Software Engineering in Embedded Systems

Stephan Heidinger

Seminar: Software Engineering
Fachbereich für Informatik und Informationssysteme
Universität Konstanz

19. January 2012

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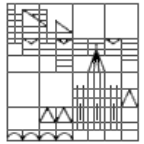
Embedded Systems - What's that? - I
Definition
"An embedded software system is part of a hardware/software system that reacts to events in its environment. The software is 'embedded' in the hardware. Embedded systems are nominaly real-time systems."
Software Engineering, p.561, Edited by Ian Sommerville, Ninth Edition



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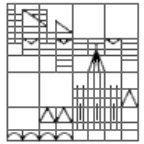

Embedded Systems - What's that? - II

- Embedded Systems: ...
  - ... respond to physical world
  - ... respond in real time ("have a *deadline*")
  - ... often have little resources
  - ... run on special purpose hardware
  - ... run in real-time operating systems

respond to physical world

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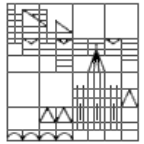
Embedded Systems: ...
...respond to physical world



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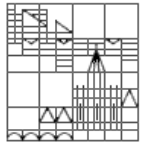
resüpm om real time
("have a deadline") → time in which the result is produced



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i.e. not 'computers'

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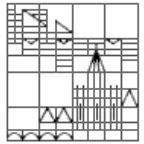

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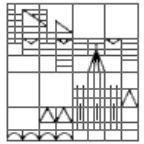

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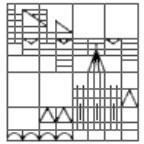

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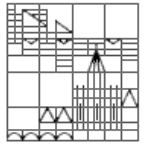
- Examples for Embedded Systems:
  - airbag
  - cell phone / 'modern' phone
  - burglar alarm
  - (fully automatic) coffee machine
  - danger detection
  - ...



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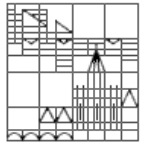
airbag:
strict deadline
catastrophic result on failure

Embedded Systems - What's that? - III
Examples for Embedded Systems:
airbag



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cell phone:
phone must be answered before call quit vom other side

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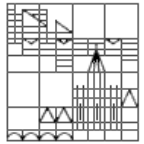

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burglar alarm:

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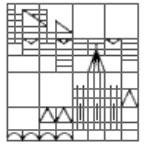

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coffee machine:
dont want to have coffee, when its cold...

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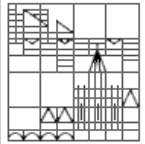

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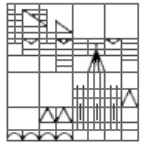
danger detection:
earthquake, toxins, . . .
depending on the kind of danger, absolutely no time to spare.



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One can produce more examples on a whim especially in cars

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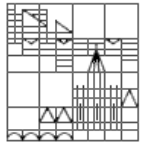

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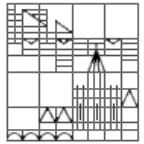
Why embedded sytems



Motivation

- Why embedded systems:
  - Embedded Systems are everywhere!
  - There are probably more Embedded Systems than computers out there!
  - Man, they must be important.
  - There sure is some money in this.

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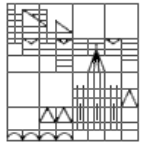

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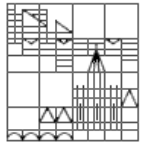

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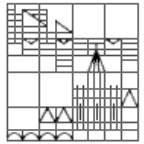

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there sure is some money in this
some money:
C-programing
special skillsand i did an internship
producing an embedded system at PSI
monitoring device for the detector of an particle accelerator

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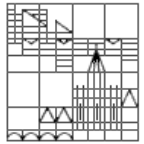

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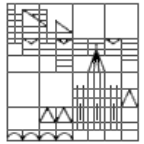

