technische universität
dortmund

fakultät für informatik
informatik 12

Teaching
Embedded Systems Foundations of Cyber-Physical Systems

A (partially) European view

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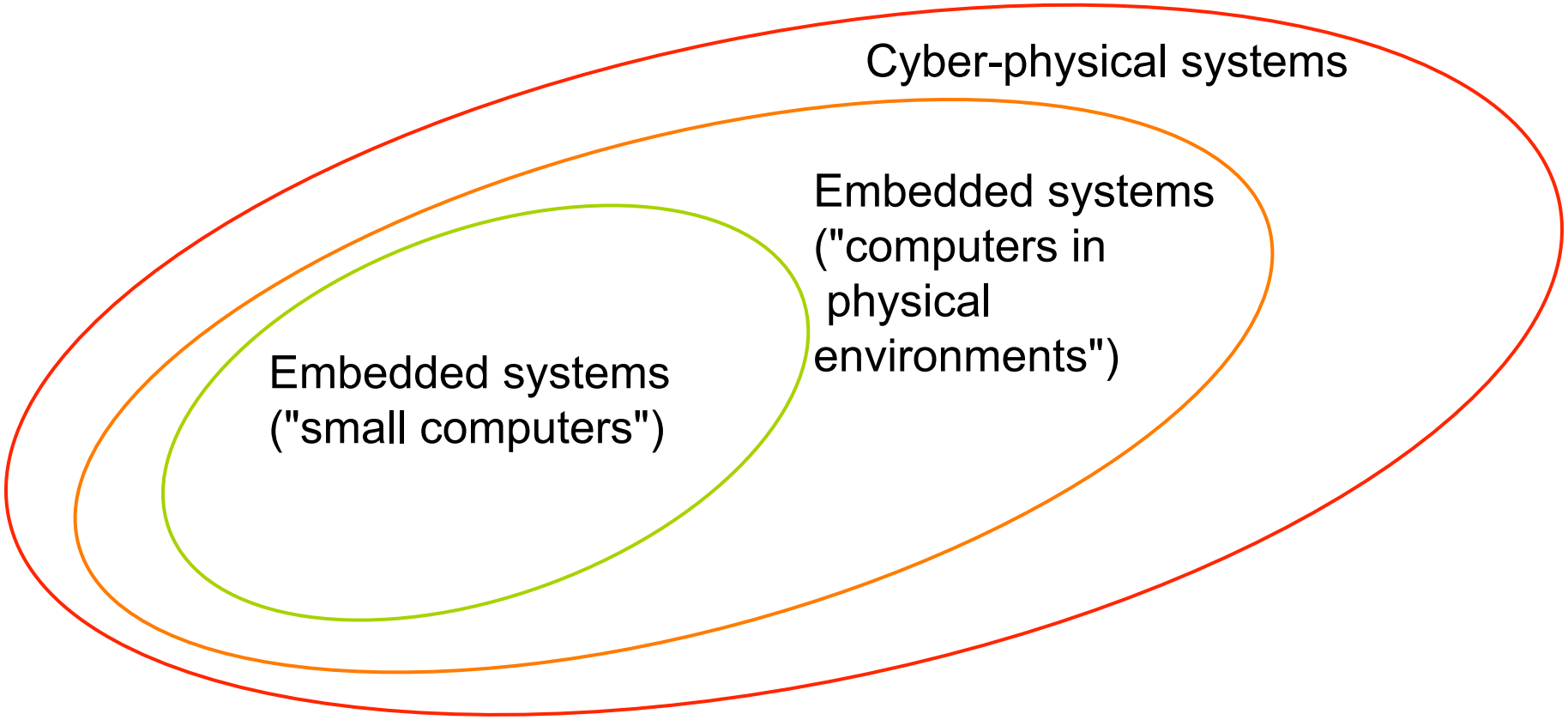
Cyber-physical systems and embedded systems

