Concurrency Theory

Lecture 1: Introduction

Joost-Pieter Katoen   Thomas Noll

Lehrstuhl für Informatik 2
(Software Modeling and Verification)

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http://www-i2.informatik.rwth-aachen.de/i2/ct13/

Winter Semester 2013/14

Outline

People

- Lectures:
  - Joost-Pieter Katoen (katoen@cs.rwth-aachen.de)
  - Thomas Noll (noll@cs.rwth-aachen.de)
- Exercise classes:
  - Benjamin Kaminski (Benjamin.Kaminski@rwth-aachen.de)
  - Stephen Wu (Hao.Wu@cs.rwth-aachen.de)
- Student assistant:
  - Christoph Matheja (christoph.matheja@rwth-aachen.de)

Target Audience

- Master program Informatik
  - Theoretische Informatik
- Master program Software Systems Engineering
  - Theoretical CS

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- In general:
  - interest in formal models for concurrent (software) systems
  - application of mathematical modelling and reasoning methods
- Expected: basic knowledge in
  - essential concepts of operating systems and system software
  - formal languages and automata theory
  - mathematical logic

Course Objectives

Objectives

- Understand the foundations of concurrent systems
- Model (and compare) concurrent systems in a rigorous manner
- Understand the main semantical underpinnings of concurrency

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  - "Programming Concurrent Systems"
  - synchronization, scheduling, semaphores, ...

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- Verifying functional correctness properties
  - "Model Checking"
  - validation of mutual exclusion, fairness, no deadlocks, ...

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  - "Programming Concurrent Systems"
  - synchronization, scheduling, semaphores, ...
- Verifying functional correctness properties
  - "Model Checking"
  - validation of mutual exclusion, fairness, no deadlocks, ...
- Comparing expressivity of models of concurrency
  - "interleaving" vs. "true concurrency"
  - equivalence, refinement, abstraction, ...

Organization

- Schedule:
  - Lecture Wed 10:15–11:45 AH 2 (starting 16 Oct)
  - Lecture Thu 14:15–15:45 AH 1 (starting 17 Oct)
  - Exercise class Tue 12:15–13:45 AH 6 (starting 29 Oct)
- Irregular lecture dates – checkout web page!

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  - submission by 29 Oct before exercise class
  - presentation on 29 Oct
- Work on assignments in groups of three

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- Work on assignments in groups of three
- Examination (6 ECTS credits):
  - oral or written (depending on number of participants)
  - date to be fixed
- Admission requires at least 50% of the points in the exercises
- Solutions to exercises and exam in English or German

Outline

Concurrency and Interaction by Example

Observation: concurrency introduces new phenomena

Example 1.1

$$x := 0;$$
$$(x := x + 1 \parallel x := x + 2)$$

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- At first glance: x is assigned 3

Concurrency and Interaction by Example

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$$\begin{array}{c} x := 0; \\ (x := x + 1 \parallel x := x + 2) \end{array}$$

- At first glance: x is assigned 3
- But: both parallel components could read x before it is written

Observation: concurrency introduces new phenomena

Example 1.1

$$x := 0;$$
$$(x := x + 1 \parallel x := x + 2) \qquad \text{value of } x\text{: } 0$$

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Observation: concurrency introduces new phenomena

Example 1.1

$$\begin{array}{c} x := 0; \\ (x := x+1 \parallel x := x+2) \\ 1 \end{array} \qquad \text{value of } x\text{: } 0$$

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Concurrency and Interaction by Example

Observation: concurrency introduces new phenomena

Example 1.1

$$x := 0;$$
$$(x := x + 1 \parallel x := x + 2) \qquad \text{value of } x\text{: } 2$$
$$2$$

- At first glance: x is assigned 3
- But: both parallel components could read x before it is written
- Thus: x is assigned 2,

Observation: concurrency introduces new phenomena

Example 1.1

$$x := 0;$$
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- Thus: x is assigned 2,

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- Thus: x is assigned 2, 1,

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- But: both parallel components could read x before it is written
- Thus: x is assigned 2, 1, or 3

