Teaching Concurrency to Freshmen?

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Dependable Systems and Software

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***also with INRIA Rhônes-Alpes**

Context: CS-related degrees offered at Saarland University

- Computer Science – Bachelor/Master of Science
  - about 150
- Bioinformatics – Bachelor/Master of Science
  - about 20
- Computer and Communication - Bachelor/Master of Science
  - about 40
- Computer Vision – Master of Science
  - less than 10

Context: Freshmen

- No entrance level requirements

  except a general university entrance diploma
  (German “Abitur” or equivalent).

- Basic knowledge in calculus and linear algebra is assumed

- Department offers a dedicated preparatory course (discrete math)
  - 20 lectures and 40 tutorials
  - spans entire September
  - preceeds the start of the academic year
  - optional offer, but strongly encouraged

Context: Mandatory courses in CS Bachelor

- Math for Computer Scientists 1, 2, 3 (9 CP each)
- Programming 1 (9 CP)
- Programming 2 (9 CP)
- Software Practice Lab (14 CP)
- System Architecture (9 CP)
- Information Systems (9 CP)
- Theoretical Computer Science (9 CP)

ETCS credit points

Each 30 hours of work of the average student is worth one ETCS credit point.

9 CP thus amount to an average workload of 270 hours

Context: Programming Education

- Programming 1 (9 CP)
  - Foundations of computing
  - SML

Computer science
as executable mathematics

- Programming 2 (9 CP)
  - Algorithms and Data Structures
  - C/C++
- Software Practice Lab (14 CP)
  - large software designs
  - teams of up to 5 students
  - block project during summer break

Programming 1: Original Setup

- Basic abstract data structures and algorithms
  - Lists, trees and graphs, list and tree traversal, sorting,....
  - Practical experiments with their concrete realisations in SML.

- Basic considerations of program verification and analysis
  - Program correctness as integral part of program design
  - Inductive correctness and termination proofs
  - Runtime Analysis

- Formal syntax and semantics
  - Abstract and concrete syntax
  - Lexing and parsing, type checking and
  - Static and dynamic semantics
  - Interpreter for a simple subset of SML is developed

Sucess ratio of first years' students is in the order of 70%. (lower for students who need to retake)

- Compilation and execution
  - Programming a virtual machine in SML.
  - Developing a compiler from an imperative language to VM assembler code.
  - features: arithmetic operations, jumps, dynamic heap memory allocation, (recursive) procedure calls.

Basics of Concurrency Theory: What we asked ourselves

- Which aspects of concurrency theory are of **maximal benefit to the students** for the subsequent courses?
- How can we **use general concepts already taught** effectively in order to build up a theory of concurrency?
- Do we need to **sacrifice other parts** of the course we are focusing on?
- Do we manage to **keep the overall flavor** of the course?

Programming 1: Our twist

- Basic abstract data structures and algorithms
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- Compilation and execution
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Basics of Concurrency Theory

What the students know by then

Basic axiomatic set theory

- Boolean algebra, relations, functions, recursion, and inductive proofs

Principal concepts of programming languages

- grammars, type checking, semantics, inference rule and trees

Properties of programs

- termination and correctness, semantical equivalences of programs, time complexity;

Basic data structures

- lists, trees, graphs and their representation in SML;

Principles of recursive algorithms

- list and tree traversals, sorting, divide-and-conquer;