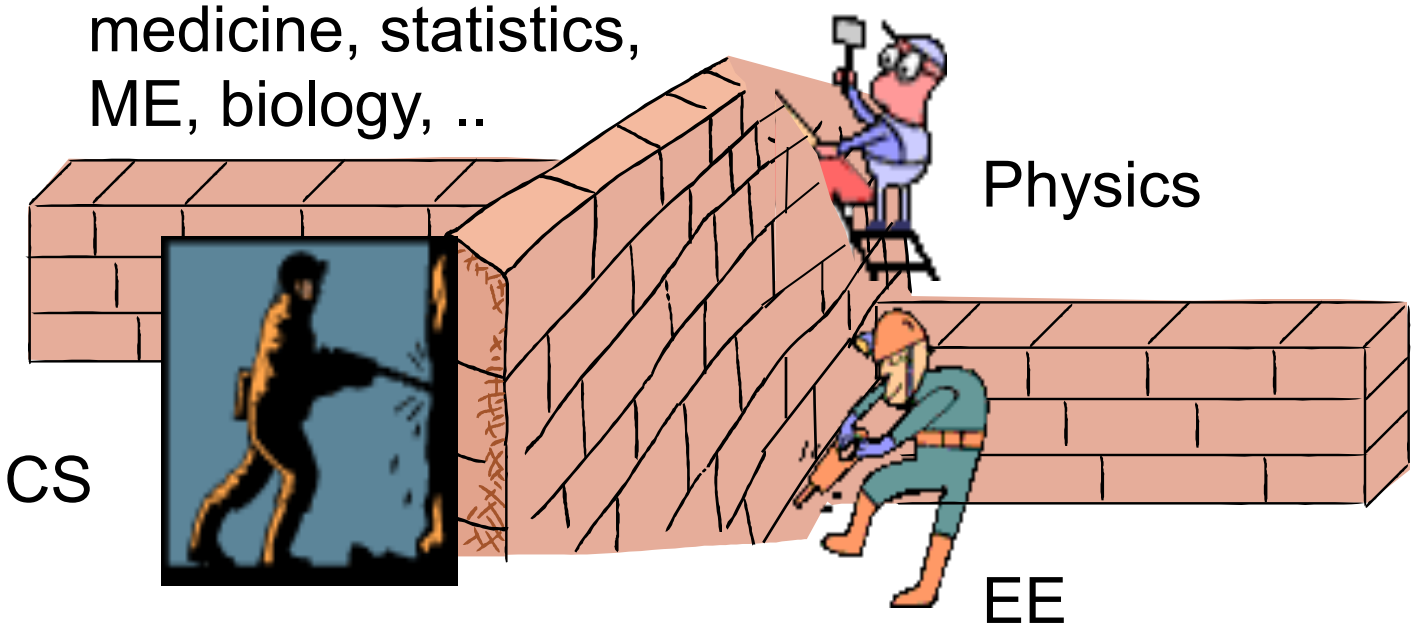
CPS = ES + physical environment



☞ CPS education comprises ES education

Walls between departments must be torn down

Knowledge from many areas must be available,



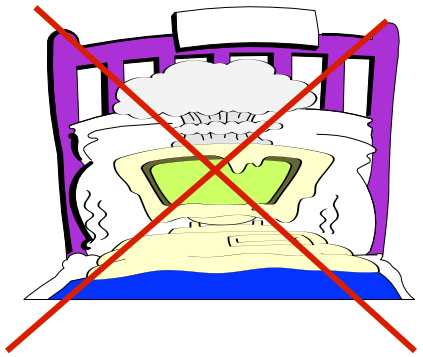
Topics to be taught

Sources include

- ARTIST network of excellence: Guidelines for a Graduate Curriculum on Embedded Software and Systems, http://www.artist-embedded.org/Education/Education.pdf, 2003
- A. Burns, A. Sangiovanni-Vincentelli: Special Issue on Embedded System Education, ACM Trans. Embed. Comput. Syst., August, 2005

CPS topics include

- Embedded systems material
- Physics
- Mechanical engineering
- Control
- Math
- Application areas



Requirements according to the ARTIST guidelines

"It seems that fundamental bases are really difficult to acquire during continuous training if they haven't been initially learned, and we must focus on them."

"The development of ES cannot ignore the underlying HW characteristics. Timing, memory usage, power consumption, and physical failures are important."

$$\int P\,dt$$

Requirements according to the ARTIST guidelines (2)

"The lack of maturity of the domain results in a large variety of industrial practices, often due to cultural habits"

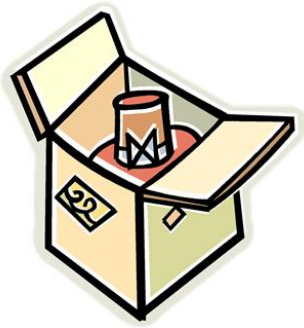
"curricula … concentrate on one technique and do not present a sufficiently wide perspective."

"As a result, industry has difficulty finding adequately trained engineers, fully aware of design choices."

CS, EE or physics specialization vs. separate CPS/ES program

	Specialization	Separate program
Well-known degrees	+	-
Enough headroom for teaching integrated CPS/ES material	-	+
Headroom for more depth in physics, mechanical engineering, ..	-	+
Effort for introduction	small	large
No. of faculty members required	moderate	larger
Building community?	difficult	easier
Is it feasible?	For ES ok, for CPS questionable	Yes, but there are also constraints

