Concurrent Systems

Nebenläufige Systeme

III. Processes

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Agenda

Preface

Fundamentals
- Program
- Process

Characteristics
- Physical
- Logical

Summary

Outline

Subject Matter

- discussion on **abstract concepts** as to multiplexing machines:

program
- concretized form of an algorithm
- static sequence of actions <u>to be</u> 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

Subject Matter

- discussion on **abstract concepts** as to multiplexing machines:

program
- concretized form of an algorithm

process
- a program in execution

- explanation of **process characteristics** in physical and logical terms
  - appearance of a process as kernel thread and/or user thread
  - sequencing of processes, process states, and state transitions

Subject Matter

- discussion on **abstract concepts** as to multiplexing machines:

  program ▪ concretized form of an algorithm

  process ▪ a program in execution

- explanation of **process characteristics** in physical and logical terms

- 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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Operating systems bring programs to execution by creation, releasing, controlling and timing of processes

- 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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acc. [9], cf. p. 33

Operating systems bring programs to execution by creation, releasing, controlling and timing of processes

- in computer sciences, a process is unimaginable without a program

- a program (also) describes the kind of flow (Ger. *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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- in both kinds does the program flow consist of **actions** (p. 7 *ff.*)

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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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Program I

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For a certain machine concretised form of an algorithm.

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- virtual machine ASM (x86)
  - after compilation[2] and
  - before assembly

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

[2] `gcc -O4 -m32 -static -fomit-frame-pointer -S`, also below

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6 inc64:
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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] `gcc -O4 -m32 -static -fomit-frame-pointer -S`, also below

Program II

- address space and virtual machine SMC[3]
  - text segment
  - Linux
  - after linking/binding and
  - before loading

```
0x080482f0:     mov  0x4(%esp),%eax
0x080482f4:     add  $0x1,(%eax)
0x080482f7:     adc  $0x0,0x4(%eax)
0x080482fb:     ret
```

[3] *symbolic machine code*: x86 + Linux.

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2 0x080482f4:    add $0x1,(%eax)         83 00 01
3 0x080482f7:    adc $0x0,0x4(%eax)      83 50 04 00
4 0x080482fb:    ret                     c3
```

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

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```

- 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 (`gdb, disas /rm main`):

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

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A program P that allows several execution threads[a] in P itself.

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

```
pthread_t tid;

if (!pthread_create(&tid, NULL, thread, NULL)) {
  /* ... */
  pthread_join(tid, NULL);
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- the parallel flow allowed in P itself:

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void *thread(void *null) {
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- the parallel flow allowed in P itself:

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void *thread(void *null) {
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}
```

Hint

It is not mandatory that these threads of execution must take place simultaneously!

~~Non~~-Sequential Program II

- actions of parallelism—but **sequential flows** of the same program:

```
pid_t pid;

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- `fork` duplicates the address space A of P, creates A' as a copy of A
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- sequential flows can establish parallel ones within a domain that logically comprises those sequential flows

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```
pid_t pid;

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- the shown actions cause parallel flows within an operating system
  - multiprocessing (Ger. *Simultanbetrieb*) of sequential programs requires the operating system in the shape of a non-sequential program
  - serviceable characteristic is multithreading <u>within</u> the operating system

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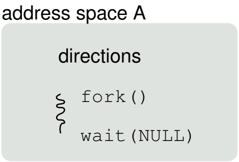
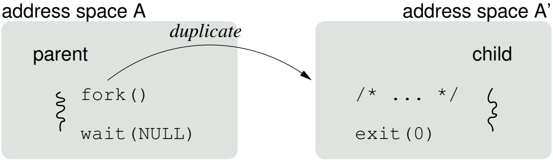
↪ concept "operating system" is epitome of "non-sequential program"[4]