SML basics and some advanced features

- such as polymorphism

Basics of Concurrency Theory: What we teach

1. We familiarise the students with LTS
   - as a mild extension of directed graphs

2. We introduce a language of processes to generate LTS
   - basically sequential CCS

3. We introduce the composition of processes interacting on complementary signals
   - yielding full CCS

4. We let them implement fragments of syntax and semantics
   - yielding an interactive step-simulator for CCS

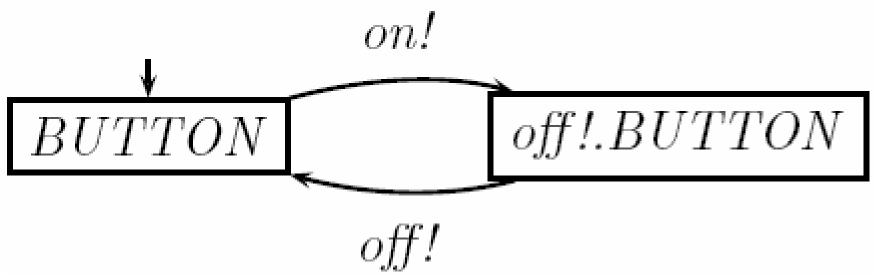
5. We elaborate on intriguing concurrency phenomea
   - deadlocks, livelocks, dining philosophers, TODO

What we teach #1: Labelled transition systems and processes

Definition 1. *A (directed) labelled graph G is a triple (V, M, E) with V an arbitrary set of vertices, M an arbitrary set of labels, and $E \subseteq V \times M \times V$ a set of directed labelled edges.*

The students are already familiar with graphs.

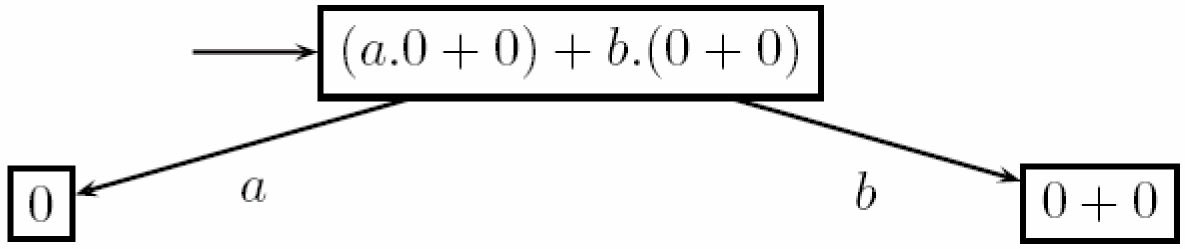
Definition 2. *A process is a pair (G, v) where G is a graph $G = (V, M, E)$ and $v \in V$ is vertex of G.*



- We avoid to emphasize the meaning of labelled graphs and processes as models of concurrency.
- Instead we treat them as academic objects.
- We only provide hints that a process might be an abstract view on what a computer program does.

What we teach #2:
A language for acyclic processes

$$P \in L_0 \quad = \quad 0 \quad | \quad a.P \quad | \quad P + P \qquad \text{where } a \in M$$



- with structural operational semantics

$$[\![\_]\!] \in L_0 \rightarrow \mathcal{G}_{L_0} \times L_0 \quad \text{where } [\![P]\!] = ((L_0, M, \rightarrow), P)$$

$$\mathcal{G}_{L_0} = \{(L_0, M, E) \mid E \subseteq L_0 \times M \times L_0\}$$

where $\rightarrow \subseteq L_0 \times M \times L_0$ is given by the smallest relation satisfying the inference rules

prefix $\dfrac{}{a.P \stackrel{a}{\rightarrow} P}$ choice_l $\dfrac{P \stackrel{a}{\rightarrow} P'}{P + Q \stackrel{a}{\rightarrow} P'}$ choice_r $\dfrac{Q \stackrel{a}{\rightarrow} Q'}{P + Q \stackrel{a}{\rightarrow} Q'}$

What we teach #3:
A language for processes

$$P \in L \;=\; 0 \;\mid\; a.P \;\mid\; P + P \;\mid\; X$$

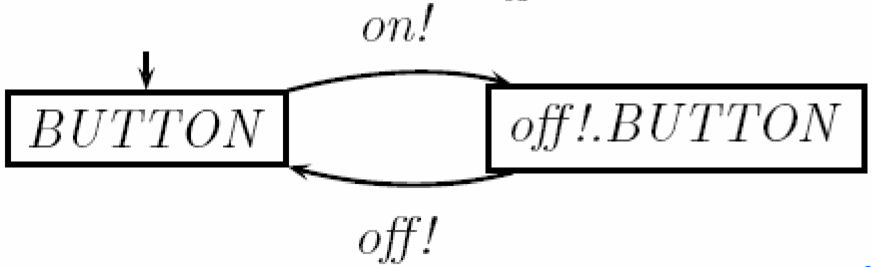
- We add a set of defining equations Γ

In Γ all equations have the form $X = E$ where X is a process variable and E is an arbitrary term