Outline



- Scope
- Requirements for CPS/ES education
  - Linking separate disciplines
  - Artist sources: focus on fundamentals, HW, wide perspective
- ES/CPS education at Dortmund
  - ES/CPS content, context
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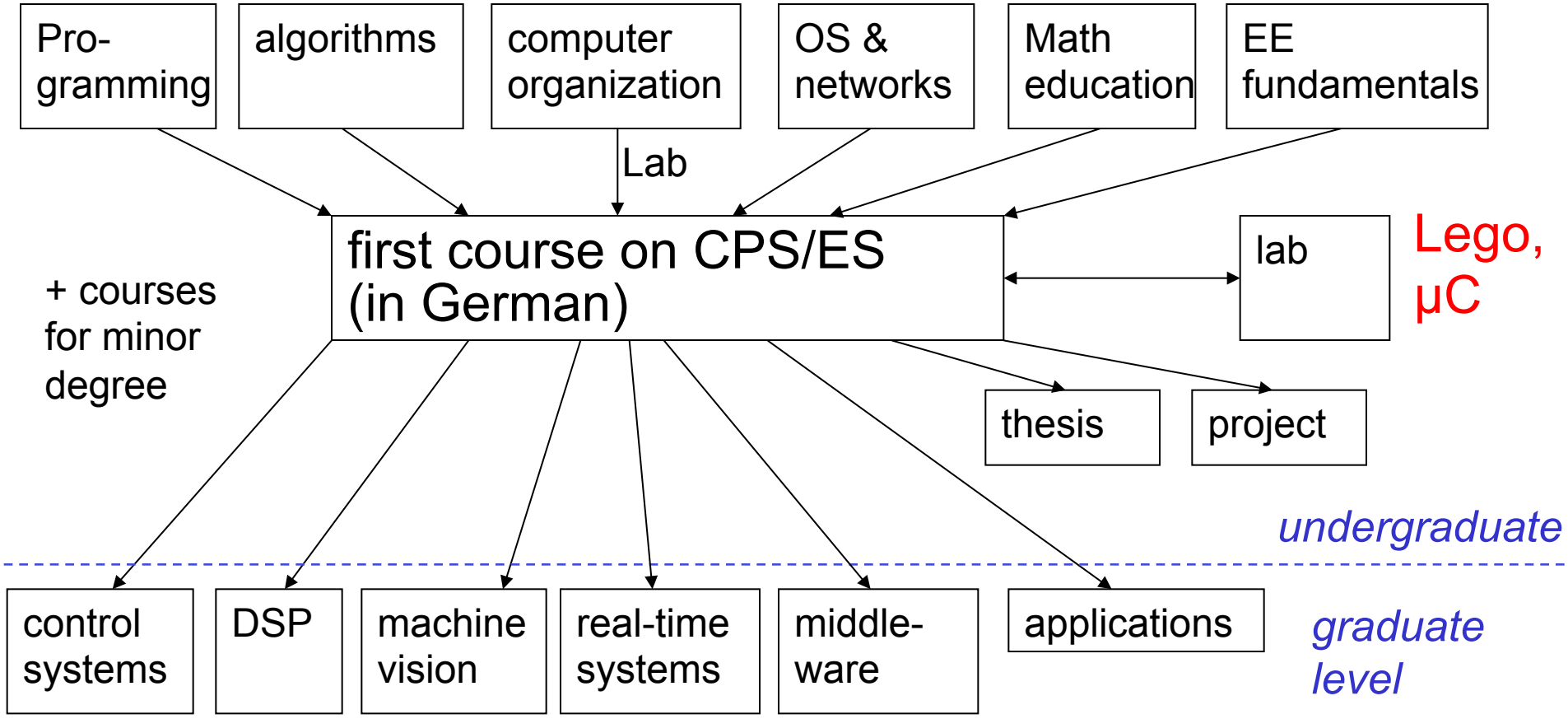
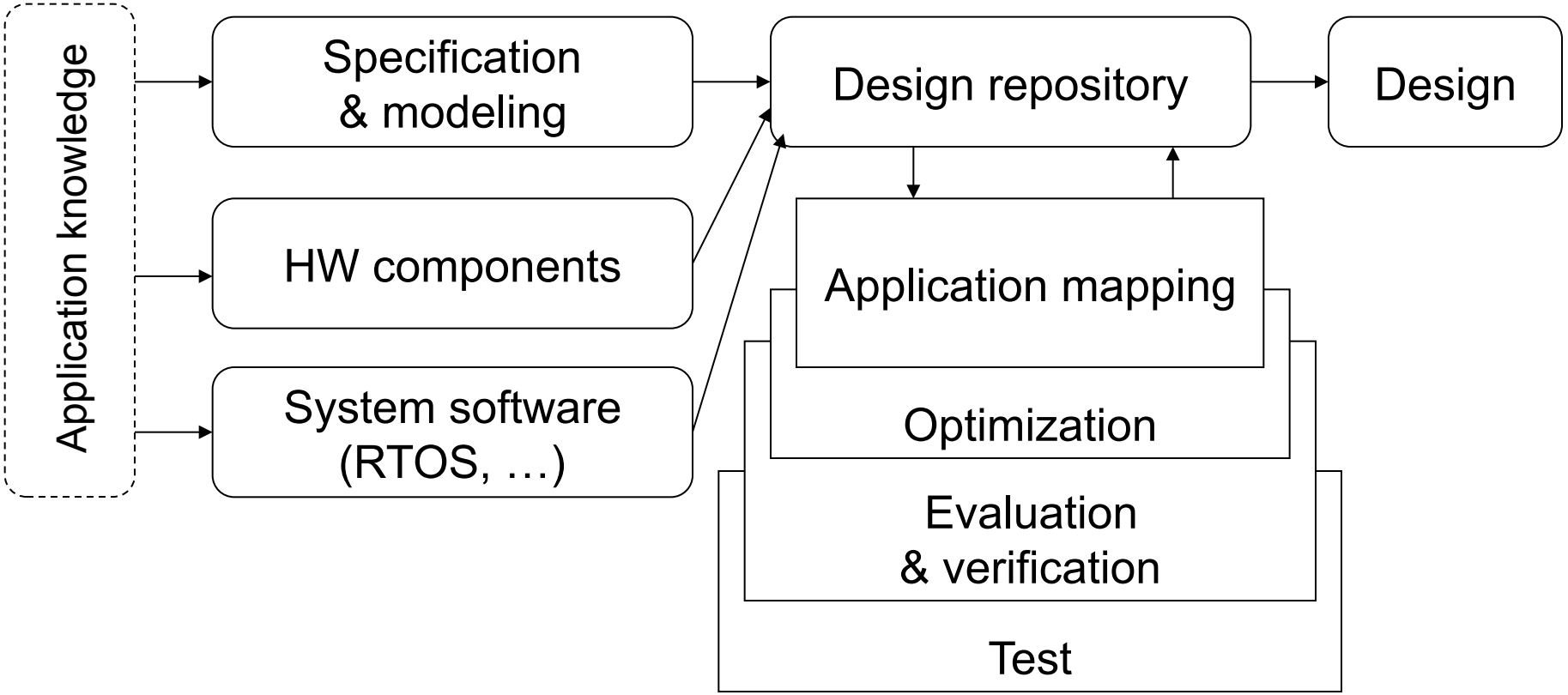
CPS/ES CS undergraduate education at TU Dortmund