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

Multiprocessing of Sequential Programs



Multiprocessing of Sequential Programs



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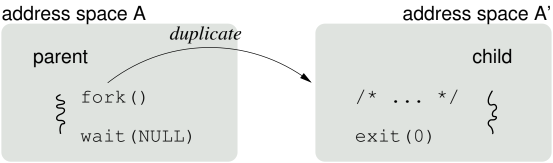

sequential program flows

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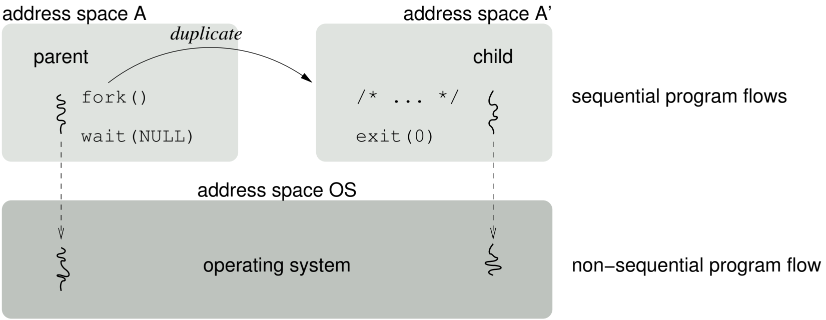

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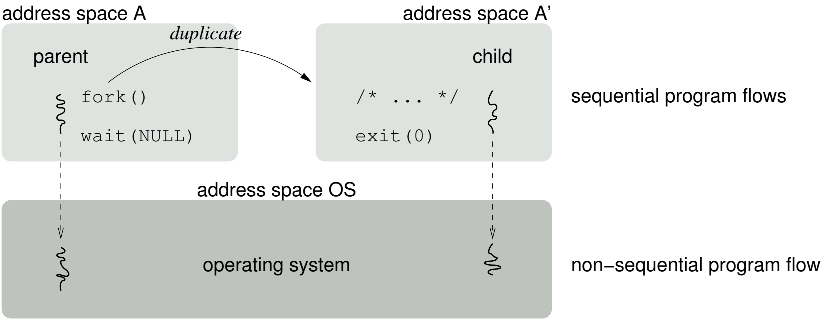

- processor (core) characteristic:

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

  Multi
  - ditto

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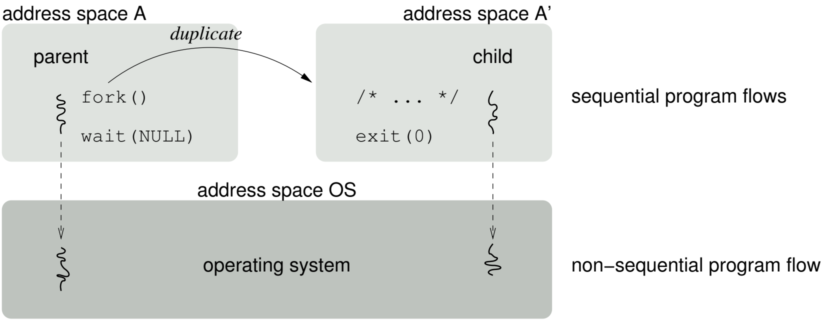
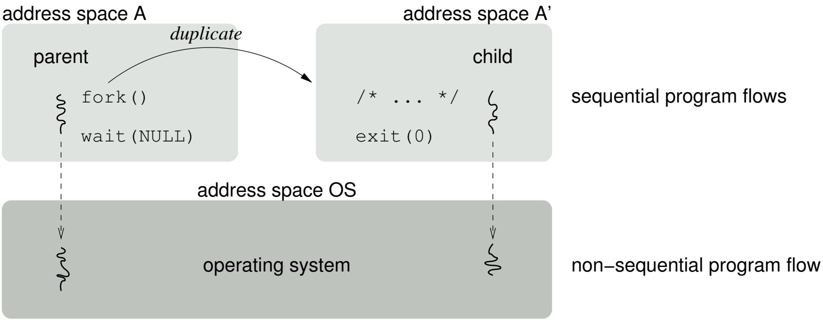