- and add a rule to deal with recursion

$$\text{rec}\quad \frac{\Gamma(X) = P \quad P \xrightarrow{a} P'}{X \xrightarrow{a} P'}$$

$$BUTTON = on!.off!.BUTTON$$



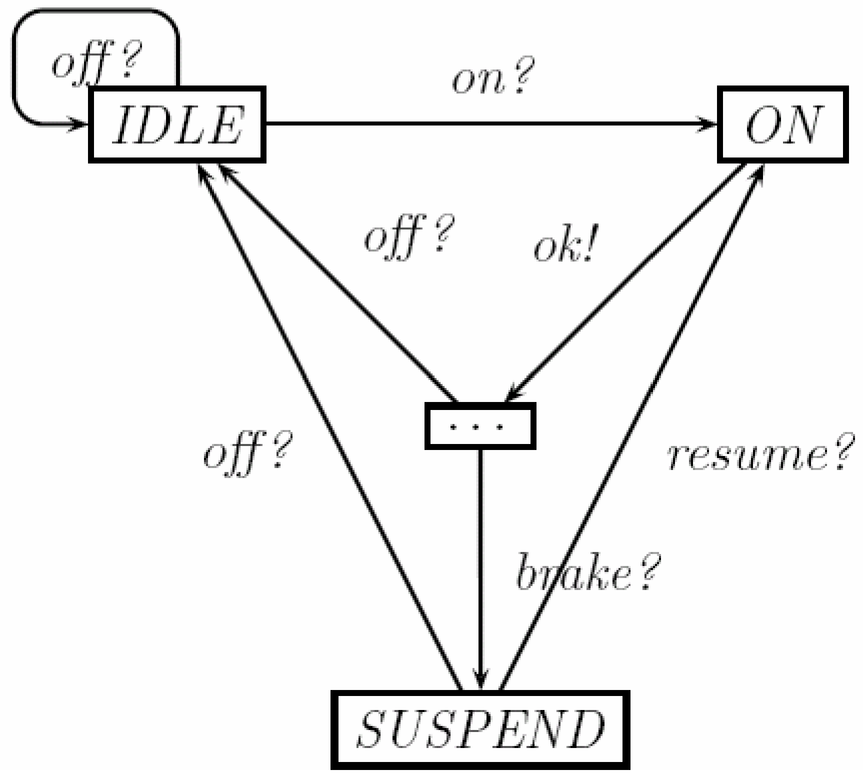
What we teach #4:
A cruise control example

[Kramer/Magee]