- Integrated as a specialization into CS curriculum



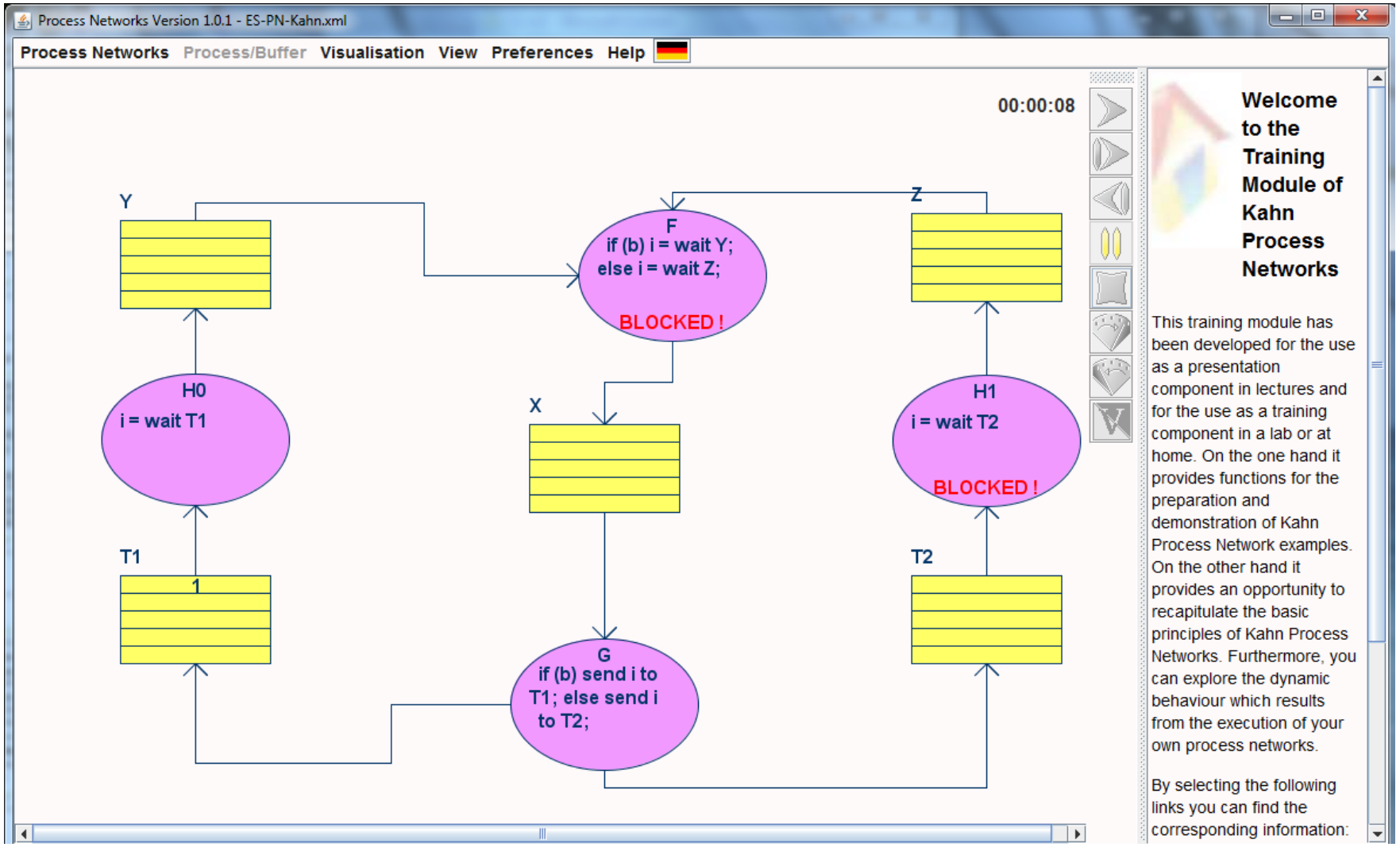
Course content



Example: Specification and modeling

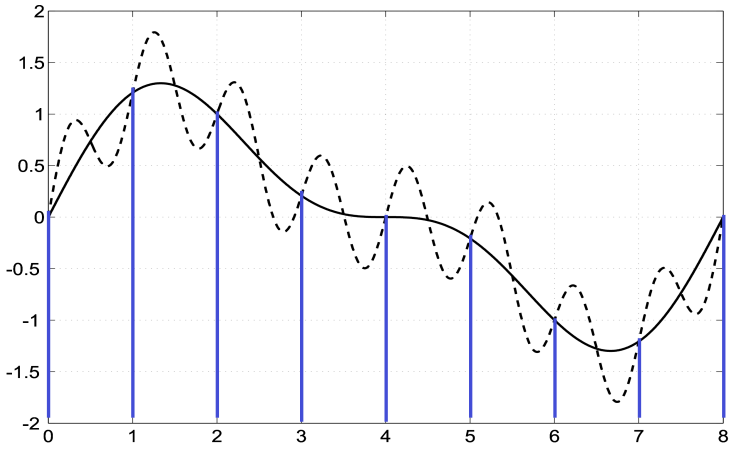
- Requirements, Models of computation
- Early design phases
  - Use cases, sequence charts
- Communicating finite state machines
  - Timed automata, StateCharts, synchronous languages
  - SDL (as an example of message passing)
- Data flow
  - KPN, synchronous data flow
- Petri nets
- Discrete event based languages
  - VHDL simulation cycle
- Von-Neumann languages
- Levels of hardware modeling, comparison of MoCs