- processor (core) characteristic:
  - Uni
    - operated by a process-based operating system, namely:
    - pseudo-parallelism by means of processor (core) multiplexing
  - Multi
    - ditto; but also event-based operating system, namely:
    - real parallelism by means of processor (core) multiplication

Multiprocessing of Sequential Programs



- processor (core) characteristic:
  - Uni ▪ operated by a process-based operating system
  - Multi ▪ ditto; but also event-based operating system
- both cause **parallel processes** (p. 16) within the operating system

Process

Definition (Program flow)

A program in execution.

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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

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    level $_5$ $\mapsto$ program statement ≥ 1 assembly mnemonics
    level $_4$ $\mapsto$ assembly mnemonic ≥ 1 machine instructions
    level $_3$ $\mapsto$ machine instruction ≥ 1 microprogram directives
    level $_2$ $\mapsto$ microprogram directive
  - the actions of a processor thus are not imperatively indivisible (atomic)
    - this particularly holds both for the abstract (virtual) and real processor

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Hint (Process $\neq$ Process instance)

A process instance (Ger. Exemplar*) is an **incarnation** of a process.*[a]

[a] Just as an object is a "core image" of a class.

Indivisibility I

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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

level	action	sequence of actions
5	`i++`	

4–3	`incl i`*
	 `addl $1,i`*
		`movl i,%r`
		 `addl $1,%r`*
		 `movl %r,i`

2–1		* ***read*** *from memory into accumulator* ***modify*** *contents of accumulator* ***write*** *from accumulator into memory*

  - typical for a complex instruction of an "abstract processor" (C, CISC)

Indivisibility II

Entireness or unit of a sequence of actions whose solo efforts all will happen apparently simultaneous (i.e., are synchronised)

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- 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* "indivisble".

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- an/the essential non-functional property of an atomic operation[5]

- examples of (critical) actions for incrementation of a counter variable:
  - level$_{5 \mapsto 3}$

C/C++

```
i++;
```

ASM

```
movl i, %eax
addl $1, %eax
movl %eax, i
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    ```
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  - level $_{3 \mapsto 2}$

    ASM

    ```
    incl i
    ```

    ISA

    ```
    read   A from <i>
    modify A by 1
    write  A to <i>
    ```

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    incl i
    ```

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    ```

- points (`i++`, `incl`) in case of merely conditionally atomic execution
  - namely uninterruptible operation (level $_{5 \mapsto 3}$), uniprocessor (level $_{3 \mapsto 2}$)
  - problem: overlapping in time of the sequence of actions pointed here

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Sequential Process

Definition (Sequential program in execution)

A process with only a single thread of execution.

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- a sequence of actions that forms a **unique execution thread**
  - but which may develop differently with each restart of that process
    - other input data, program change, ..., transient hardware errors

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A process with only a single thread of execution.

- a sequence of actions that forms a **unique execution thread**
- the sequence is defined by a **total order** of its actions
  - it is reproducible given unmodified original conditions
    - same input data, no program changes, ..., no transient hardware errors

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Hint (Execution Thread $\neq$ 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.*

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A process consisting of several threads of execution, which may take place simultaneously (in parallel).

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- 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[6]

[6]Interrupt requests issued by some device (IRQ) or process (signal).

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- requirement is a **non-sequential program** (cf. p. 9)

- whereby sequences of actions may overlap in the first place:
  - i asynchronous program interrupts
  - ii multithreading (Ger. *simultane Mehrfädigkeit*), in fact:
    - pseudo-parallel – multiplex mode of a single processor (core)
    - real parallel – parallel mode of a (multi-core) multiprocessor

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- whereby sequences of actions may overlap in the first place:
  i asynchronous program interrupts
  ii multithreading (Ger. *simultane Mehrfädigkeit*)
- consequently, the sequence of all actions is defined by a **partial order**
  - as external processes may enable temporal/causal independent actions

Concurrent Processes

(Ger.) *gleichzeitige Prozesse* [3]

Definition (in a broader sense: "simultaneous processes")

Several threads of execution of the same non-sequential process or of multiple sequential processes taking place simultaneously.

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- "**concurrent**" only with respect to the same level of abstraction [10]
  - 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

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Several threads of execution of the same non-sequential process or of multiple sequential processes taking place simultaneously.

- "**concurrent**" only with respect to the same level of abstraction [10]
- however, to proceed, these processes compete for **reusable resources**
  - they share the processor (core), cache (line), bus, or devices
  - this also results in **interference**[7] (Ger. *Interferenz*) in process behaviour

[7] Derived from (Fre.) *s'entreferir* "to brawl each other".

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- "**concurrent**" only with respect to the same level of abstraction [10]
- however, to proceed, these processes compete for **reusable resources**
- 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

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.

Interacting Processes I

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

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 accupies a shared non-preemptable resource[8] (resource type)

[8] printer, mouse, plotter, keyboard.

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

[8] printer, mouse, plotter, keyboard.

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

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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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  - blocking ▪ prevent from executing an intended sequence of actions
  - non-blocking ▪ let a process abort and retry a started sequence of actions
  - reducing ▪ replace a sequence of actions by an atomic instruction

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- conflicts are eliminated by means of **synchronisation methods**
- founds **coordination** of cooperation and competition of processes

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Interacting Processes II