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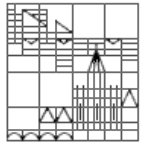
Outline

Embedded Systems Design
Architectural patterns
Timing analysis
Real-time operating systems

this is the structure of my talk:
embedded systems DESIGN
architectural patterns
timing analysis
real-time operating systems



Outline

1 Embedded Systems Design

2 Architectural patterns

3 Timing analysis

4 Real-time operating systems

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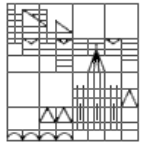
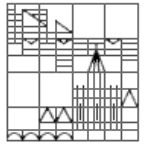
Real-time operating systems



Outline

Problems
Problems in Embedded Systems:
deadlines
environment
continuity
direct hardware interaction
safety & reliability

several problems in emb-systems that are not in “normal” systems



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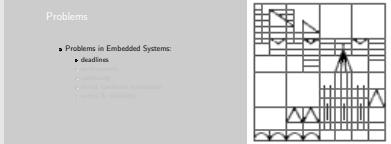


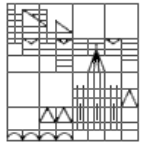
Problems

- Problems in Embedded Systems:
  - deadlines
  - environment
  - continuity
  - direct hardware interaction
  - safety & reliability

deadlines: every process has deadline until result must exist
hard systems: deadline not met, failure
soft system: deadline not met, bad results

Problems
Problems in Embedded Systems:
deadlines
environment
direct hardware interaction
safety & reliability

environment:
is unpredictable
embedded Software $\Rightarrow$ must be concurrent



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Problems
Problems in Embedded Systems:
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environment
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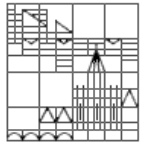
continuity:
embedded Software ⇒ does not normally terminate
software has to be reliable
may need update while operating



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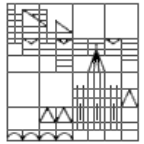
direct hardware interaction:
uncommon hardware (i.e. detonator in airbag)
speed issues (hardware is faster than software)



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Problems
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deadlines
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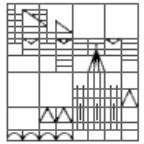
direct hardware interaction
safety & reliability

safety & reliability:
cost of failure high
either economical or in human life



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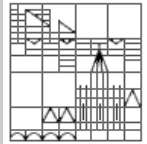
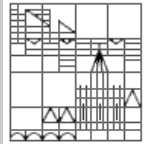
design steps
not all are necessary, but most will be.
no definite order



Embedded Systems Design

- design steps
  - platform selection
  - special purpose hardware
  - stimuli:
    1. periodic stimuli
    2. aperiodic stimuli
  - timing analysis
  - process design
  - algorithm design
  - data design
  - process scheduling

Platform selection:
what hardware?
choice of Real-time operating system (later)
power consumption (mobile device, backup)



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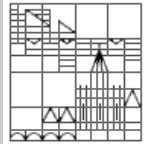
special purpose hardware:
What is to be implemented in software, what in hardware
do we need uncommon hardware?
design special hardware?
replace software by hardware?



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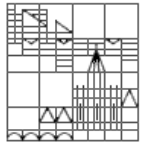
think about **stimuli:**
describe behavior of system by listing received stimuli and reactions
stimuli = signals
often: stimulus *Rightarrow* defined response

example AFTER THIS SLIDE



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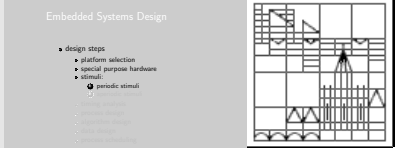

periodic stimuli:
occur at predictable intervals
predefined reaction per stimulus
i.e. polling

Embedded Systems Design

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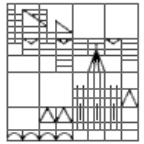
aperiodic stimuli:
occurr irregularly and unpredictably
often interrupts
i.e. alarms, failures, IO operation finished, etc**stimuli list:**
best practice: stimuli list with **all** stimuli.