KPN simulation



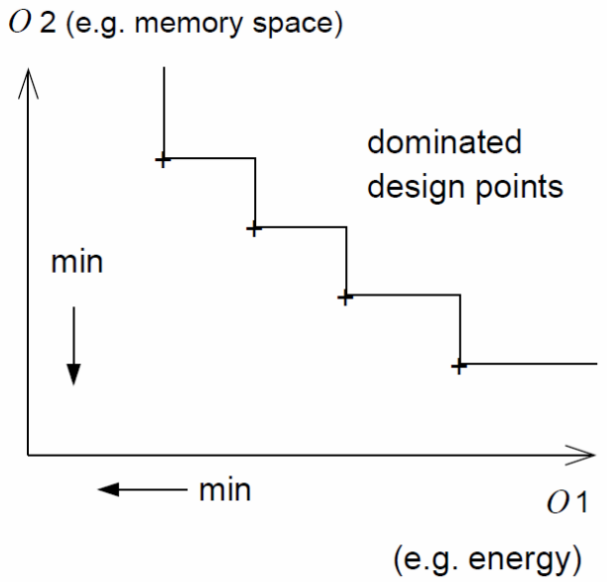
Example: CPS/ES hardware

- Input:
  - Sensors, discretization
- Processing
  - Processors, FPGAs
- Memories
- Communication
  - Requirements
  - Exemplary implementation: Guaranteeing real-time behavior
- Output
  - D/A-converters
  - Sampling theorem
- Secure hardware (brief)



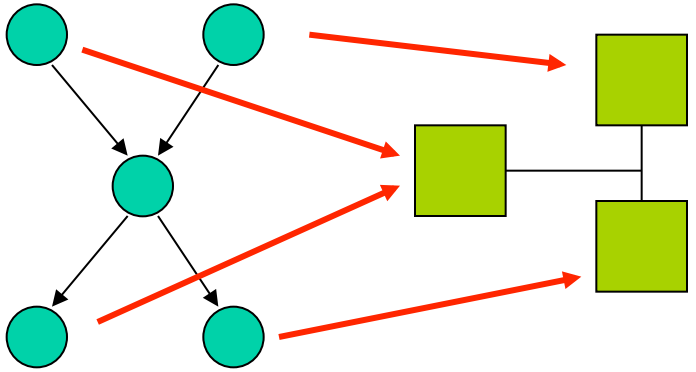
Example: Evaluation and Validation

- Multi-objective optimization, Pareto optimality
- Performance evaluation
  - Early phases
  - WCET estimation, real-time calculus
- Energy and power models
- Thermal models
- Risk- and dependability analysis
- Simulation
- Rapid prototyping and emulation
- Formal verification (brief)



Example: Mapping to execution platforms

- Scheduling in real-time systems
  - Aperiodic scheduling
  - Periodic scheduling
- Hardware/software partitioning
- Mapping to heterogeneous multi-processors
  - DOL



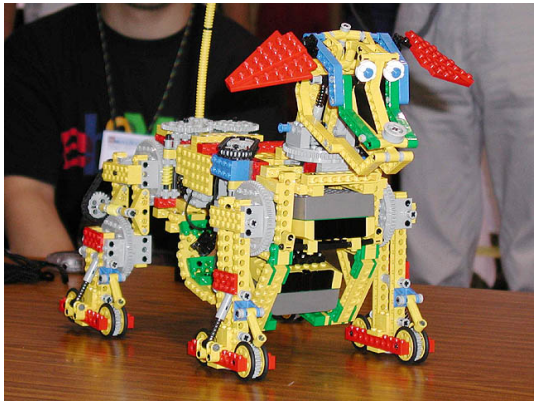
Structure of the CS curriculum at Dortmund
- 3 year bachelor program -

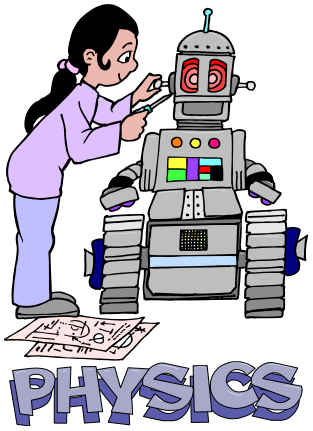
Term				
1	Computer organization		Programming & semantics	Math education
2	Circuits & communication	OS	Algorithms	
3	HW lab	Networks	SW lab	
4		Databases	…	
5	Embedded systems fundamentals	Software engineering	…	
6	Bachelor project + Thesis	…	…	

