Real-time systems SMD138

Lecture 15:

Repetition +

(In)famous real-time systems

Course focus

- Concurrency – how to write programs using parallel threads of execution
- Reactivity – how to write programs whose purpose is to react to events (ultimately in the form of interrupts)
- Real-time – how to write programs whose correctness depend on their real-time behavior

Course contents

- Introduction to real-time systems & bare metal programming in C
  - C vs. Java, pointers, type-casts, the execution stack
- Bit manipulation & hardware interfacing
  - (memory-mapped) ports, status changes, busy-waiting
- Concurrency and mutual exclusion
  - problems sequential programs, threads, critical sections
- The inner workings of a kernel
  - setjmp/longjmp, fresh stacks, the ready queue, yield, interrupts

Course contents

- Events, interrupts and reaction
  - problems with busy-waiting, the CPU as a reactive object
- A model of reactive objects
  - state, methods, self, SYNC/ASYNC, cyclic calls, deadlock, idling
- Clocks, timers and periodic execution
  - time-stamps, delays, period drift, event baselines + offsets
- Examples of reactive systems
  - counter, event filter, signal processor, clocks, reactive buffer, proxy
- Deadlines and priorities
  - WCET, timely reaction, (pre-emptive) scheduling, static/dynamic prio

Course contents

- Scheduling and feasibility
  - restricted model, RM, EDF, optimality, schedulability tests
- Priority inversion
  - sporadic tasks, DM, response times, blocking time, inheritance/ceiling
- POSIX thread programming
  - trad. OS services, thread creation, mutexes, ticks, POSIX clocks
- More on inter-process communication
  - POSIX signals & timers, event-loops, parking, select(), semaphores
- Real-time languages
  - monitors, condvars, Java threads & monitors, Ada guards & messages

Text book

- Core parts
  - Chapters 6 (except 6.5), 7, 8, 9, 10.6, 11.7, 12, 13 (except 13.12), 15 (except 15.9), 17
- Parts covered lightly
  - Chapters 1, 2, 3, 4, 15.9, 18
- Parts not covered at all
  - Chapters 5, 6.5, 10 (except 10.6), 11 (except 11.7), 13.12, 14, 16
- Regarding sections on specific languages:
  - C/POSIX parts should be fully understood
  - For other languages, only key concepts should be recognized when reading examples

Final words

- Regarding details:
  - The exam will not try to test knowledge about details that can easily be looked up in a manual
  - Knowing what techniques to use, and their limitations, is what is essential
- Regarding the remaining days until examination:
  - Read the slides and the book, in that order
  - Don't hesitate to ask questions if anything is unclear!
  - I'll try to check email frequently the remaining days until the exam
- Regarding your input:
  - Please fill out the on-line course evaluation form!

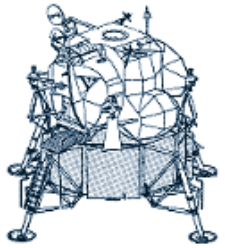
(In)famous real-time systems

- Goals:
  - To give some examples of real real-time systems that have actually been produced
  - To illustrate various ways that the concept of time may affect system design
  - To warn about the consequences of bad real-time system design!
  - To motivate programmers to do better!

Outline

- The Apollo 11 lunar lander
  - Overloaded control system that almost caused abortion of the first lunar landing
- The Therac-25 medical radiation machine
  - Various software race conditions that caused death and serious injury in the 80's
- The Mars Pathfinder
  - Spurious system resets on the Mars surface caused by priority inversion
- The Ariane 5 satelite launch rocket
  - Bad floating-point exception handling that lead rocket self destruction in 1996