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$$(x := x + 1 \parallel x := x + 2)$$

- At first glance: x is assigned 3
- But: both parallel components could read x before it is written
- Thus: x is assigned 2, 1, or 3
- If exclusive access to shared memory and atomic execution of assignments guaranteed
  $\Longrightarrow$ only possible outcome: 3

Concurrency and Interaction

The problem arises due to the combination of

- concurrency and
- interaction (here: via shared memory)

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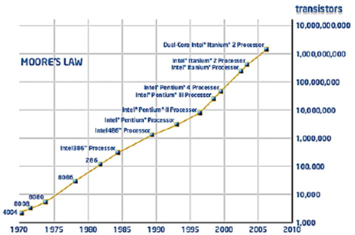
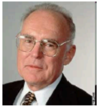
Conclusion

When modelling concurrent systems, the precise description of the mechanisms of both concurrency and interaction is crucially important.

Concurrency Everywhere

- Operating systems
- Embedded/reactive systems:
  - parallelism (at least) between hardware, software, and environment
- High-end parallel hardware infrastructure
  - high-performance computing
- Low-end parallel hardware infrastructure:
  - increasing performance only achievable by parallelism
  - multi-core computers, GPGPUs, FPGAs

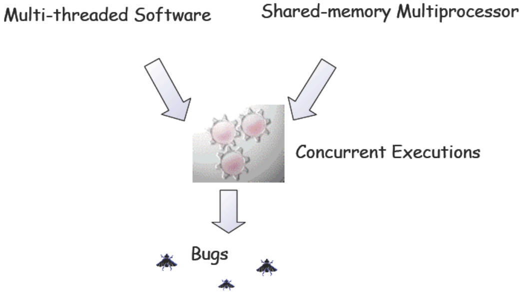




Moore's Law: Transistor density doubles every 2 years

Problems Everywhere

- Operating systems:
  - mutual exclusion
  - fairness
  - no deadlocks, ...
- Embedded systems:
  - safety
  - liveness, ...
- Shared-memory systems:
  - memory models
  - inconsistencies ("sequential consistency" vs. relaxed notions)



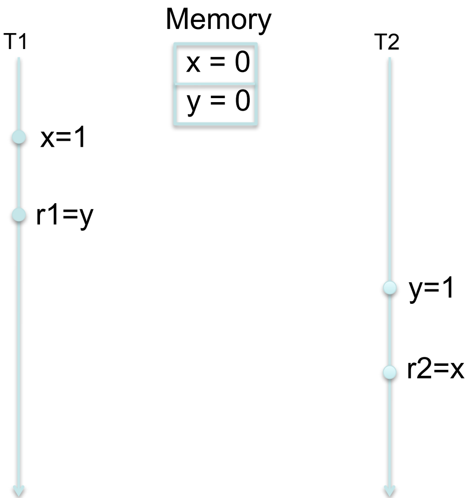
Outline

An illustrative example

Initially: x = y = 0

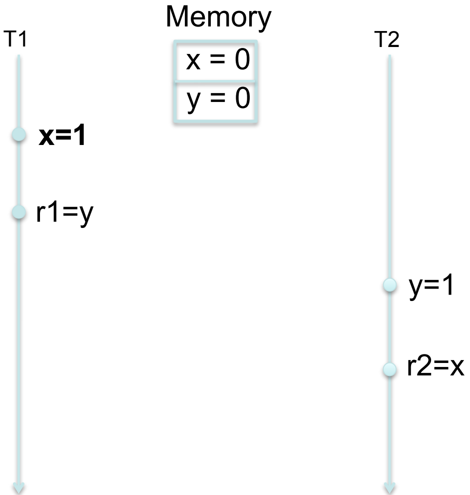
thread1:	thread2:
1: x = 1	3: y = 1
2: r1 = y	4: r2 = x

Sequential Consistency (SC)



Memory Models

Sequential Consistency (SC)