example AFTER THIS SLIDE



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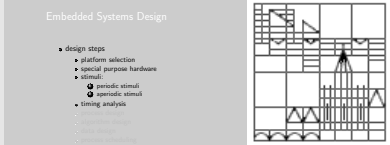

Timing analysis:
For each stimulus and response ⇒ find timing constraints
timing constraints ⇒ deadlines

Embedded Systems Design

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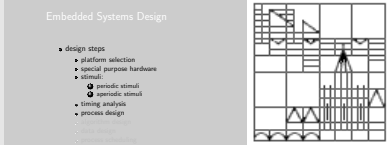

Process design:
aggregate the stimuli & responses into concurrent processes
SEE Architectural patterns

Embedded Systems Design

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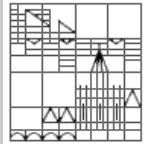
Algorithm design:
For each stimulus & response ⇒ design algorithm
especially important for computationally intensive tasks (signal processing)
Do we need to implement these in hardware? (i.e. control systems)



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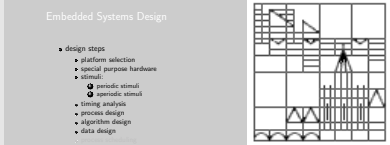

Data design:
How to store data, that will be exchanged
semaphore & critical regions & monitors & ...

circular buffer: producer & consumer may run at different speeds

Embedded Systems Design

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Embedded Systems Design

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  - stimuli:
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  - timing analysis
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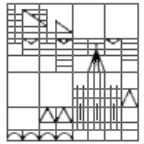
  - process scheduling

Process scheduling:
ensure, that processes meet their deadline

all shown:
not all need to be done, but most probably will
which & order depends on what we design

after this design steps:
make sure system can meet deadlines
static analysis
simulation



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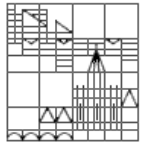
Example: radiation warning system

Now for the examples for stimuli:



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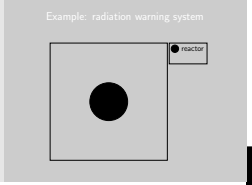
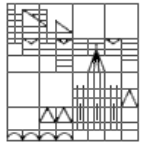


we have this room with an reactor inside



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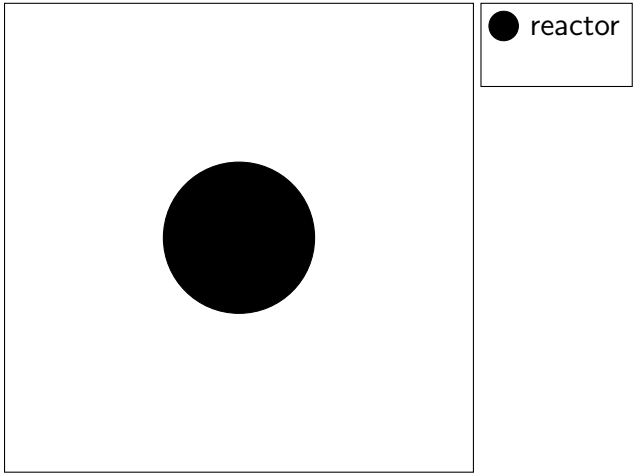
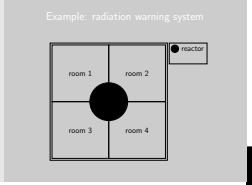
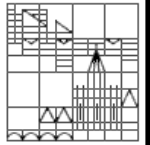