The Apollo 11 lunar lander



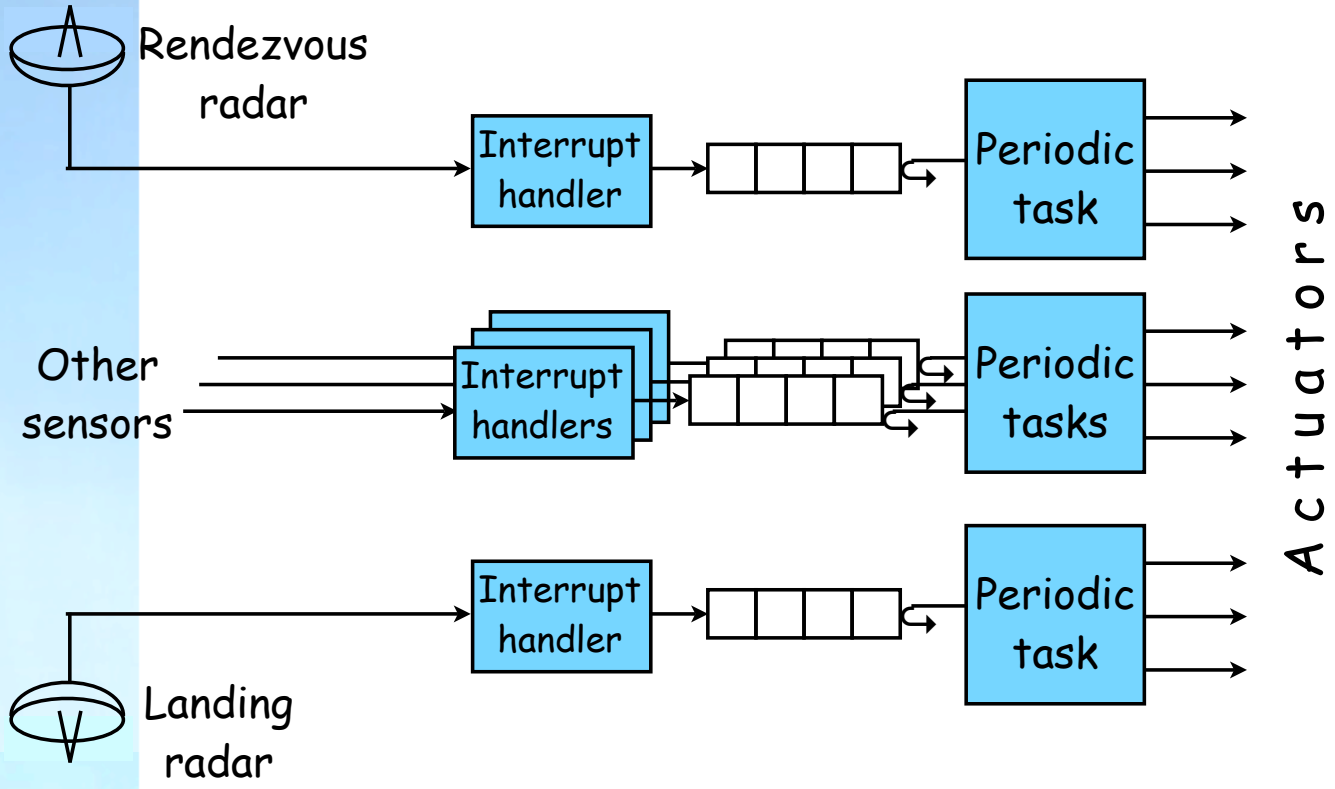
- Basic facts:
  - First manned lunar landing (July 20 1969)
  - A small 2-person spacecraft descended to the lunar surface, while mothership stayed in lunar orbit
  - Both spacecraft equipped with a computer for navigation and guidance: 100 kHz 16-bit CPU, 38 K RAM & core memory, programmed in assembly language, priority-based event-driven OS of 2 K