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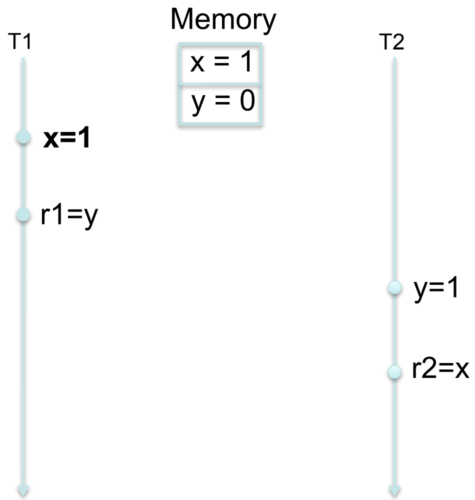

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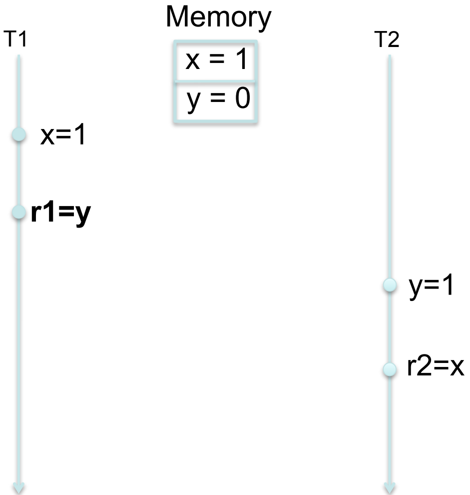

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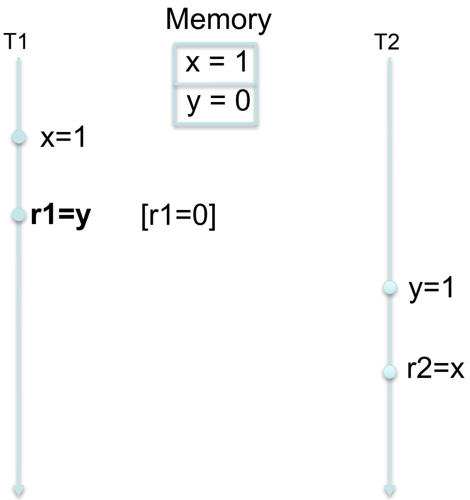

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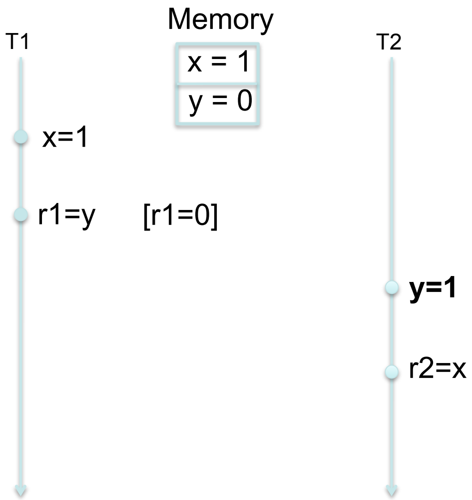

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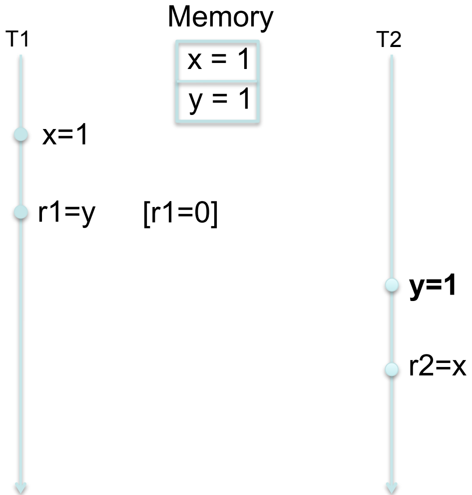