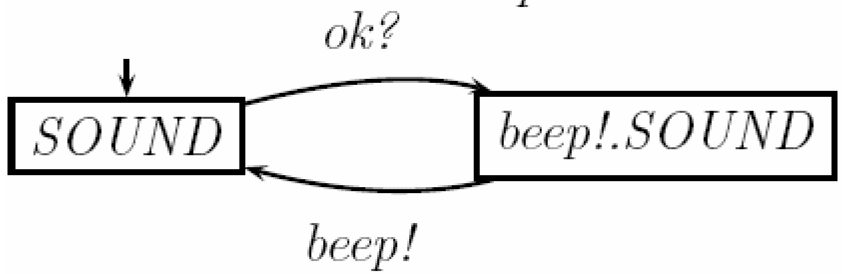
$$IDLE = on?.ON + off?.IDLE$$

$$ON = ok!.(off?.IDLE + brake?.SUSPEND)$$

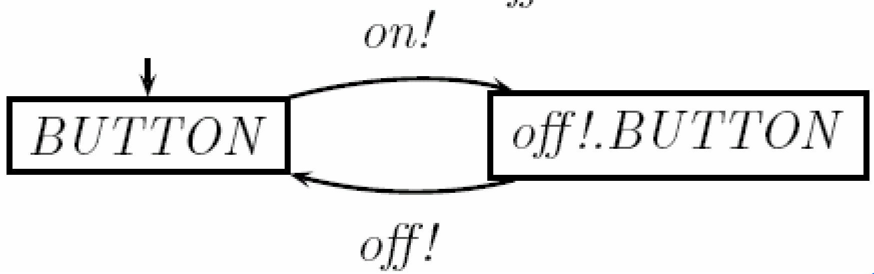
$$SUSPEND = resume?.ON + off?.IDLE$$



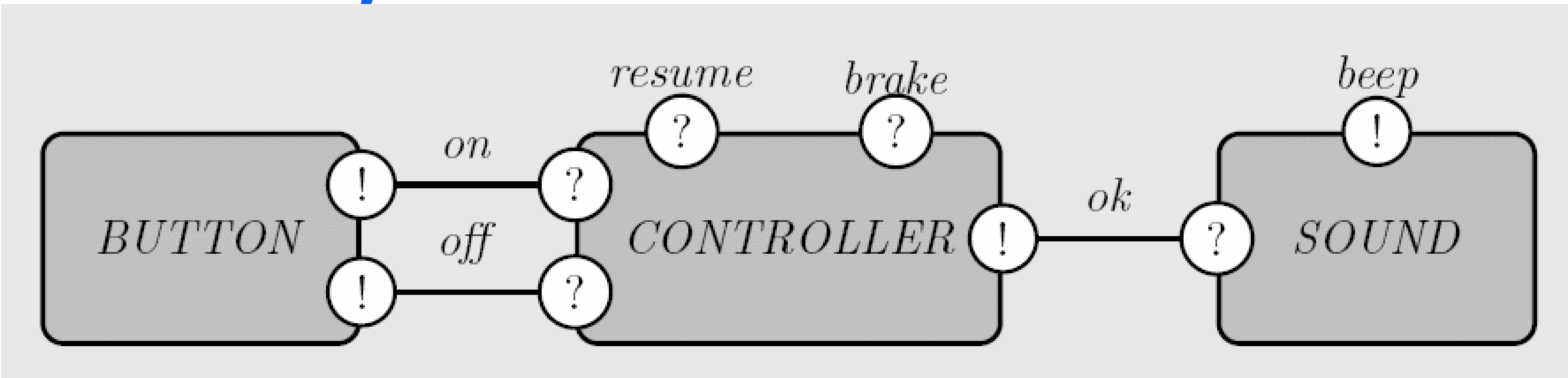
$$SOUND = ok?.beep!.SOUND$$



$$BUTTON = on!.off!.BUTTON$$



What we teach #5: Concurrency and interaction



We use this example to postulate the following **principles of concurrency**:

- Real-life processes have states. They can change states via certain actions.
- Actions are atomic, and their purpose is inter-process communication.
- Distinct processes can exists concurrently and perform actions.
- Inter-process communication can be performed whenever pairs of complementary input and output actions occur at the same time.
  - This yields process synchronisation, i.e. a simultaneous change of states.

What we teach #6:
An intermezzo on process synchronisation

We discuss different inter-process communication principles

- Shared variable vs. message passing
- Binary vs. multiway
- Directed vs. undirected
- Buffered vs. handshake

We stay on a very informal level in this intermezzo,
before we return to the above example,
which makes a clear case for
binary, handshaked, directed communication.

