* ... */

exit(0)

processor (core) characteristic:

Uni

operated by a process-based operating system, namely:
pseudo-parallelism by means of processor (core) multiplexing

Multi
ditto

but also event-based operating system, namely:
real parallelism by means of processor (core) multiplication

both cause
parallel processes
(p.16) within the operating system

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non-sequential program flow
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Definition (Program flow)

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- the program specifies a sequence of actions that are to be executed
- its kind depends on the particular level of abstraction (cf. p. 34)
  - level 5 $\mapsto$ program statement
  - level 4 $\mapsto$ assembly mnemonic
  - level 3 $\mapsto$ machine instruction
  - level 2 $\mapsto$ microprogram directive

Hint (Process $\neq$ Process instance)

A process instance (Ger. Exemplar) is an incarnation of a process. Just as an object is a "core image" of a class.
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Indivisibility I

Definition

Being indivisible, to keep something appear as unit or entireness.

- a question of the “distance” of the viewer (subject) on an object
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- a question of the “distance” of the viewer (subject) on an object
- action on higher, sequence of actions on lower level of abstraction

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<th>action</th>
<th>sequence of actions</th>
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</thead>
<tbody>
<tr>
<td>5</td>
<td>i++</td>
<td></td>
</tr>
<tr>
<td>4–3</td>
<td>incl i*</td>
<td>movl i,%r</td>
</tr>
<tr>
<td></td>
<td></td>
<td>addl $1,%r*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>movl %r,i</td>
</tr>
<tr>
<td>2–1</td>
<td></td>
<td>* read from memory into accumulator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* modify contents of accumulator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* write from accumulator into memory</td>
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</tbody>
</table>

- typical for a complex instruction of an “abstract processor” (C, CISC)
Entireness or unit of a sequence of actions whose solo efforts all will happen *apparently* *simultaneous* (i.e., are synchronised)
Entireness or unit of a sequence of actions whose solo efforts all will happen **apparently simultaneous** (i.e., are synchronised)

- an/the essential non-functional property of an **atomic operation**\(^5\)
  - logical togetherness of a sequence of actions in terms of time
  - by what that sequence appears as **elementary operation** (ELOP)

\(^5\)from (Gr.) *átomo* “indivisible”.
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- examples of (critical) actions for incrementation of a counter variable:
  - level\(_5 \mapsto \downarrow 3\)

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<th>ASM</th>
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<td>1 i++;</td>
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Examples of (critical) actions for incrementation of a counter variable:

- **level**\(^5\)\(\rightarrow\)\(^3\)
  - C/C++
    - 1 \(i++\);
  - ASM
    - 5 incl \(i\)
  - ISA
    - 6 *read* \(A\) from \(<i>\)
    - 7 *modify* \(A\) by \(1\)
    - 8 *write* \(A\) to \(<i>\)

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examples of (critical) actions for incrementation of a counter variable:

- level $5 \rightarrow 3$
  - C/C++
    - 1. `i++;
    - 3. `addl $1, %eax`
  - ASM
    - 2. `movl i, %eax`
    - 4. `movl %eax, i`
  - ISA
    - 5. `incl i`
    - 6. `read A from <i>`
    - 7. `modify A by 1`
    - 8. `write A to <i>`

- level $3 \rightarrow 2$

points $(i++, \ incl)$ in case of merely conditionally atomic execution

- namely uninterruptible operation (level $5 \rightarrow 3$), uniprocessor (Ebene $3 \rightarrow 2$)
- problem: overlapping in time of the sequence of actions pointed here

$^5$ from (Gr.) átomo “indivisible”. 

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Sequential Process

Definition

A process that is composed exclusively of a sequence of temporally non-overlapping actions.
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A process that is composed exclusively of a sequence of temporally non-overlapping actions.

- the sequence of actions forms a unique **execution thread**
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  - but which may develop differently with each restart of that process
    - other input data, program change, . . ., transient hardware errors
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- the sequence is defined by a **total order** of its actions
  - it is reproducible given unmodified original conditions
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Hint (Execution Thread ≠ Thread)

*Assumptions about the technical implementation of the sequence of actions are not met and are also irrelevant here. A thread is only one option to put the incarnation of a sequential process into effect.*
Non-Sequential Process

Definition
Also referred to as “parallel”, namely a process that is composed of a sequence of temporally overlapping actions.
**Definition**

Also referred to as “parallel”, namely a process that is composed of a sequence of temporally overlapping actions.