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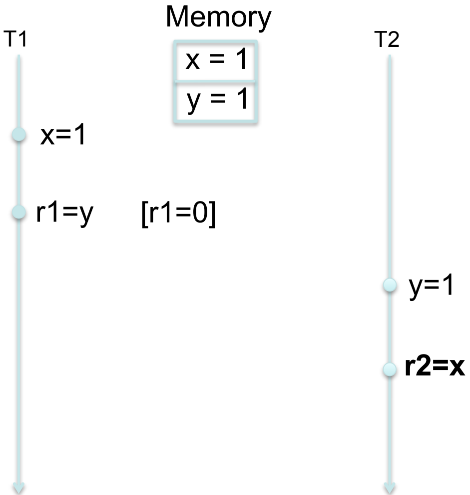

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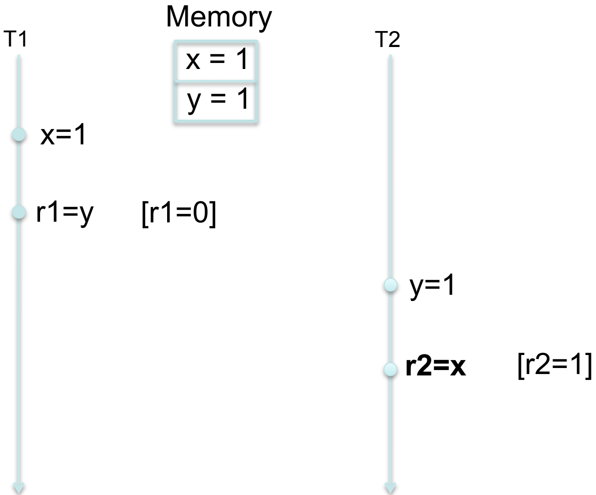

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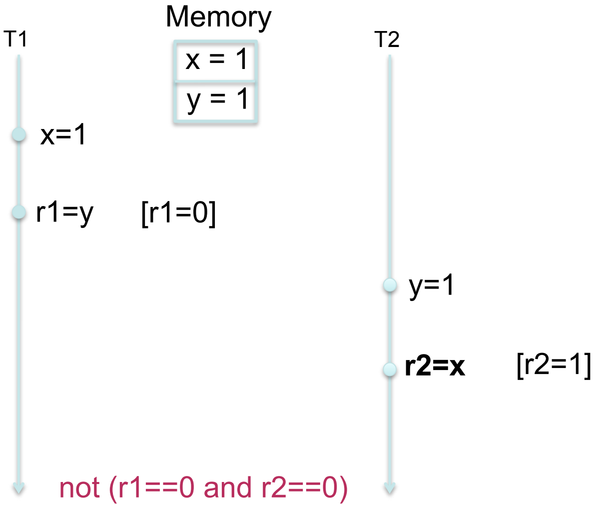
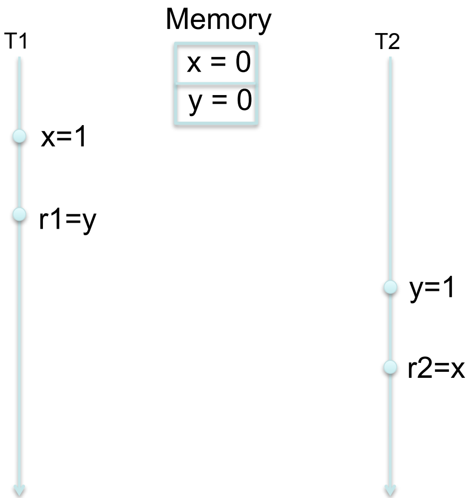


Total Store Ordering (TSO)