because several people work here, we put several rooms around the reactor

walls are shielded



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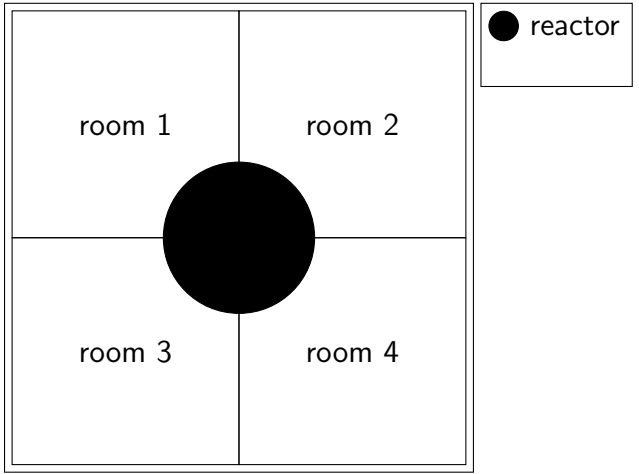
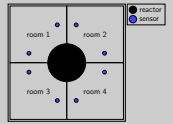
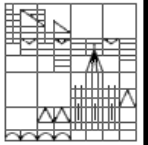




because people work here, we need some sensors to detect radiation leaks



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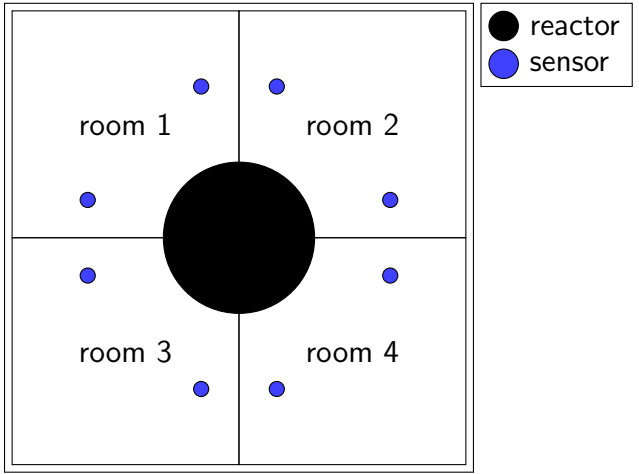
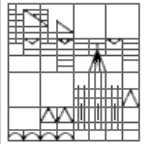


Example: Stimuli-List of a radiation warning system
Stimulus Response

Now we built a list of stimuli and responses



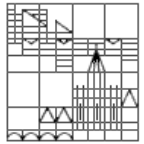
Example: Stimuli-List of a radiation warning system

Stimulus	Response

single sensor positive
want to warn people, that there is something
flash a yellow light around the sensor

Example: Stimuli-List of a radiation warning system

Stimulus	Response
single sensor positive	flash yellow light around sensor



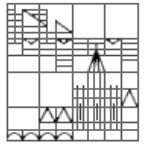
Example: Stimuli-List of a radiation warning system

Stimulus	Response
single sensor positive	flash yellow light around sensor

two sensors in one are positive
something is really wrong
flash red light in are
sound alarm

Example: Stimuli-List of a radiation warning system

Stimulus	Response
single sensor positive	flash yellow light around sensor
both sensors in one area positive	flash red light in area, sound acoustic alarm in area



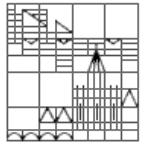
Example: Stimuli-List of a radiation warning system

Stimulus	Response
single sensor positive	flash yellow light around sensor
both sensors in one area positive	flash red light in area, sound acoustic alarm in area

small voltage drop
probably nothing bad
switch to backup power
run power supply test

Example: Stimuli-List of a radiation warning system

Stimulus	Response
single sensor positive	flash yellow light around sensor
both sensors in one area positive	flash red light in area, sound acoustic alarm in area
Voltage drop of 10-20%	switch to backup power; run power supply test



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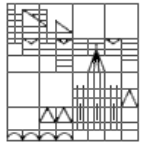
Voltage drop of 10-20%	switch to backup power; run power supply test

big voltage drop
do the same as on small drop
call technician
LAST CELL:

Example: Stimuli-List of a radiation warning system

Stimulus	Response
single sensor positive	flash yellow light around sensor
both sensors in one area positive	flash red light in area, sound acoustic alarm in area
Voltage drop of 10-20%	switch to backup power; run power supply test
Voltage drop of more than 20%	switch to backup; run power supply test; call technician



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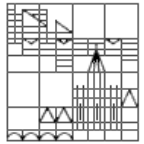
Embedded Systems ⇒ often build as state machines



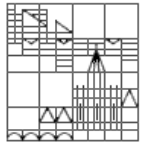
Embedded system modeling

- Embedded Systems are often built as state machines.

  ⇒ UML state diagrams

of course ⇒ UML state diagrams
very good for understanding the workings of the system
something like thismodelled stimuli+responses into states
here i modelled two sensor as a result of one sensor ⇒ may be done differently

Embedded system modeling
• Embedded Systems are often built as state machines.
⇒ UML state diagrams



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Embedded system modeling

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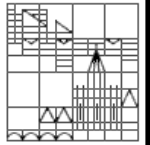
⇒ UML state diagrams



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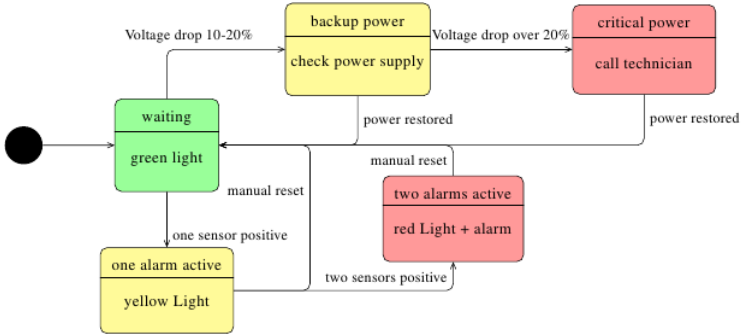
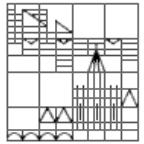


the programming language
several things need to be taken into account

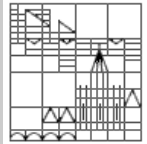
program has to be



Programming language

- program has to be...
  - ...fast (i.e. C, Assembler)
  - ...concurrent (i.e. C++, real time Java, ...)
- speed looses importance
- it's up to you in the end ...

fast: C, Assembler:
No concurrency
no built-in system for shared resources



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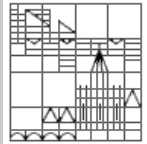
concurrent:
and manage shared resources

concurrent or speed??:
depends on what is more important
simulate concurrency with frequent polling
do something yourself about shared resources



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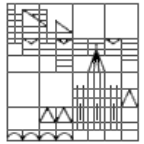
speed:
due to faster hardware
ie monitoring device written in C++
ie cell phones in java, objective C, ...
still there are some areas, where you need C & assembler...



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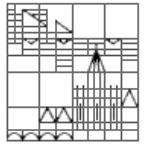
Programming language
- program has to be...
  - ...fast (i.e. C, Assembler)
  - ...concurrent (i.e. C++, real time Java, ...)
- speed looses importance
- it's up to you in the end ...

it's up to you in the end...
evaluate the needs and decide...



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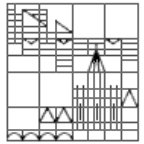
Outline
Embedded Systems Design
Architectural patterns
Timing analysis
Real-time operating systems



Outline

Architectural patterns
Architectural patterns are used to describe a system in an abstract way and help to understand the architecture.