```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

Interacting Processes II


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- inc64: see p. 7

- which cycle values prints the minder thread (Ger. *Aufpasserfaden*)?

Interacting Processes II


```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

- 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

Interacting Processes III

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

Interacting Processes III

- 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:
  movl 4(%esp), %eax
  addl $1, (%eax)
  adcl $0, 4(%eax)
  ret

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

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

- minder thread

```
movl cycle+4, %edx  ; high &
movl cycle, %eax    ; low word
movl $.LC0, (%esp)
movl %edx, 8(%esp)
movl %eax, 4(%esp)
call printf
```

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  - instances of `int64_t` then form a pair of 32-bit words: <u>double word</u>
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- assume $cycle = 2^{32} - 1$

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3    addl $1, (%eax)
4    adcl $0, 4(%eax)
5    ret

6  .L6:
7    movl $cycle, (%esp)
8    call inc64
9    jmp  .L6
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- minder thread

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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
```

- assume *cycle* $= 2^{32} - 1$
  - `inc64` overlaps actions 10–11

Interacting Processes III

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14 movl %eax, 4(%esp)
15 call printf
```

- assume *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

Interacting Processes IV

- 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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inc64:
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  adcl $0, 4(%eax)
  ret
```

- GCC 4.2.1, MacOSX

```
_inc64:
  movl 4(%esp), %eax
  movl (%eax), %ecx
  movl 4(%eax), %edx
  addl $1, %ecx
  adcl $0, %edx
  movl %edx, 4(%eax)
  movl %ecx, (%eax)
  ret
```

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```

- **pseudo-parallel actions** (case 4.2.1)
  - (UNIX-) signal
  - asynchronous program interrupt
- GCC 4.2.1, MacOSX

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_inc64:
  movl 4(%esp), %eax
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8    movl (%eax), %ecx
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11   adcl $0, %edx
12   movl %edx, 4(%eax)
13   movl %ecx, (%eax)
14   ret
```

- **pseudo-parallel actions** (case 4.2.1)
- **real parallel actions**: (multi-core) multiprocessor
  - the actions in lines 3–4 are critical as well: divisible *read-modify-write*

Interacting Processes IV

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  addl $1, %ecx
  adcl $0, %edx
  movl %edx, 4(%eax)
  movl %ecx, (%eax)
  ret
```

- **pseudo-parallel actions** (case 4.2.1)