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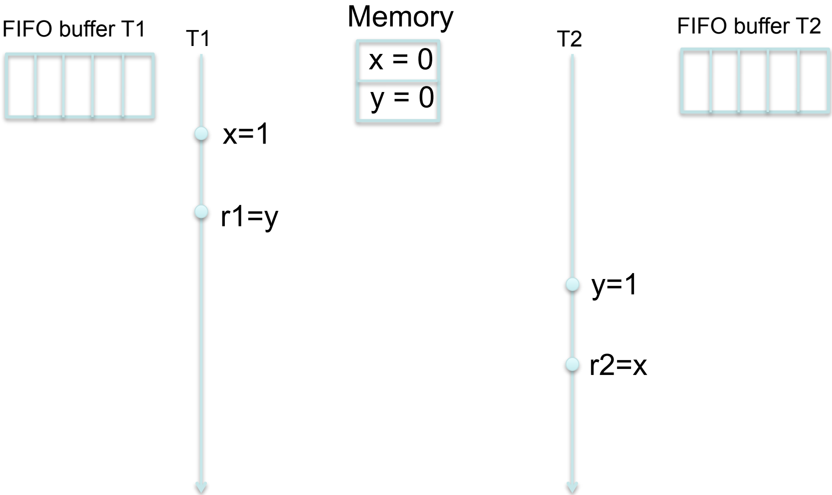

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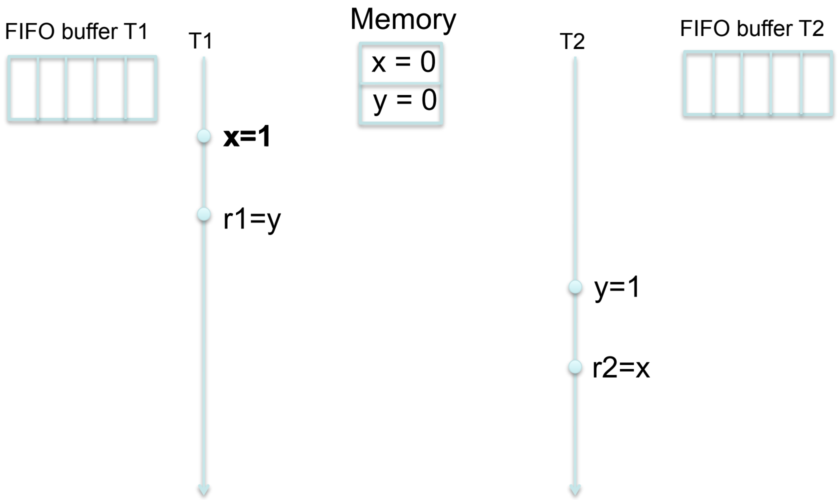

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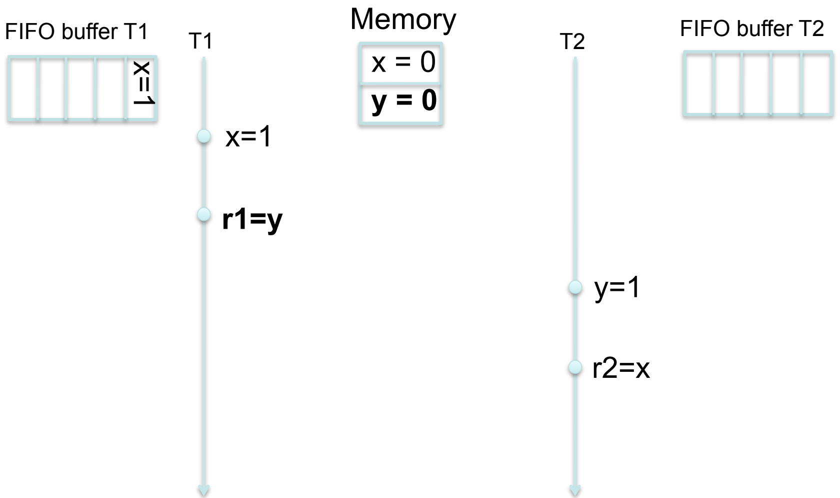