The first lunar landing events

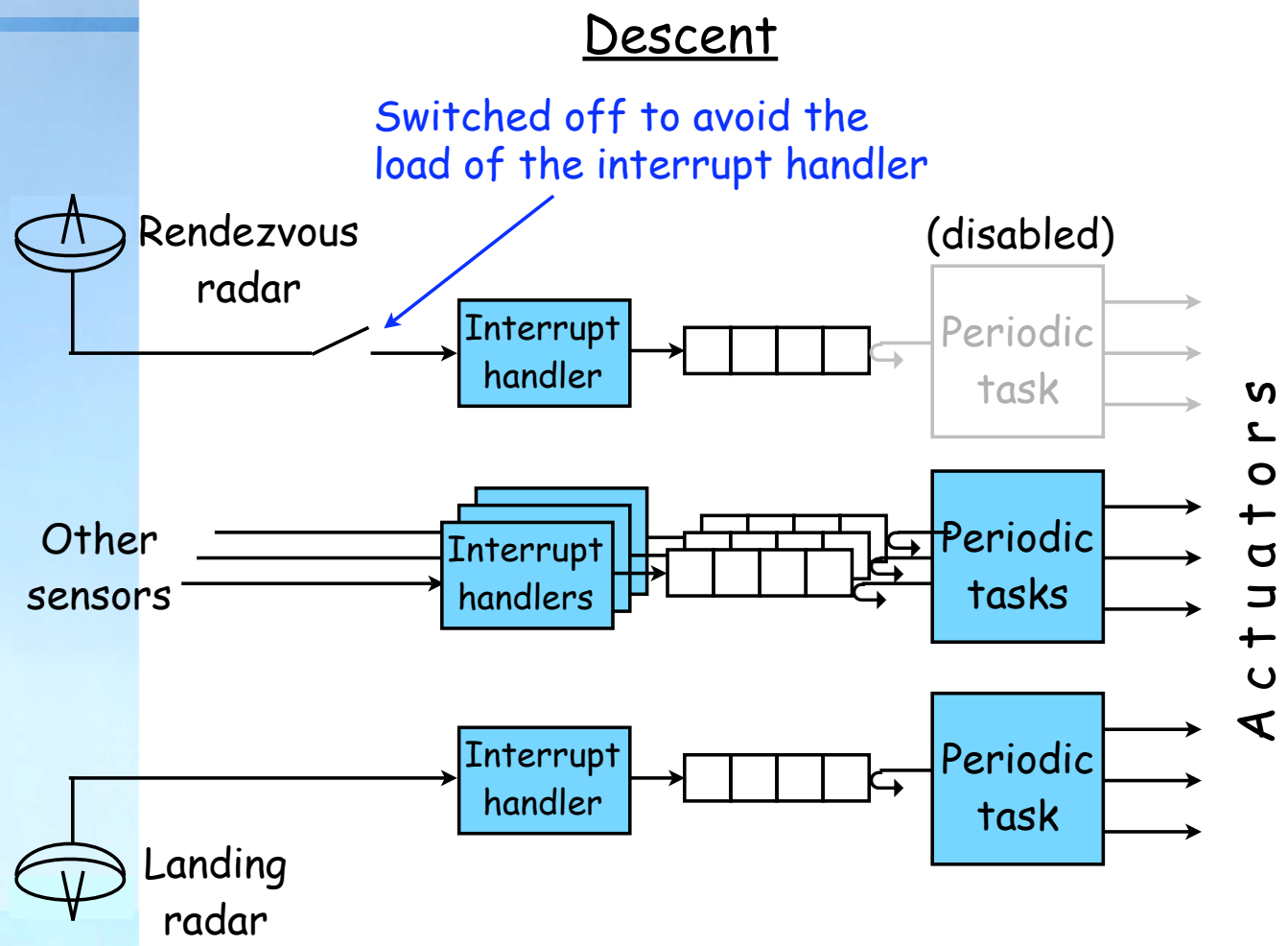
- During the landing phase, the role of the lunar lander computer was to measure altitude, and control the overal attitude of the spacecraft
- In the middle of descent, with only minutes to go before landing, the computer started to display "1202 alarm"
- This alarm kept repeating itself every 10 seconds
- As the minimum altitude for aborting was approaching, the software engineers had to decide whether the alarm was fatal or not
- The advice was to ignore the alarm, and the landing also proceeded successfully