- requirement is a **non-sequential program** (cf. p. 9)
  - that allows for at least one more process incarnation (child process) or
  - that makes arrangements for the handling of events of external processes

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6. Interrupt requests issued by some device (IRQ) oder process (signal).
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whereby sequences of actions may overlap in the first place:

i. multithreading (Ger. *simultane Mehrfädigkeit*), in fact:
   - pseudo-parallel – multiplex mode of a single processor (core)
   - real parallel – parallel mode of a (multi-core) multiprocessor

ii. asynchronous program interrupts

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- whereby sequences of actions may overlap in the first place:
  1. multithreading (Ger. *simultane Mehrfärdigkeit*), in fact:
     - pseudo-parallel – multiplex mode of a single processor (core)
     - real parallel – parallel mode of a (multi-core) multiprocessor
  2. asynchronous program interrupts
- consequently, the sequence of all actions is defined by a **partial order**
  - as external processes may enable temporal/causal independent actions

⁶Interrupt requests issued by some device (IRQ) oder process (signal).
Concurrent Processes

Definition (in a broader sense: “simultaneous processes”)

One or more non-sequential processes in which at least two sequences of actions will overlap in time area by area (Ger. *bereichsweise*).
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One or more non-sequential processes in which at least two sequences of actions will overlap in time area by area (Ger. *bereichsweise*).

Areas are **concurrent** (Ger. *nebenläufig*) only if they are independent:
- None of these concurrent processes is cause or effect of the other.
- None of these actions of these processes requires the result of any other.
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- to proceed, concurrent processes compete for **reusable resources**
  - they share the processor (core), cache (line), bus, or devices
  - outcome of this is **interference**\(^7\) (Ger. *Interferenz*) in process behaviour

\(^7\)Derived from (Fre.) *s'entreferir* “to brawl each other”.

Definition (in a broader sense: “simultaneous processes”)

One or more non-sequential processes in which at least two sequences of actions will overlap in time area by area (Ger. *bereichsweise*).

- areas are **concurrent** (Ger. *nebenläufig*) only if they are independent
  - none of these concurrent processes is cause or effect of the other
  - none of theses actions of these processes requires the result of any other
- to proceed, concurrent processes compete for **reusable resources**
  - they share the processor (core), cache (line), bus, or devices
  - outcome of this is **interference**\(^7\) (Ger. *Interferenz*) in process behaviour
- the effective degree of overlapping is irrelevant for the simultaneity
  - apart from time-dependent processes that have to keep deadlines
  - note that the larger the overlapping, the larger the time delay
    - and the more likely will a delayed process miss its deadline
  - just as interference, which may also cause violation of timing constraints

\(^7\)Derived from (Fre.) *s’entreferir* “to brawl each other”.

© wosch CS (WS 2014, LEC 3) Fundamentals – Process
### Definition (also: “depending processes”)

Simultaneous processes that, directly or indirectly, interact with each other through a shared variable or by accessing a shared resource.

---

8 printer, mouse, plotter, keyboard.
Definition (also: “depending processes”)

Simultaneous processes that, directly or indirectly, interact with each other through a shared variable or by accessing a shared resource.

Their actions get into **conflict** if at least one of these processes... 

- will change the value of one of the shared variables (*access pattern*) or 
- already occupies a shared non-preemptable resource$^8$ (*resource type*)
Interacting Processes I

( Ger.) gekoppelte Prozesse [3, p. 77]

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- this may emerge as a **race condition** (Ger. Wettlaufsitiuation)
  - for shared variables or (reusable/consumable) resources, resp.
  - for starting or finishing an intended sequence of actions

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- conflicts are eliminated by means of **synchronisation methods:**
  - **blocking** prevent from executing an intended sequence of actions
  - **non-blocking** let a process abort and retry a started sequence of actions

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Interacting Processes I  

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    - replace a sequence of actions by an atomic instruction

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Interacting Processes I

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  - reducing: replace a sequence of actions by an atomic instruction

- founds **coordination** of cooperation and competition of processes

---

\(^8\) printer, mouse, plotter, keyboard.
```c
int64_t cycle = 0;

void *thread_worker(void *null) {
    for (;;) {
        /* ... */
        inc64(&cycle);
    }
}

void *thread_minder(void *null) {
    for (;;) {
        printf("worker cycle \%lld\n", cycle);
        pthread_yield();
    }
}
```

- `inc64`: see p. 7
int64_t cycle = 0;

void *thread_worker(void *null) {
    for (;;) {
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which cycle values prints the minder thread (Ger. *Aufpasserfaden*)?
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}
```

- which cycle values prints the minder thread (Ger. *Aufpasserfaden*)?
- which are produced by multiple worker threads (Ger. *Arbeiterfäden*)?
- in case *thread_worker* exists in several identical incarnations
assuming that the non-sequential program runs on a 32-bit machine

- instances of `int64_t` then form a pair of 32-bit words: double word
- operations on instances of `int64_t` cease to be solo efforts
assuming that the non-sequential program runs on a 32-bit machine

- instances of `int64_t` then form a pair of 32-bit words: _double word_
- operations on instances of `int64_t` _cease to be solo efforts_

**worker thread**