All dependences met

Additional teaching elements

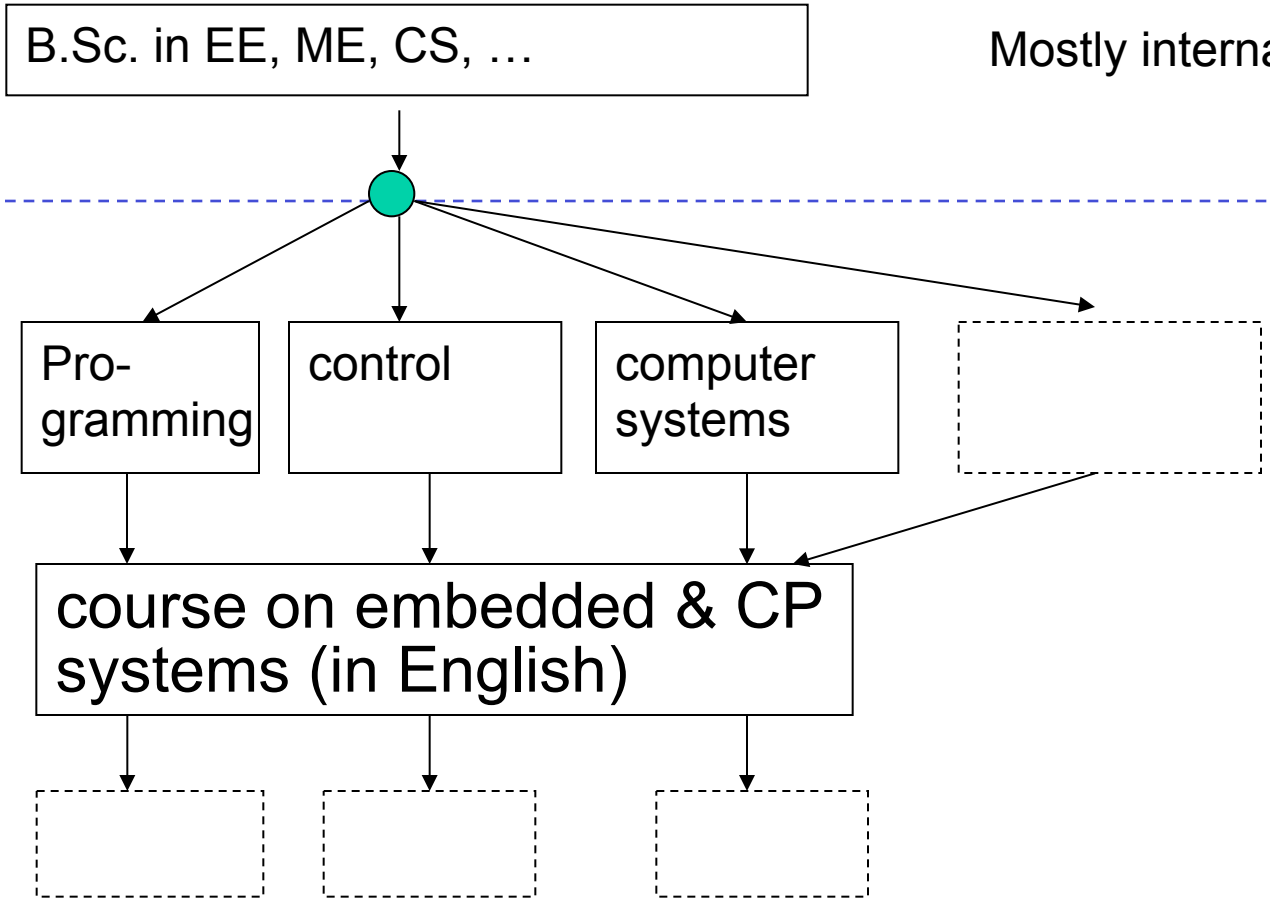
- Lab & assignments during course (hierarchical state machines, Mindstorms, scheduling examples)
- Project, optionally in this area
- Bachelor thesis, optionally in this area, optionally in industry
- Courses at the graduate level
  - Software of ubiquitous systems
  - Evaluation
  - ….





CPS/ES robotics and automation graduate education at TU Dortmund

- Specialization of robotics & automation program



Experience

- Content of courses is broad and comprehensive
- Extremely popular among students (>100 students @ undergraduate, ~20 students @ graduate course)
- Welcome by local employers
- Limited headroom for advanced topics for undergraduates
- Students sometimes ask for more hands-on experience, but there are tight constraints for this
- No major problems for comprehension (missing prerequisites turned into textbook appendix)
- Heterogeneity of students in robotics program a hurdle
- **ES education as a specialization works, but has inherent limitations**

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Textbook(s)

Several editions/translations:

- 1st edition
  - English
    - Original hardcover version
    - Reprint, soft cover, 2006
  - German, 2007
  - Chinese, 2006
  - Macedonian, 2010
- 2nd edition, with CPS
  - English, Dec. 2010/Jan. 2011
  - Contracts for German and (translated) Chinese edition