What we teach #7: Semantics of CCS parallel operator

We discuss different inter-process communication principles

- Shared variable vs. message passing
- Binary vs. multiway
- Directed vs. undirected
- Buffered vs. handshake

We stay on a very informal level in this intermezzo,
before we return to the above example,
which makes a clear case for (CCS style)
binary, handshaked, directed communication.

$$\text{par\_l}\ \frac{P \xrightarrow{m} P'}{P \mid Q \xrightarrow{m} P' \mid Q} \qquad \text{par\_r}\ \frac{P \xrightarrow{m} P'}{Q \mid P \xrightarrow{m} Q \mid P'} \qquad \text{sync}\ \frac{P \xrightarrow{\alpha} P' \quad Q \xrightarrow{\overline{\alpha}} Q'}{P \mid Q \xrightarrow{\tau} P' \mid Q'}$$

What we teach #8: Semantic Equivalence

When should two processes be considered equivalent?

This question re-appeared at various points in our lectures

We reviewed

- graph isomorphism, trace equivalence, and bisimulation equivalence.

The lessons learnt by the students:

- Trace equivalence is the *weakest common criterion*
- The process' *branching structure must be preserved* so as to avoid deadlocks in the context of parallel composition,
  - isomorphism or bisimulation
- It should be a *congruence for the operators of the language*
  - trace equivalence or bisimulation

In summary, the students understand that for CCS, *bisimulation equivalence* is the central notion of equivalence.

What the students practice #1: They step-simulate CCS examples

```
CCS> Environment:
 X=a!.Z,
 Y=((a?.Z + a!.0) + b!.X),
 Z=Y
       Process:
                ((X | Y) | Z)
CCS-
CCS> All successors:
0.) --a!-->     ((Z | Y) | Z)
1.) --a?-->     ((X | Z) | Z)
2.) --a!-->     ((X | 0) | Z)
3.) --b!-->     ((X | X) | Z)
4.) --tau-->    ((Z | Z) | Z)
5.) --a?-->     ((X | Y) | Z)
6.) --a!-->     ((X | Y) | 0)
7.) --b!-->     ((X | Y) | X)
8.) --tau-->    ((X | 0) | Z)
9.) --tau-->    ((X | Z) | 0)
10.) --tau-->   ((Z | Y) | Z)
```

```
CCS- succ 6
CCS> 6-th successor via action a!:
                ((X | Y) | 0)
CCS- steps
CCS> All successors:
0.) --a!-->     ((Z | Y) | 0)
1.) --a?-->     ((X | Z) | 0)
2.) --a!-->     ((X | 0) | 0)
3.) --b!-->     ((X | X) | 0)
4.) --tau-->    ((Z | Z) | 0)

CCS-
```

What the students practice #2: They implement fragments of the simulator

Parts of Lexer, Parser, Operational Semantics

For instance, they were given this

$$
\begin{aligned}
&\mathit{steps}\ \Gamma\ 0 && = \emptyset \\
&\mathit{steps}\ \Gamma\ m.P && = \{(m, P)\} \\
&\mathit{steps}\ \Gamma\ X && = \mathit{steps}\ \Gamma\ (\Gamma X) \\
&\mathit{steps}\ \Gamma\ (P + Q) && = (\mathit{steps}\ \Gamma\ P) \cup (\mathit{steps}\ \Gamma\ Q) \\
&\mathit{steps}\ \Gamma\ (P|Q) && = \{(m, P'|Q) \ \mid\ (m, P') \in \mathit{steps}\ \Gamma\ P\} \\
& && \cup \{(m, P|Q') \ \mid\ (m, Q') \in \mathit{steps}\ \Gamma\ Q\} \\
& && \cup \{(\tau, P'|Q') \ \mid\ \exists \alpha :\ (\alpha, P') \in \mathit{steps}\ \Gamma\ P\ \wedge\ (\overline{\alpha}, Q') \in \mathit{steps}\ \Gamma\ Q\}
\end{aligned}
$$

and had to complete this

```
(* env -> ccs -> (lab * ccs) list  *)
fun steps env Stop              = []
  | steps env (Var X)           = steps env (env X)
  | steps env (Pre (u,P))       = ...
  | steps env (Chc (P,Q))       = (steps env P) @ (steps env Q)
  | steps env (Par (P,Q))       = (map (fn (a,G) => (a,Par(G,Q)))
                                       (steps env P))@ ...
```