- **real parallel actions**: (multi-core) multiprocessor

- a classical error: as the case may be, ineffective numeration

Outline

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

- prevention of race conditions by the **protection of critical sections**

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

- blocking of interacting processes

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

- prevention of race conditions by the **protection of critical sections**

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

- blocking of interacting processes: comparatively long time span

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

Consistency

- prevention of race conditions by the **protection of critical sections**

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

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

```
void inc64(int64_t *i) {        /* renew code @ p.7 */
  asm ("lock incq %0" : : "m" (*i) : "memory");
}
```

  - anywhere applicable and by orders of magnitude more efficient solution

Localisation

- **anchoring** of processes can be different within a computing system

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  - namely inside or outside the operating-system machine level:

    inside – originally, within the operating system or its kernel

    outside – optional, within run-time or even application system

Localisation

- **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)
    $\hookrightarrow$ "*kernel thread*", in computer science folklore

Localisation

- **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

    outside – optional, within run-time or even application system
    – incarnation of the process as leaf or inner node (of a graph)
    – partial virtualisation of the root process as an abstract processor
    ↪ "*user thread*", in computer science folklore

Localisation

- **anchoring** of processes can be different within a computing system

- usually, a processor (core) is entirely unaware of being multiplexed
  - threads evolve from time sharing their underlying processor (core)
    - a kernel thread may serve as an **abstract processor** for user threads

- **anchoring** of processes can be different within a computing system

- usually, a processor (core) is entirely unaware of being multiplexed
  - threads evolve from time sharing their underlying processor (core)
    - 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, <u>all</u> of its user threads will as well

Localisation

- **anchoring** of processes can be different within a computing system
  - namely inside or outside the operating-system machine level:

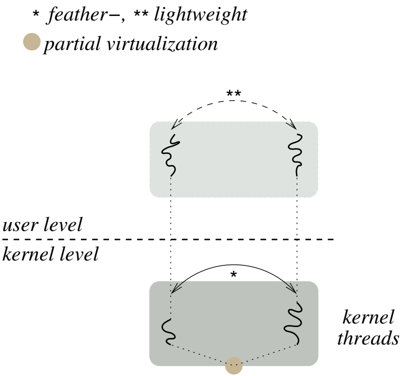
    inside – originally, within the operating system or its kernel

    ↪ "*kernel thread*", in computer science folklore

- usually, a processor (core) is entirely unaware of being multiplexed

- operating systems are aware only of their own "first-class citizens"

Weight Category



- 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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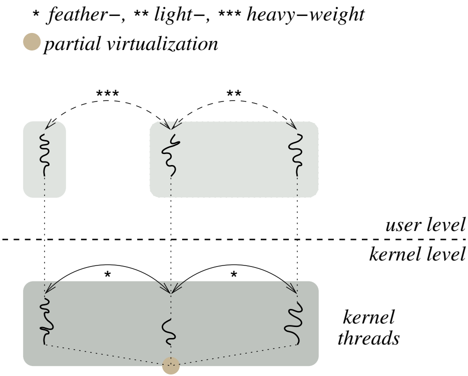

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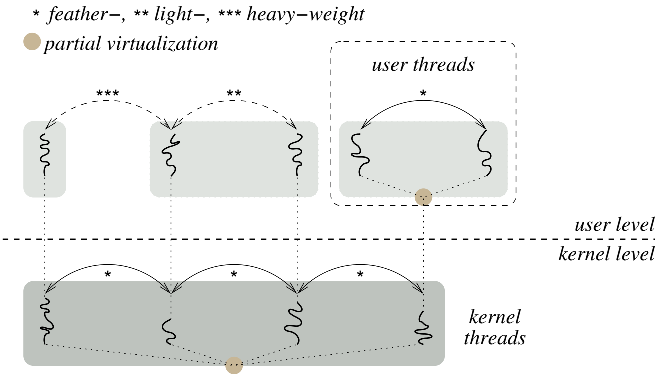