```
inc64:
1    movl 4(%esp), %eax
2    addl $1, (%eax)
3    adcl $0, 4(%eax)
4    ret
5
.L6:
6    movl $cycle, (%esp)
7    call inc64
8    jmp .L6
```
assuming that the non-sequential program runs on a 32-bit machine
- instances of int64_t then form a pair of 32-bit words: double word
- operations on instances of int64_t cease to be solo efforts

worker thread

```assembly
inc64:
  movl 4(%esp), %eax
  addl $1, (%eax)
  adcl $0, 4(%eax)
  ret

.L6:
  movl $cycle, (%esp)
  call inc64
  jmp .L6
```

minder thread

```assembly
10  movl cycle+4, %edx ; high &
11  movl cycle, %eax ; low word
12  movl $.LC0 , (%esp)
13  movl %edx, 8(%esp)
14  movl %eax, 4(%esp)
15  call printf
```
assuming that the non-sequential program runs on a 32-bit machine

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worker thread

\begin{verbatim}
inc64:
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  adcl $0, 4(%eax)
  ret

.L6:
  movl $cycle, (%esp)
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  jmp .L6
\end{verbatim}

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assume \textit{cycle} = 2^{32} - 1
\end{verbatim}
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```

- assume \( \text{cycle} = 2^{32} - 1 \)
  - inc64 overlaps actions 10–11
  - then, \( edx = 0 \) and \( eax = 0 \)
  - effect is, printf displays 0
    - not \( 2^{32} \), as would have been right

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assuming that the development or run-time environment varies
  - different compilers, assemblers, linker, or loaders
  - different operating systems—but the same real processor (x86)
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GCC 4.7.2, Linux

```assembly
inc64:
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```

real parallel actions: (multi-core) multiprocessor

the actions in lines 3–4 are critical as well: divisible read-modify-write

a classical error: as the case may be, ineffective numeration
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pseudo-parallel actions (case 4.2.1)
- (UNIX-) signal
- asynchronous program interrupt
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Outline

Preface

Fundamentals
  Program
  Process

Characteristics
  Physical
  Logical

Summary
Consistency

- prevention of race conditions by the **protection of critical sections**
- transfer a non-sequential process into a temporary sequential process
  - strictly: the shorter the sequential time span, the better the solution
- or, if applicable, rewrite conflict-prone program sequences as a transaction
Consistency

Coordination of Interacting Processes

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**Lookahead:** prevent overlapping by means of **mutual exclusion**

blocking of interacting processes

```c
void mutex_inc64(int64_t *i, pthread_mutex_t *lock) {
    pthread_mutex_lock(lock); /* indivisible, now */
    inc64(i); /* reuse code @ p.7 */
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}
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Consistency

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```

- reducing to a 64-bit ELOP of the real processor