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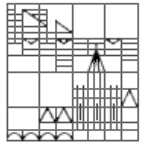
note on the 3 patterns:
The summerville book describes three rough design pattern there are finer patterns that will lead to more exact design



Architectural patterns

- Architectural patterns are used to describe a system in an abstract way and help to understand the architecture.
  - Observe and React
  - Environmental Control
  - Process Pipeline

Observe and React:
set of monitored sensors
Something exeptional happens ⇒ we do something
i.e. monitoring, incoming phone call

Architectural patterns
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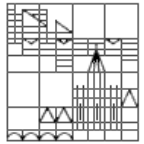
Observe and React



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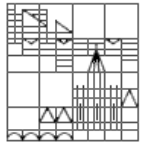
Observe and React
Environmental Control

Environmental Control:
set of sensors and actuators
can change environment
i.e. flash light, when sensor fires
i.e. control water level in a tank



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Architectural patterns
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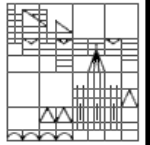
Observe and React
Environmental Control
Process Pipeline

Process Pipeline:
data transformation
series of processing steps
preferably concurrent

all of those: can be combined
often more than one pattern in the system
ie monitor the actuators

design patterns: will lead to **inefficient** system $\Rightarrow$ only for understanding system



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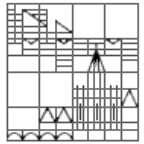
Observer & React



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  - monitor the system with a set of sensors
  - display something
  - primarly used in: Monitoring Systems

Observe and React
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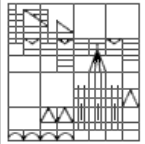
monitoring:
monitor the system with a set of sensors



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Observe and React
Observe and React
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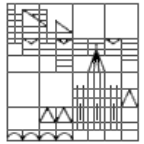
display something
primarily used in: Monitoring Systems

display:
monitoring screen
on exceptional behaviour: alarms, shutdown



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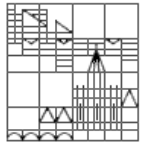
primarly in **monitoring systems:**
often consist of more than one O&R pattern
one for each sensor
optimisation: combine something, ie display on one monitor



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Environmental Control
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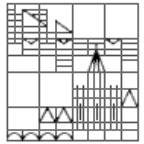
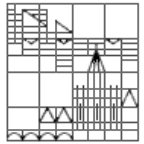


Environmental Control

- Environmental Control
  - monitor the system and react to any changes
  - Used when there is no requirement for user interaction. . .
  - . . . or no time for the user to interact . . .
  - . . . no way a user can interact . . .
  - . . . or there is too much information for users to process.

monitor sytem and react to any changes



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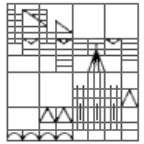
no required user interaction
examples:
cruise control
water level
pressure control
. . .



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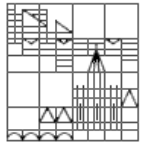
no time for user interaction
examples:
break assist
airbag



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no way for user interaction

example:

CYPRES (parachute, Möllemann did not activate his in 2003)

self desctruct of military/sensitive equipment

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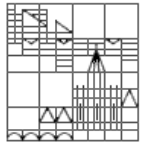

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too much information for users
example:
Nuclear Power Plant
Airplane
Car
virtually any big system with many subsystems

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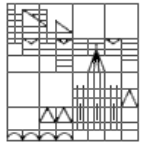

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Process Pipeline
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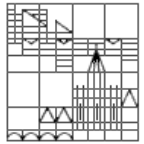


Process Pipeline

- Process Pipeline
  - transform data
  - often huge amounts of data to be converted in real time
  - data aquisition system: storing of data may need to be fast

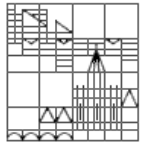
transform data

examples:

signal processing from sensors in other systems

optical sensor

convert digital data to audio



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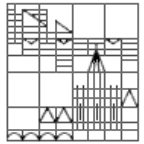
huge amount in real time:
concurrency + multicore is the key