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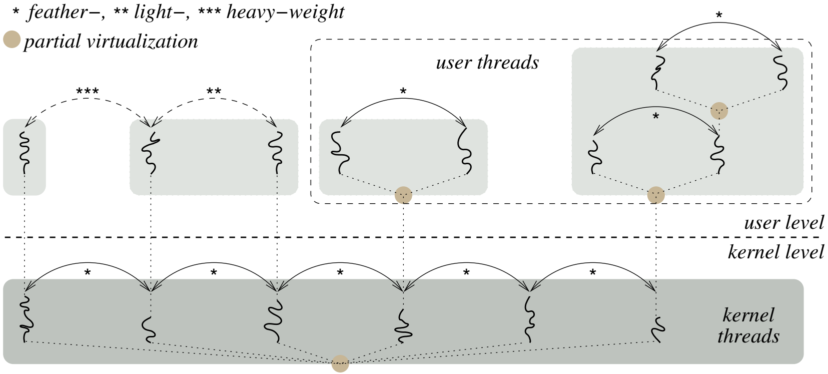

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Sequencing of Processes

- **scheduling** (Ger. *Ablaufplanung*) the **dispatching** (Ger. *Einlastung*) of processes or, to be precise, process incarnations

Sequencing of Processes

- **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

Sequencing of Processes

- **scheduling** (Ger. *Ablaufplanung*) the **dispatching** (Ger. *Einlastung*) of processes or, to be precise, process incarnations

- unpredictable dynamic system behaviour at run-time dashes hopes
  - on the one hand interrupts, on the other hand resource sharing
  - breeds **asynchronism** and, as a result, foregrounds **heuristic**

Sequencing of Processes

- **scheduling** (Ger. *Ablaufplanung*) the **dispatching** (Ger. *Einlastung*) of processes or, to be precise, process incarnations

- unpredictable dynamic system behaviour at run-time dashes hopes

- process **synchronisation** is notorius 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

Sequencing of Processes

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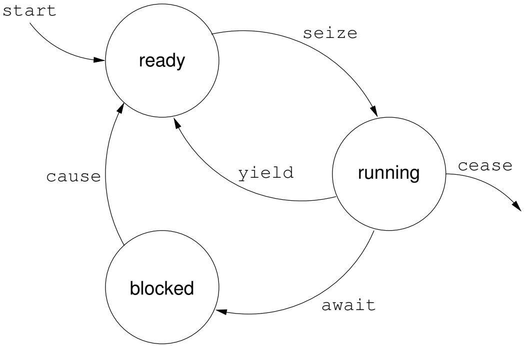
- unpredictable dynamic system behaviour at run-time dashes hopes

- process **synchronisation** is notorius for producing interference

- 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



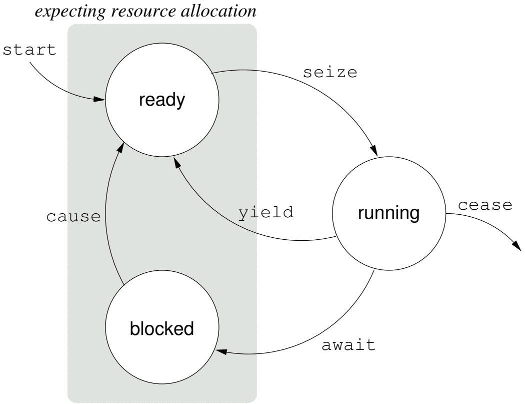
- typical **life time cycle** of processes:

  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



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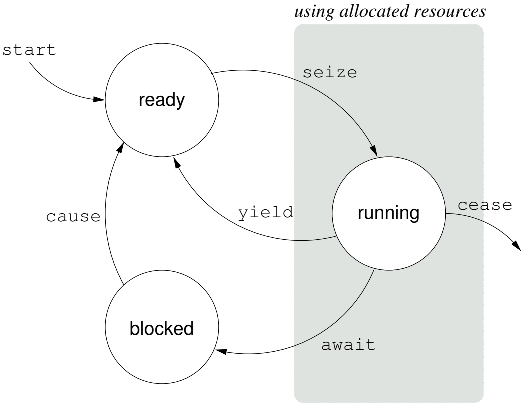