What the students practice #3: They investigate concurrency phenomena

Exercise 136. Consider the following set of recursive equations Γ.

$$
\begin{aligned}
Fork1 &= getF1?.putF1?.Fork1 \\
Fork2 &= getF2?.putF2?.Fork2 \\
Fork3 &= getF3?.putF3?.Fork3
\end{aligned}
$$

$$
\begin{aligned}
PhilA &= getF1!.getF2!.eat!.putF1!.putF2!.think!.PhilA \\
PhilB &= getF2!.getF3!.eat!.putF2!.putF3!.think!.PhilB \\
PhilC &= getF3!.getF1!.eat!.putF3!.putF1!.think!.PhilC
\end{aligned}
$$

Use *Google* to learn about the "dining philosophers". Explore

$$Reach([\![\, (Fork1 \mid PhilA \mid Fork2 \mid PhilB \mid Fork3 \mid PhilC \,]\!]_\Gamma) \setminus H$$

where H contains all actions except $eat!$, $eat?$, $think!$ and $think?$. After which trace will the philosophers have to starve.

with their own implementation!

What is the effect of all this?

- Concurrency basics integrated in very first Bachelor course
- Smooth integration, overall flavor is kept

  Computer science as executable mathematics
- First major programming exercise is about concurrency semantics
- Success ratio unchanged wrt. earlier editions
- Quite succesful
  - Positive evaluation from students
  - Positive feedback from colleagues

➡ Department decided to revise the Bachelor curriculum, to devote a complete mandatory course to concurrency

Revised CS Bachelor: Mandatory courses

- Math for Computer Scientists 1, 2, 3 (9 CP each)
  - unchanged
- Programming 1 (9 CP)
  - unchanged
- Programming 2 (9 CP)
  - OO and Software Architecture, now Java
- Software Practice Lab (9 instead of 14 CP)
  - streamlined
- System Architecture (9 CP)
  - unchanged
- Information Systems (6 instead of 9 CP)
  - shortened
- Algorithms and Data Structures (6 CP)
  - stripped out of Programming 2
- **Concurrent Programming (6 CP)**
  - **new course**
- Theoretical Computer Science (9 CP)
  - unchanged

New mandatory course: Concurrent computation

- Concurrency as a concept
  - Potential Parallelism
  - Actual Parallelism
  - Conceptual Parallelism
- Concurrency in practice
  - Object orientation
  - Operating Systems
  - Multi-core processors, coprocessors
  - Programmed Parallelism
  - Distributed Systems (client-server, peer-2-peer, data bases, Internet)
  - Business Processes
- The Difficulty of Concurrency
  - Conflicting ressources
  - Fairness
  - Mutual exclusion
  - Deadlock, Livelock, Starvation
- Basics of Concurrency Modelling
  - Sequential Processes
  - States, Events, and Transitions
  - Transition systems
  - Observable Behaviour
  - Determinism vs. Non-Determinism
  - Algebras and Operators
- CCS: calculus of communicating systems
  - Sequencing, Choice, Recursion
  - Concurrency and interaction
  - Structural operational semantics
  - Equality of observations
  - Implementation relations
  - CCS and data transfer
- True concurrency models
  - Petri nets
  - Partial orders
  - Event structures
  - CCS and true concurrency
  - Other formalisms: MSCs, Statecharts
- Concurrent Hardware
  - Transaction Level Modelling
  - threads, locks, notify, wait.
  - System C Realisation
- Programming of Concurrency
  - Java vs. C++
  - Objects in Java
  - Sockets, protocols, and data streams
  - Shared Objects and Threads in Java
  - Monitors and Semaphoren
- Analysis and Programming support