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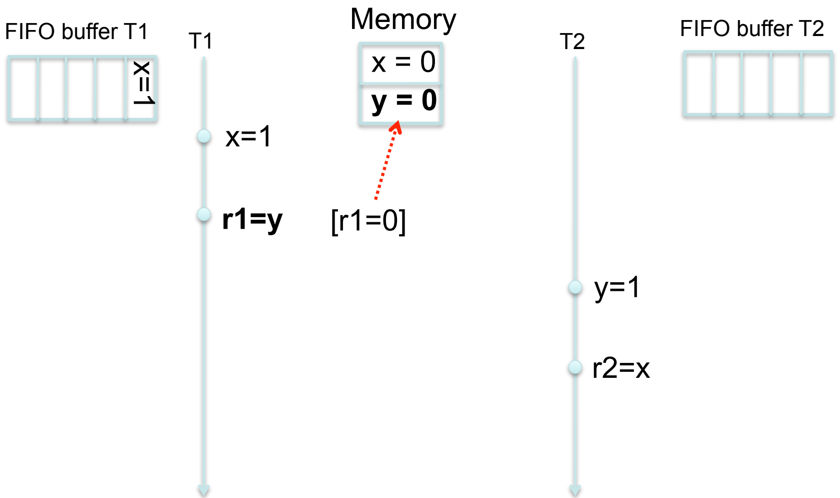

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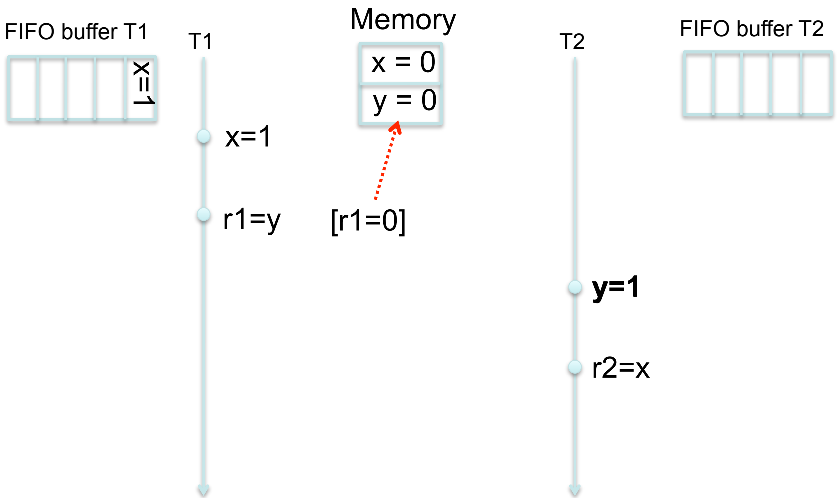

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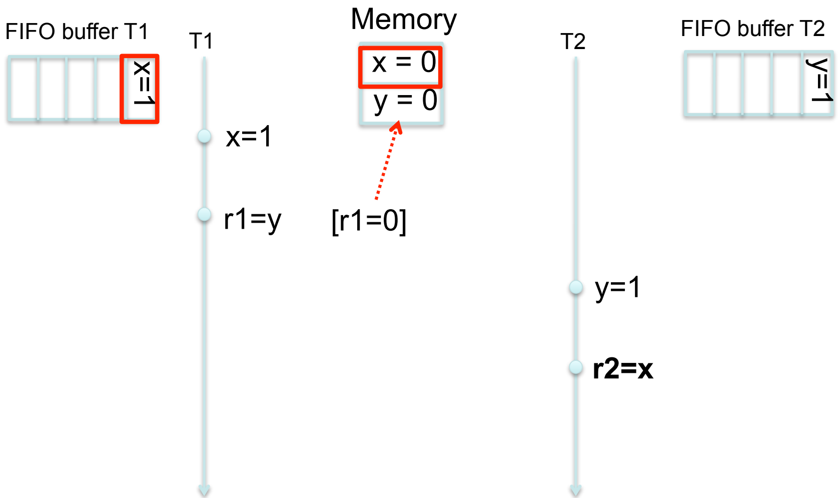