Book & slides

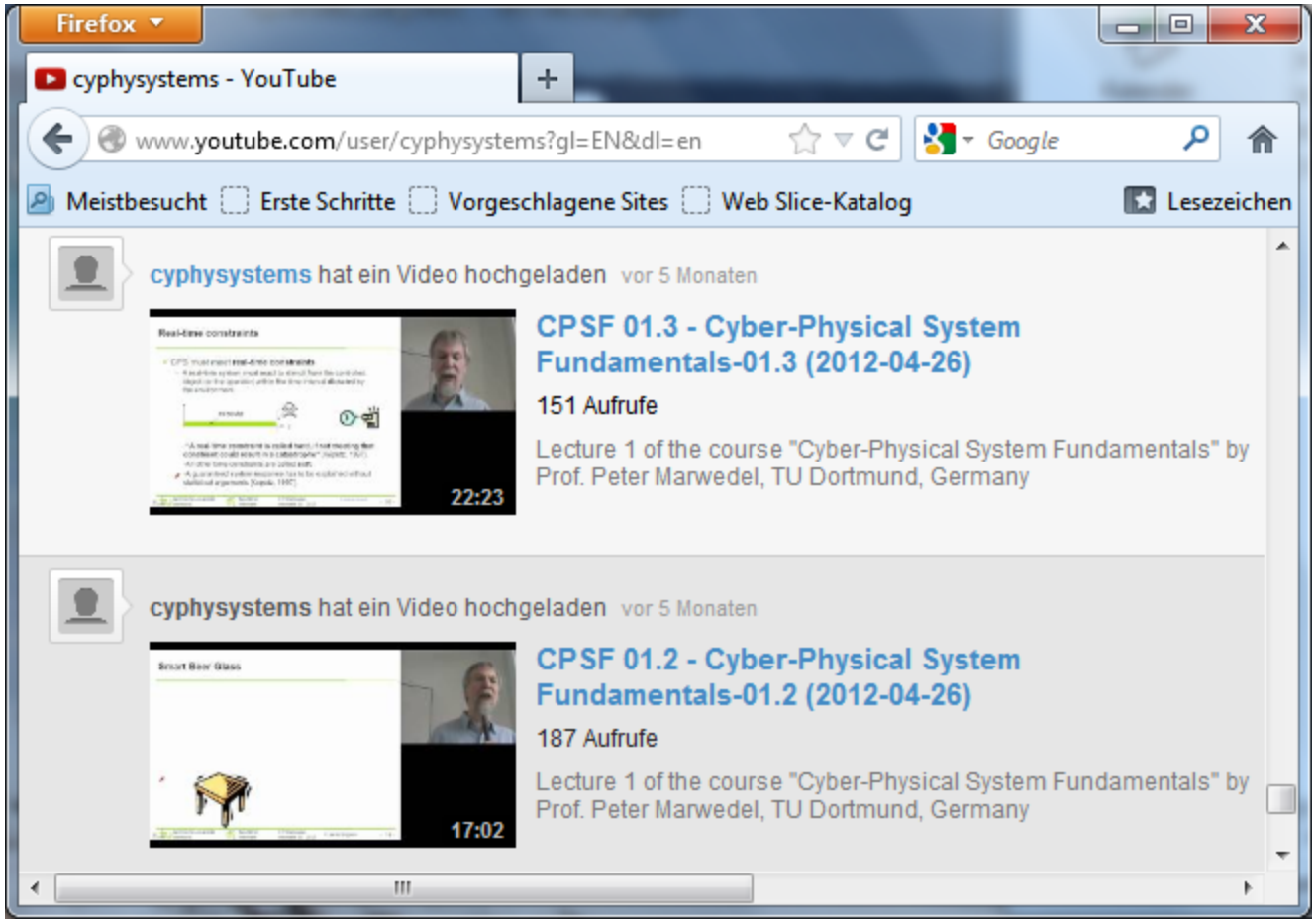
- Courseware available via //ls12-www.cs.tu-dortmund.de/~marwedel (click on Embedded Systems Textbook)

Language	First Edition (first printing)	First Edition (second printing)	Second Edition
English	Kluwer 2003 Downloads	Springer 2006 Downloads	Springer 2011 Downloads
German	Springer 2007 Downloads	Springer 2007 Downloads	(in preparation)
Chinese 中文	Science Publishers 2007 Downloads 勘误表		(in preparation)
Macedonian македонски јазик	Ad Verbum АД ВЕРБУМ 2010		

DOWNLOADS: SLIDES, REFERENCES, ASSIGNM

- Youtube videos: http://www.youtube.com/user/cyphysystems
- Slides (summer term 2012)
- Slides, references and assignments (winter term 2011/12)
- Slides, references and assignments (winter term 2010/11)

Recorded lectures available on youtube



http://www.youtube.com/user/cyphysystems

Example

Why not use von-Neumann (thread-based) computing (C, C++, Java, ...) ?

Potential race conditions (☞inconsistent results possible)
☞ Critical sections = sections at which exclusive access to resource *r* (e.g. shared memory) must be guaranteed.

```
thread a {
  ..
  P(S)  //obtain lock
  ..    // critical section
  V(S)  //release lock
}
```

```
thread b {
  ..
  P(S)  //obtain lock
  ..    // critical section
  V(S)  //release lock
}
```

Race-free access to shared memory protected by S possible

This model may be supported by:
- mutual exclusion for critical sections
- special memory properties