Process Pipeline

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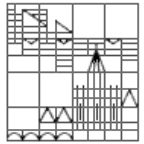
  - transform data
  - often huge amounts of data to be converted in real time
  - data aquisition system: storing of data may need to be fast

data aquisition system**example:**
particle accelerator
chemical reactions
...
if storing not fast, data will be lost

Process Pipeline
Process Pipeline
transform data
often huge amounts of data to be converted in real time
data aquisition system: storing of data may need to be fast



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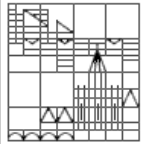
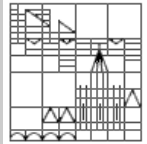
Outline
1 Embedded Systems Design
2 Architectural patterns
3 Timing analysis
4 Real-time operating systems



Outline

timing analysis

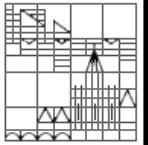


Timing Analysis - I

- timing analysis
  - Correctness of systems depends not only on result, but also on the time at which the result is produced.
  - How often does each process need to be executed?
  - aperiodic stimuly $\Rightarrow$ make assumptions

not only result, also time is important
soft and hard systems

Timing Analysis - I
timing analysis
Correctness of systems depends not only on result, but also on the time at which the result is produced.



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how often?:
then we check, if our system can deliver this
this can be quite hard, when *mixture of aperiodic and periodic stimuli* or *many aperiodic stimuli* are expected

Timing Analysis - I
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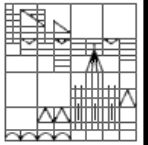
Correctness of systems depends not only on result, but also on the time at which the result is produced.
How often does each process need to be executed?



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aperiodic stimuli:
make assumptions

fast systems:
use only periodic stimuli
poll frequently for aperiodic stimuli

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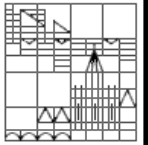
How often does each process need to be executed?
aperiodic stimuly ⇒ make assumptions



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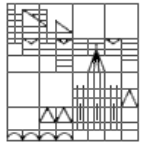
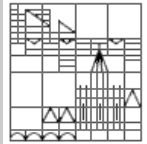
Timing analysis must consider:



Timing Analysis - II

- Consider:
  - deadlines
  - frequency
  - execution time

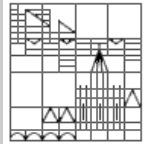
deadlines:
By which time must the process have ended.



Timing Analysis - II

- Consider:
  - deadlines
  - frequency
  - execution time

frequency:
The number of times a process must be executed in a given span, so that the *system* meets all deadlines

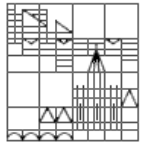


Timing Analysis - II

- Consider:
  - deadlines
  - frequency
  - execution time

Timing Analysis - II
Consider:
deadlines
frequency
execution time

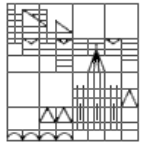
execution time:
How long does each single process take (average & worst case)
hard: conditional execution, delays waiting, ...
hard systems: always worst case



Timing Analysis - II

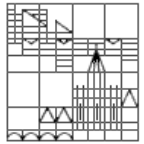
- Consider:
  - deadlines
  - frequency
  - execution time

We list stimuli and response
then think about how fast this needs to work



Stimulus/Response Timing requirements

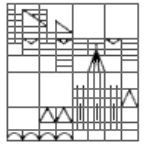
Stimulus/Response | Timing requirements
voltage drop | switch to backup: 50ms



Stimulus/Response	Timing requirements
voltage drop	switch to backup: 50ms

voltage drop $\Rightarrow$ 50ms

Stimulus/Response	Timing requirements
voltage drop	switch to backup: 50ms
sensor reaction	poll twice a second

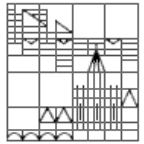


sensor reaction $\Rightarrow$ poll twice a second

Stimulus/Response	Timing requirements
voltage drop	switch to backup: 50ms
sensor reaction	poll twice a second