Lunar lander system design

Problem: computer too slow to handle all tasks concurrently

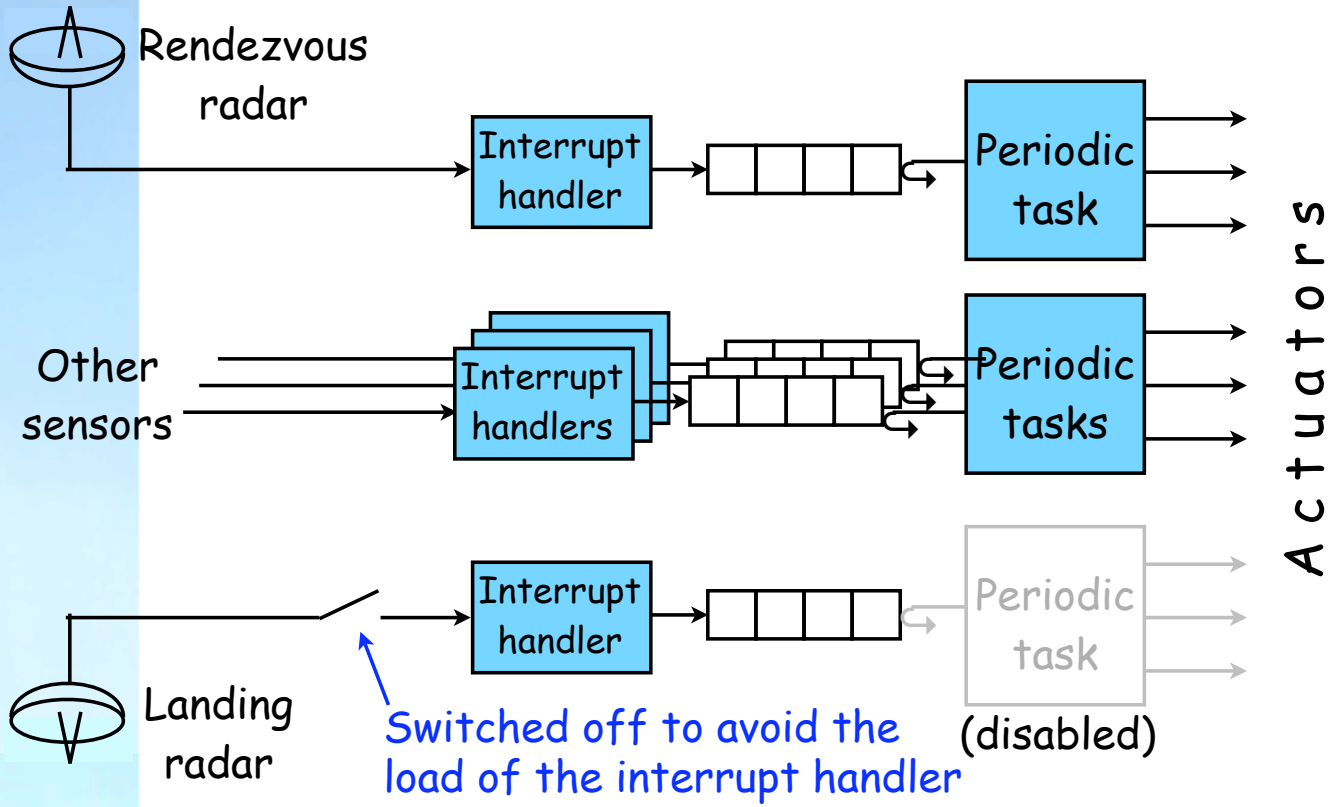


Solution: working modes

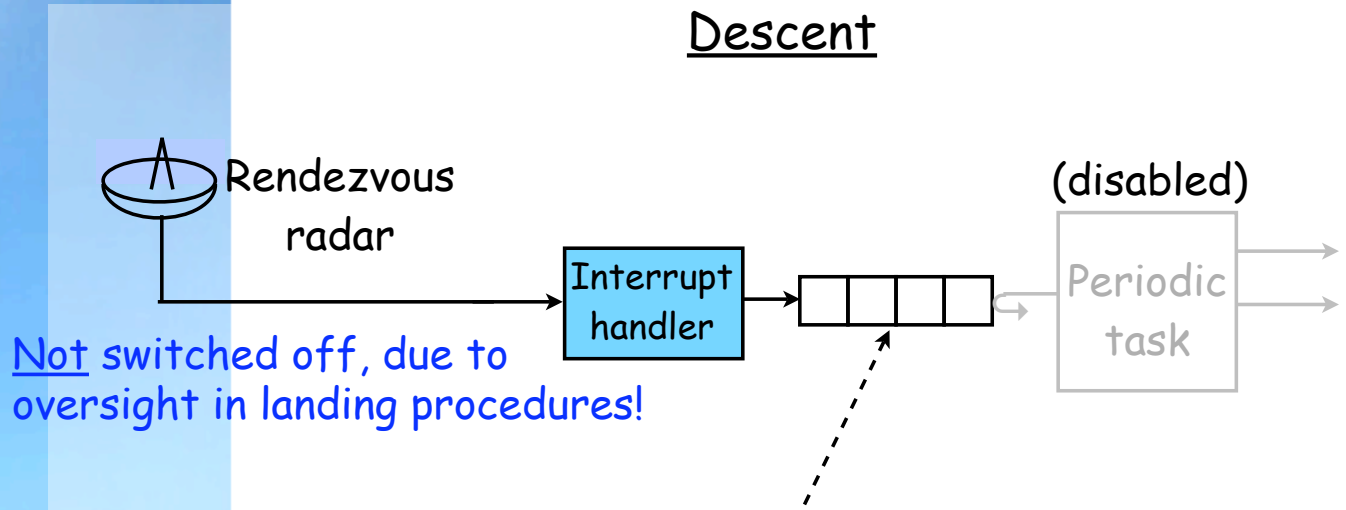


Solution: working modes

Ascent



Cause of the alarms



Consequence 1: event buffer overflow every 10 s

Consequence 2: about 20% of the CPU cycles spent in the rendezvous radar interrupt handler

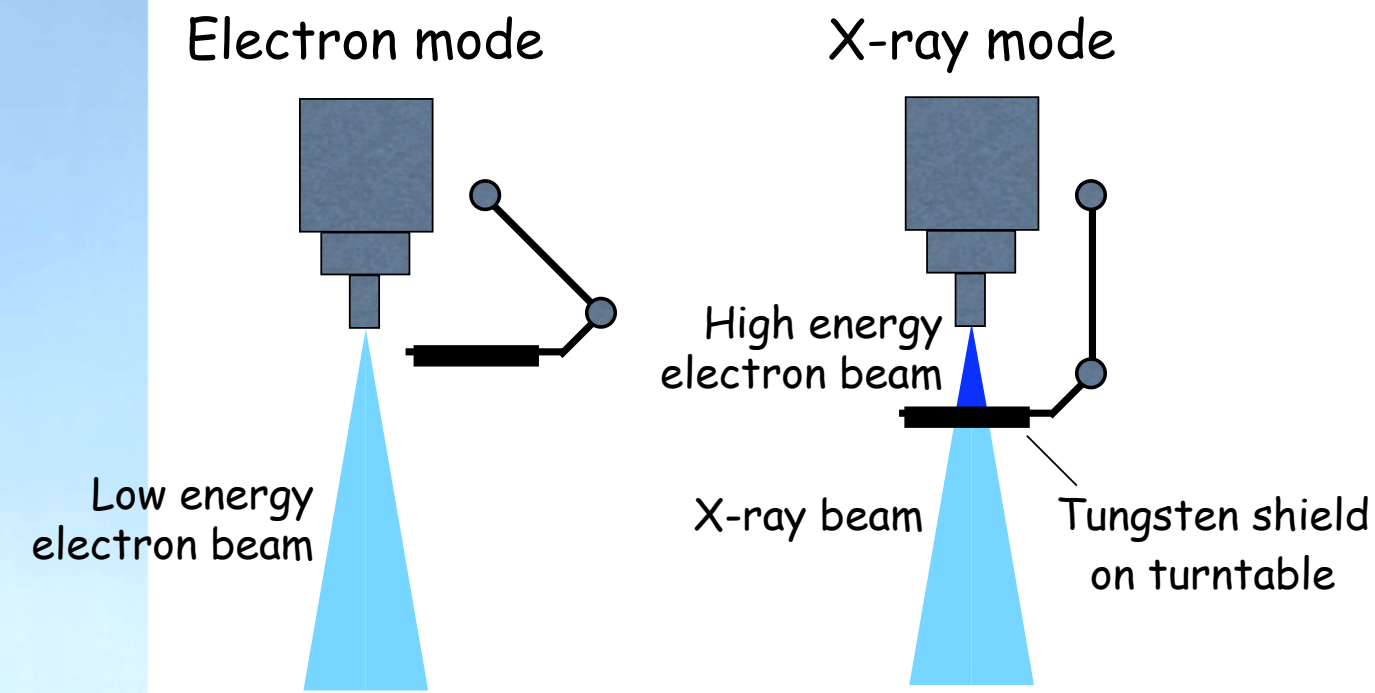
Additional facts

- The engineers knew "1202 alarm" meant overflow of some event buffer, not clear which one
- However, because of the fixed priorities used, judgement was that whatever events and computations being lost, they would be the least important ones
- The decision to ignore the alarms was taken on basis of that "gut feeling", rather than knowledge
- Analysis and simulations during the 24h moon stay found the exact alarm cause (the erroneous switch)
- (The engineer in charge of the decision to proceed was later awarded the president's medal together with the astronauts!)