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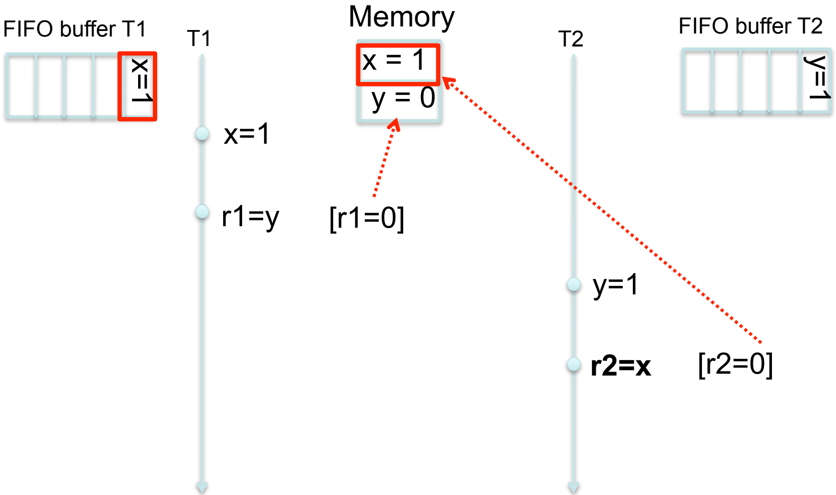

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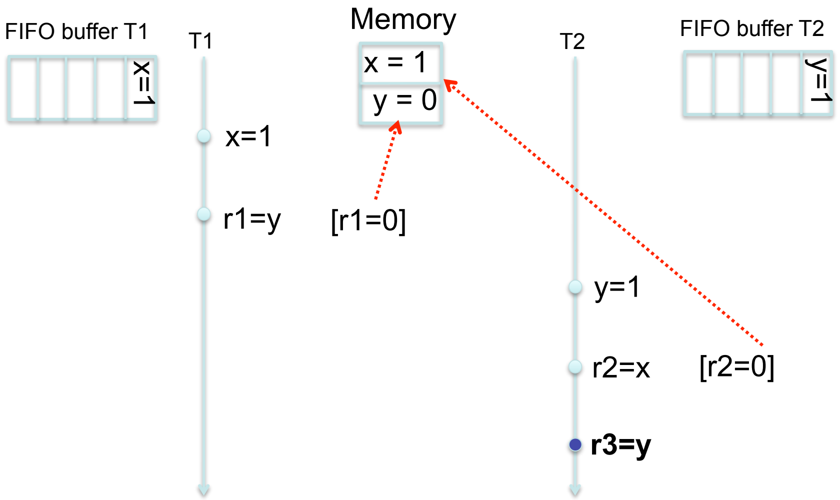

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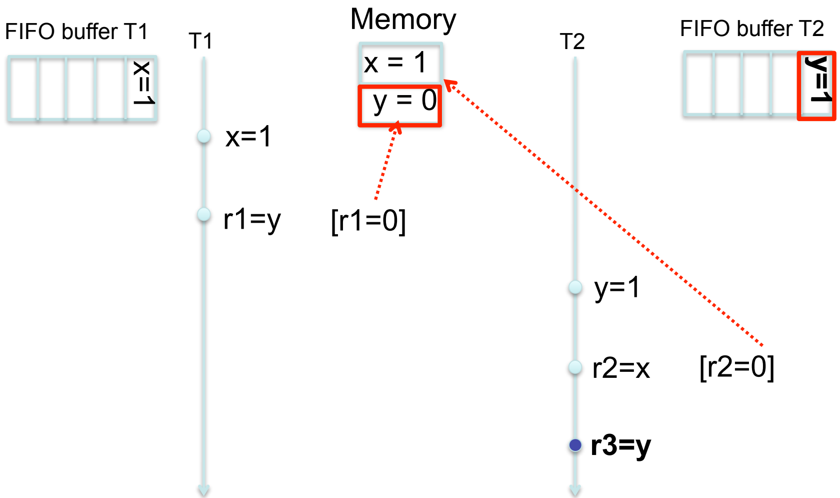