```c
void inc64(int64_t *i) {
    asm ("lock incq %0" : : "m" (*i) : "memory");
}
```

- anywhere applicable and by orders of magnitude more efficient solution
anchoring of processes can be different within a computing system
Localisation

Operating-System v. Application Context

- **anchoring** of processes can be different within a computing system
  - namely inside or outside the operating-system machine level:
    - **inside**  – originally, within the operating system or its kernel
      - incarnation of the process is root of possibly other processes
      - partial virtualisation of the CPU as the real processor (core)
      - → "kernel thread", in computer science folklore
    - **outside**  – optional, within run-time or even application system
      - incarnation of the process as leaf or inner node (of a graph)
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    - when it gets switched or delayed, all of its user threads will as well
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      - a kernel thread may serve as an **abstract processor** for user threads
    - no nowadays known (real) processor is aware of what it is processing
      - particularly, a kernel thread does not know about potential user threads
      - when it gets switched or delayed, **all** of its user threads will as well
  - operating systems are aware only of their own “first-class citizens”
Weight Category

* feather–, ** lightweight

- partial virtualization

**
*

* **feather-, lightweight
kernel level
threads
user level
kernel

modes of process switches as to partial processor virtualisation:

* inside the same (user/kernel) address space, *ibidem*\(^9\) continuing
** inside kernel address space, same user address space sharing

\(^9\)(Lat.), “at the same place”
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sequencing (Ger. Ablaufplanung) the dispatching (Ger. Einlastung) of processes or, to be precise, process incarnations
Sequencing of Processes

Scheduling v. Synchronisation

- **scheduling** (Ger. *Ablaufplanung*) the **dispatching** (Ger. *Einlastung*) of processes or, to be precise, process incarnations
  - a big theoretical/mathematical side of operating systems [2, 1, 6, 7]
  - but enforcing the scheduling policies faces several practical challenges
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- unpredictable dynamic system behaviour at run-time dashes hopes
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  - breeds **asynchronism** and, as a result, foregrounds **heuristic**
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- process **synchronisation** is notorious for producing interference
  - once it comes to contention resolution, which **implies sequencing**
    - blocking – in matters of allocating consumable and/or reusable resources
    - non-blocking – pertaining to indivisible machine (CPU) instructions
  - especially susceptible for inducing interference is **blocking synchronisation**
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- to **control resource usage**, processes pass through logical states
  - whereby synchronisation emerges jointly responsible for state transitions
  - taken together, scheduling *and* synchronisation are **cross-cutting concerns**
Process States and State Transitions

- **start**
- **ready**
- **seize**
- **yield**
- **running**
- **cease**
- **blocked**
- **await**

### Relevant Resources:
- Processor

### Signal Paths:
- **start**
- **seize**
- **yield**
- **cease**

### Waitlists:
- Ready list of runnable processes
- Blocked list of processes

### Typical Lifetime Cycle of Processes:
- **ready**
  - Ready to run, but still waiting for a processor (core)
- **running**
  - Executing on a processor (core), performing a CPU burst
- **blocked**
  - Waiting for an event (being in sync), performing an I/O burst
Process States and State Transitions

- **expecting resource allocation**

- **start**
- **seize**
- **yield**
- **cease**

**typical life time cycle** of processes:

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Process States and State Transitions

- **relevant resources:**
  - processor
    - start
    - seize
    - yield
    - cease
  - signal
    - await
    - cause

- **typical life time cycle** of processes:
  - ready
    - ready to run, but still waiting for a processor (core)
  - running
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  - blocked
    - waiting for an event (being in sync), performing an I/O burst

- **expecting resource allocation**
  - start
  - cause

- **using allocated resources**
  - seize
  - yield
  - cease
  - await
Process States and State Transitions

- **relevant resources:**
  - processor
  - **start**
  - **seize**
  - **yield**
  - **cease**
  - **signal**
  - **await**
  - **cause**

- **waitlists involved:**
  - **ready list** of runnable processes
  - **blocked list** of processes unable to run

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  - **ready**
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  Physical
  Logical

Summary
Résumé

- a process is **predetermined by a program** that is to be executed
  - the process inherits the static characteristics of its program
  - when being existent, the process adds dynamic characteristics
    - as a function of data processing and interaction with the environment
- a process may be **sequential or non-sequential** (as to its program)
  - that is to say, composed of non-overlapping or overlapping actions
  - whereby overlapping is caused by multiprocessing in a wider sense
    - real parallelism, but also pseudo-parallelism in its various forms
- processes are **parallel, concurrent, simultaneous, or interacting**
  - simultaneous processes comprise concurrent and interacting periods
  - each of these can be parallel on their part, i.e., if their actions overlap
    - by either multiplexing or multiplication of the necessary processing units
- as to implementation, processes may be **kernel or user threads**
  - regardless of which, logical states report on the life time cycle of a process
  - whereby synchronisation emerges jointly responsible for state transitions
    - taken together, scheduling *and* synchronisation need to be complementary
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CS (WS 2014, LEC 3)  Summary 29 – 34
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Process “particularly, describes the formal notice or writ used by a court to exercise jurisdiction over a person or property”

- analogy in computer science or operating-system concepts, resp.: 
  - **writ**  
    - order to abandon rivalry\(^{10}\) in the claiming of resources  
    - direction to resolve competition of resource contenders  
  - **court**  
    - incarnation of the function of scheduling or coordination  
    - point of synchronisation in a program  
  - **jurisdiction**  
    - sphere of authority of contention resolution  
    - zone of influence of the synchronisation policy  
  - **property**  
    - occupancy/ownership of resources, ability to proceed  
    - functional or non-functional attribute

- generally, the action or trial, resp., follows a hierarchical jurisdiction  
  - thereby, the process step related to a certain level is denoted as *instance*  
    - in informatics, translation to (Ger.) “Instanz” however was rather unept !!!  
  - operating systems often command a multi-level processing of processes

\(^{10}\)Lat. *rivalis* “in the use of a watercourse co-authored by a neighbour”
refinement of [11, p. 5]: levels present on today’s computers
right, the method and (bracketed) program that supports each level