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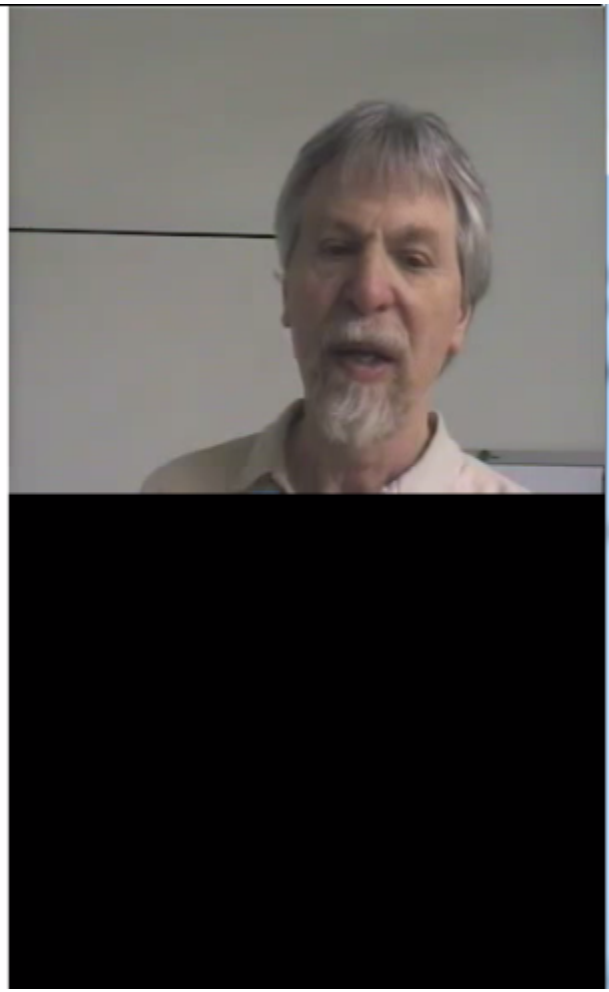

Selected set of universities using the book

- University of California, San Diego (Tajana Šimunic Rosing)
- Lund Institute of Technology, Sweden (Krzysztof Kuchcinski)
- Universidad De Las Palmas De Gran Canaria (Nunez)
- Politecnico Di Milano (Christina Silvano)
- University of Cyprus (Theocharis Theocharides)
- University of Linköping, Schweden (Petru Eles)
- University of Saskatchewan, Canada (A. Dinh & D. Teng)
- Democritus University of Thrace, Greece (Dimitrios Soudris)
- KIT - Karlsruhe Institute of Technology (J. Henkel)
- TU Berlin (Glesner, Pockrandt)
- TU Braunschweig (Rolf Ernst)
- University of Augsburg (Alexander Knapp)
- University of Kiel (Reinhard von Hanxleden)
- University of Leipzig (Martin Bogdan)
- Hochschule Rhein-Main (Marcus Thoss)
- University of Buenos Aires (Andrés Djordjalian)
- University of Stuttgart (Martin Radetzki)
- University of Tübingen (Lange Tafaj)
- University of Lübeck (Erik Maehle)
- University of Torino (Luciano Lavagno)
- Colorado State University (Sudeep Pasricha)
- Johannes Kepler University, Linz (Alois Ferscha)
- Ruprecht-Karls-University Heidelberg (Udo Kepschull)
- Federal University of Santa Catarina, Brazil (Antônio Augusto Fröhlich)
- Lucian Blaga University, Romania (Macarie Breazu)
- …..

Sometimes at the graduate level

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The Artist Network of Excellence

- Goal: Establish links between top researchers from various domains
- http://www.artist-embedded.org
- Web site a key reference for finding researchers highly qualified research within Europe
- Members agree that establishing links was the key benefit
- Several efforts on education, see http://www.artist-embedded.org/artist/-Education,839-.html

EMSIG, the successor to Artist

- Goals: leverage experiences gained in the Artist network & stimulate future cooperation
- Legally a special interest group of EDAA (the lead organizer of DATE)
- see http://emsig.embedded-systems-portal.org

Artist Summer Schools

Summer schools (//www.artist-embedded.org/artist/-Schools-and-Seminars,59-.html) are crossing the boundaries between disciplines. They were held at

- Europe
- Latin America
- Asia (China)
- Africa (1)

Rabat, Morocco

Continued in cooperation between EMSIG and Nano-Tera (Swiss project), see //artist-summer-school.epfl.ch/, areas:

- Component-based design, efficient computing for CPS, many-core design case, switched network in safety critical systems, medical cyber-physical systems, verification

WESE: Workshop on Embedded (and Cyber-Physical) Systems Education:

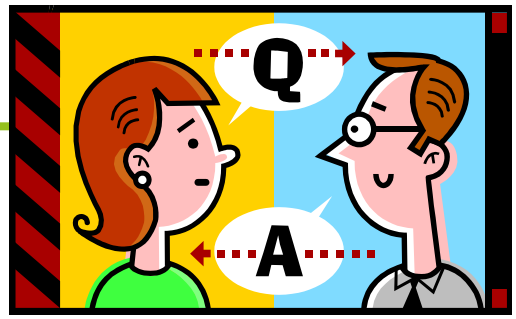
- 1st WESE 2005: Jersey City, US, see //www.lulu.com
- 2nd WESE 2006: Seoul, Korea, see //www.lulu.com
- 3nd WESE 2007: Salzburg, Austria, see //www.lulu.com
- 4th WESE 2008: Atlanta, see //www.lulu.com
- 5th WESE 2009: Grenoble, see ACM digital library
- 6th WESE 2010: Scottsdale, see ACM digital library
- 7th WESE 2011: Taipei, see ACM digital library
- 8th WESE 2012: to take place during ESWEEK at Tampere on Oct. 12th, ACM digital library
- 9th WESE 2013: Montreal, Canada, 10/3/2013

Separate programs (samples)

- ALARI @ University of Lugano: master programs (www.alari.ch)
- Joint program of the 3 Dutch Technical Universities (Eindhoven, Twente, Delft): http://www.utwente.nl/master/international/esys/masterprogramme/3tu.doc/
- University of Passau: undergraduate program for mobile and embedded systems, http://www.uni-passau.de/mes.html (in German)
- UPenn (according to info on Monday)
- …

Still open issues for the design of such programs

Summary



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