Memory Models

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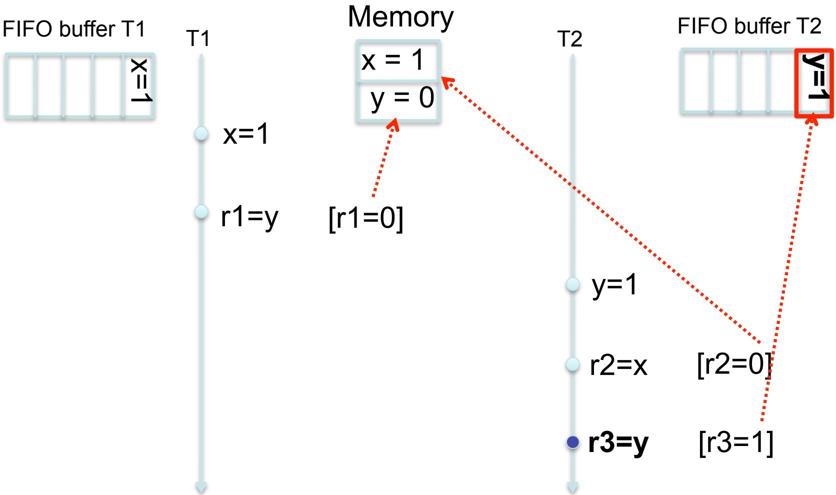

Outline

Reactive Systems I

- Thus: "classical" model for sequential systems

$$\mathit{System} : \mathit{Input} \to \mathit{Output}$$

  (transformational systems) is not adequate

- Missing: aspect of interaction

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$$System : Input \rightarrow Output$$

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- Rather: reactive systems which interact with environment and among themselves

Reactive Systems I

- Thus: "classical" model for sequential systems

$$\mathit{System} : \mathit{Input} \rightarrow \mathit{Output}$$

  (transformational systems) is not adequate
- Missing: aspect of interaction
- Rather: reactive systems which interact with environment and among themselves
- Main interest: not terminating computations but infinite behavior (system maintains ongoing interaction with environment)
- Examples:
  - embedded systems controlling mechanical or electrical devices (planes, cars, home appliances, ...)
  - power plants, production lines, ...

Reactive Systems II

Observation: reactive systems often safety critical

$\Longrightarrow$ correct behavior has to be ensured

- Safety properties: “Nothing bad is going to happen.”
  E.g., “at most one process in the critical section”
- Liveness properties: “Eventually something good will happen.”
  E.g., “every request will finally be answered by the server”
- Fairness properties: “No component will starve to death.”
  E.g., “any process requiring entry to the critical section will eventually be admitted”

Outline

Overview of the Course

1. Introduction and Motivation
2. The "Interleaving" Approach
   - Syntax and semantics of CCS
   - Hennessy-Milner Logic
   - Case study: mutual exclusion
   - Alternative approaches (value passing, CSP, ACP, ...)
3. Equivalence, Refinement and Compositionality
   - Behavioural equivalences ((bi-)simulation)
   - Case study: mutual exclusion
   - (Pre-)congruences and compositional abstraction
   - HML and bisimilarity
4. The "True Concurrency" Approach
   - Petri nets: basic concepts
   - Case study: mutual exclusion
   - Branching processes and net unfoldings
   - Analyzing Petri nets
   - Alternative models (trace languages, event structures, ...)
5. Extensions

Literature

(also see the collection "Handapparat Softwaremodellierung und Verifikation" at the CS Library)

- Fundamental:
  - Luca Aceto, Anna Ingólfsdóttir, Kim Guldstrand Larsen and Jiří Srba: *Reactive Systems: Modelling, Specification and Verification*. Cambridge University Press, 2007.
  - Wolfgang Reisig: *Understanding Petri Nets: Modeling Techniques, Analysis Methods, Case Studies*. Springer Verlag, 2012.
- Supplementary:
  - Maurice Herlihy and Nir Shavit: *The Art of Multiprocessor Programming*. Elsevier, 2008.
  - Jan Bergstra, Alban Ponse and Scott Smolka (Eds.): *Handbook of Process Algebra*. Elsevier, 2001.