Concurrent Systems
*Nebenläufige Systeme*

III. Processes

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Outline

Preface

Fundamentals
  Program
  Process

Characteristics
  Physical
  Logical

Summary

Subject Matter

- 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
- 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
- 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
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
- 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
- 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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**Program I**

**Problem-Oriented/Assembly Language Level**

**Definition**

For a certain machine concretised form of an algorithm.

- virtual machine C
  - after editing and
  - before compilation

```
#include <stdint.h>

void inc64(int64_t *i) {
  (*i)++;
}
```

- one action (line 4)

**Definition (Action)**

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

---

**Program II**

**Operating-System Machine Level**

- address space and virtual machine SMC
  - text segment
  - Linux

```
0x080482f0:
  movl $0x80d37b0 , (% esp )

0x080481c9:
  c7 04 24 b0 37 0d 08 movl $0x80d37b0 , (% esp )
```

- three actions (lines 7–9)

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**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)
2 0x08048140:    e8 1b 01 00 00   call 0x80482f0 <inc64>
```

---

1 Provided that the operating system offers all necessary commands.

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Non-Sequential Program I

Definition
A program $P$ specifying actions that allow for parallel flows in $P$ itself.

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

```c
1  pthread_t tid;
2  if (!pthread_create(&tid, NULL, thread, NULL)) {
3      /* ... */
4          pthread_join(tid, NULL);
5  }
```

the parallel flow allowed in $P$ itself:

```c
7  void *thread(void *null) {
8      /* ... */
9          pthread_exit(NULL);
10 }
```

Non-Sequential Program II

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

```c
1  pid_t pid;
2  if(!(pid = fork())) {
3      /* ... */
4          exit(0);
5      }
6  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 $A'$

sequential flows can establish parallel ones within a domain that logically comprises those sequential flows

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 within the operating system

concept “operating system” is epitome of “non-sequential program”

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

Multiprocessing of Sequential Programs

address space $A$

fork()

wait(NULL)

sequential program flows

child

address space $A'$

parent
duplicate

operating system

non-sequential program flow

process (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

Process

Definition (Program flow)
A program in execution on and through a processor.

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 $\geq 1$ assembly mnemonics
  - $level_4 \mapsto$ assembly mnemonic $\geq 1$ machine instructions
  - $level_3 \mapsto$ machine instruction $\geq 1$ 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

- this sequence is static (passiv), while a process is dynamic (active)

Hint (Process $\neq$ Process instance)
A process instance (Ger. Exemplar) is incarnation of a process.

3Just as an object is a “core image” of a class.
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
- **action** on higher, **sequence of actions** on lower level of abstraction

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

- 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)

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

- examples of (critical) actions for incrementation of a counter variable:
  - **level**, \( i \rightarrow 3 \)  
  - **ASM**  
  - **ISA**

<table>
<thead>
<tr>
<th>C/C++</th>
<th>ASM</th>
<th>ISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>i++;</td>
<td>5 incl i</td>
<td>6 read A from &lt;i&gt;</td>
</tr>
<tr>
<td>addl $1, %eax</td>
<td>7 modify A by 1</td>
<td></td>
</tr>
<tr>
<td>movl %eax, i</td>
<td>8 write A to &lt;i&gt;</td>
<td></td>
</tr>
</tbody>
</table>

- 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

Sequential Process

**Definition**

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

- the sequence of actions forms a unique **execution thread**
  - of which always only a single one exists within a sequential process
  - but which may develop differently with each restart of that process
    - other input data, program change, ... , transient hardware errors
- the sequence is defined by a **total order** of its actions
  - it is reproducible given unmodified original conditions

**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.

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

\(^5\)from (Gr.) **átomo** "indivisible".

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

(Ger.) gleichzeitige Prozesse [3]

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 these 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* (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.”

Interacting Processes II

Race Conditions

```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();
  }
}
```

- 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

Inc64: see p. 7

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 occupies a shared non-preemptable resource (resource type)
- 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
- Conflicts are eliminated by means of *synchronisation methods*:
  - Prevent from executing an intended sequence of actions
  - Let a process abort and retry the intended sequence of actions
  - Replace a sequence of actions by an atomic instruction
- Finds coordination of cooperation and competition of processes

Interacting Processes III

1. Race Condition

- 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

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

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

- Worker thread
- Minder thread

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

GCC 4.7.2, Linux

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

GCC 4.2.1, MacOSX

```c
_inc64:
6 movl 4(%esp), %eax
7 movl (%eax), %ecx
8 movl 4(%eax), %edx
9 addl $1, %ecx
10 adcl $0, %edx
11 movl %edx, 4(%eax)
12 movl %ecx, (%eax)
13 ret
```

pseudo-parallel actions (case 4.2.1)
  - (UNIX-) signal
  - asynchronous program interrupt

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

looking ahead: prevent overlapping by means of mutual exclusion

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

blocking of interacting processes: comparatively long time span

```c
void mutex_inc64(int64_t *i, pthread_mutex_t *lock) {
1  pthread_mutex_lock(lock); /* indivisible, now */
2  inc64(i); /* reuse code @ p. 7 */
3  pthread_mutex_unlock(lock); /* divisible, again */
4 }
```

reducing to a 64-bit ELOP of the real processor

```c
void inc64(int64_t *i) {
1  asm ("lock incq %0" : : "m" (*i) : "memory");
2 }
```

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
    - 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
    - partial virtualisation of the root process as an abstract processor
    - "user thread", in computer science folklore

usually, a processor (core) is entirely unaware of being multiplexed
  - 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 Interruption and Resumption Overhead

- * feather-, ** light-, *** heavy-weight
- partial virtualization

```
* user threads
** kernel level
** partial virtualization
* user threads
** kernel
*
** feather-, light-, heavy-weight
```

** modes of process switches** as to partial processor virtualisation:

- * inside the same (user/kernel) address space, *ibidem* continuing
- ** inside kernel address space, same user address space sharing
- *** inside kernel address space, at other user address space landing

\(^9\text{(Lat.), “at the same place”}\)

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

- 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

- 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

- 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

- relevant resources:
  - processor
    - start
    - seize
    - yield
    - cease
    - 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)
  - running
    - executing on a processor (core), performing a CPU burst
  - blocked
    - waiting for an event (being in sync), performing an I/O burst

```

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Preface

Fundamentals
  - Program
  - Process

Characteristics
  - 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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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
  - court: incarnation of the function of scheduling or coordination
  - jurisdiction: sphere of authority of contention resolution
  - property: occupancy/ownership of resources, ability to proceed
- 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"