Stimulus/Response	Timing requirements
voltage drop	switch to backup: 50ms
sensor reaction	poll twice a second
turn on light	500ms

turn on light $\Rightarrow$ 500ms



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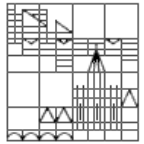
sensor reaction	poll twice a second
turn on light	500ms

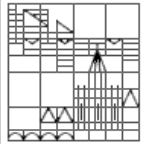
Stimulus/Response	Timing requirements
voltage drop	switch to backup: 50ms
sensor reaction	poll twice a second
turn on light	500ms
call technician	5000ms

call technician $\Rightarrow$ 5000ms
may take longer, as technician reaction time is low anyways**LAST CELL:**



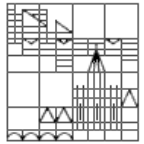
Stimulus/Response	Timing requirements
voltage drop	switch to backup: 50ms
sensor reaction	poll twice a second
turn on light	500ms
call technician	5000ms

Outline
Embedded Systems Design
Architectural patterns
Timing analysis
Real-time operating systems



Outline

normal operating systems:
too large, too bulky, too slow

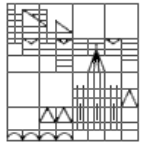


Real-time operating systems

- normal operating systems not feasible
- special "real-time operating systems" exist
- RTOS must include:
  - real-time clock
  - interrupt handler
  - process manager: scheduler & resource manager
  - dispatcher

real-time operating systems:
Windows/CE
Vxworks
RTLinux
emdebian

they are small and damn fast



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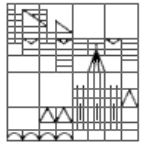

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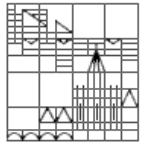
real-time clock:
provides information required to schedule processes



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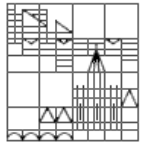
interrupt handler:
manages aperiodic requests for service
may be inside process manager
at least **2 levels:**
interrupt for processes with fast response time & *clock level* fore regular processes
often also background processes with low priority (self checks etc)



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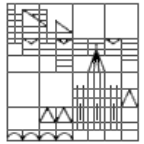
scheduler
examines processes and chooses one for execution
processes need enough processor time to *finish before their deadline*
commonly used:
non-pre-emptive & pre-emtive (execution of processes may be stopped)
round robin
rate monolithic scheduling (SJF)
shortes deadline first (HPF)
resource manager:
allocates memory and processor resources scheduled for execution



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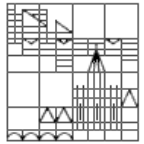
dispatcher:
starts execution of processes



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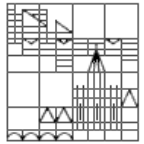
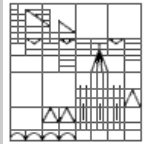
nearly done
important stuff in short



30 minutes in short

- What you should (at least) remember:
  - Embedded Systems react to events in real time.
  - Embedded Systems are a set of processes reacting to stimuli
  - State models help understanding the System.
  - Architectural patterns can be used to help in designing the system.
  - Always do timing analysis in (hard) Embedded Systems.

Embedded Systems
react to events in real time



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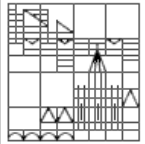

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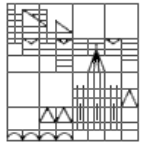

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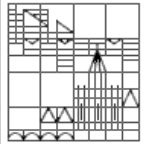

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state model help understanding the system
Architectural patterns help designing the system especially first steps
timing analysis must always be done in (hard) systems

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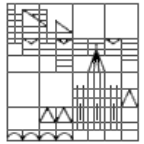

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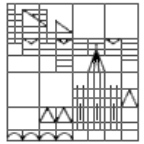

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