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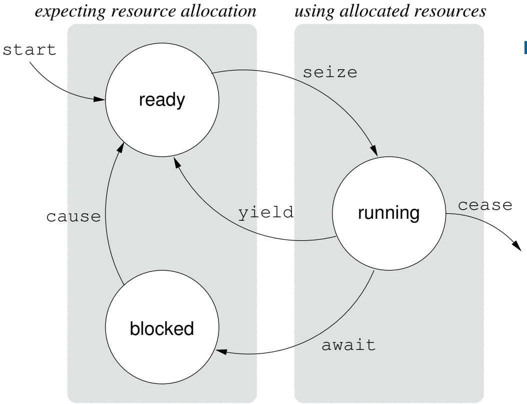

- relevant resources:

  processor
  - `start`
  - `seize`
  - `yield`
  - `cease`

  signal
  - `await`
  - `cause`

- typical **life time cycle** of processes:

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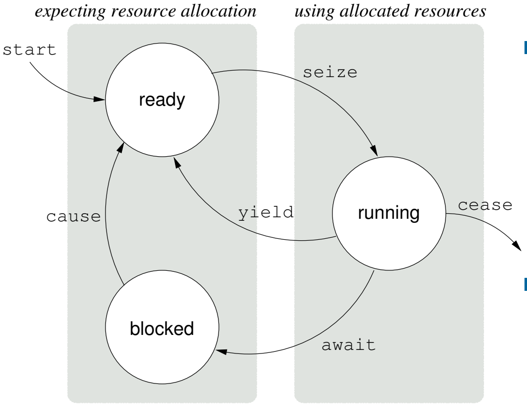

- relevant resources:
  - processor
    - start
    - seize
    - yield
    - cease
  - signal
    - await
    - cause
- waitlists involved:
  - ready list of runnable processes
  - blocked list of processes unable to run
- typical **life time cycle** of processes:
  - ready: ready to run, but still waiting for a processor (core)
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Outline

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
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    - taken together, scheduling *and* synchronisation need to be complementary

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Originally as a Concept of Law

acc. [12, Legal process]

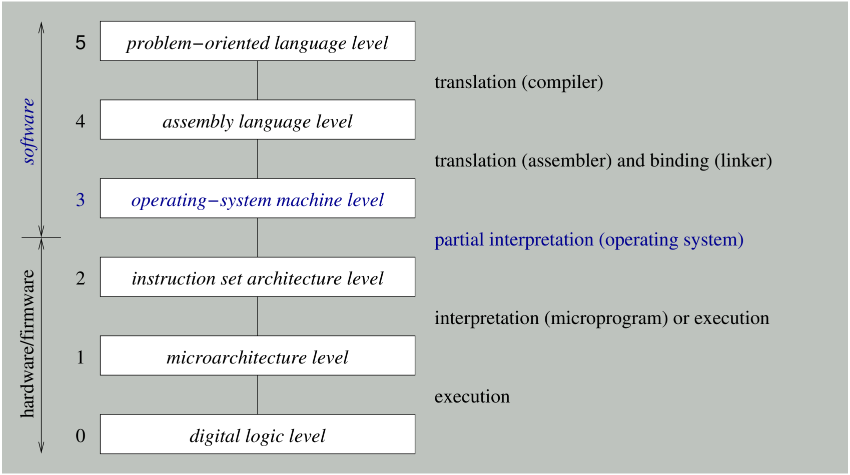
> Process "particularly, describes the formal notice or writ used by a court to exercise jurisdiction over a person or property"

- 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 todays computers
  - right, the method and (bracketed) program that supports each level