Therac 25

- The Therac-25 was a computer controlled therapeutic radiation machine for the treatment of tumors
- Deployed in the mid 80's, it was a modernized successor to a highly successful, but slow and bulky machine: the Therac-20
- Massive radiation overdozes generated by the machine resulted in deaths or severe injuries for at least six people in the USA and Canada 1985-1987
- The machine was redesigned in 1987 as the result of multiple federal investigations

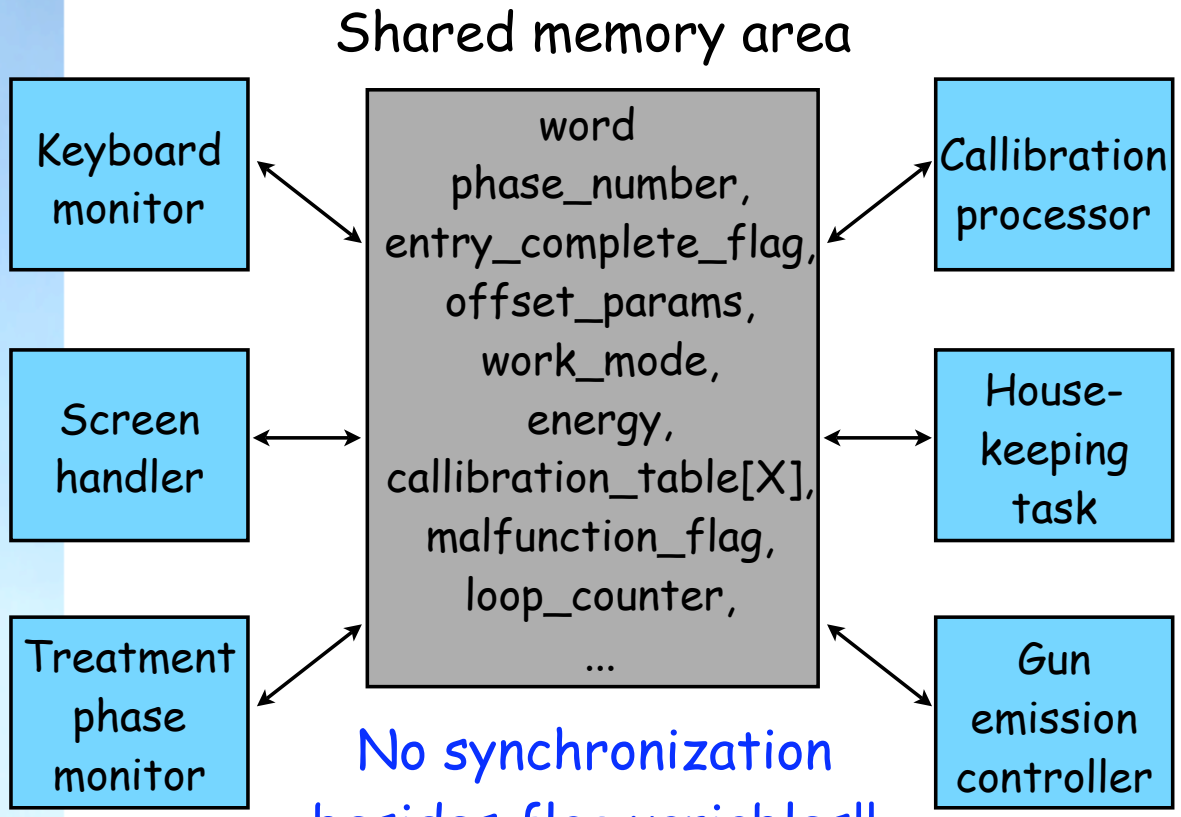
Therac-25 functionality



Therac-25 computer

- DEC PDP-11 responsible for
  - Scanning operator input
  - Positioning the turntable with the tungsten shield
  - Setting up the electron gun, bending magnets, and various other devices
  - Performing treatment timing
  - Executing extensive safety checks
- Controlled via an ASCII-based terminal in a remote room, using cursor keys for moving between input fields

Therac-25 software design



Reconstructed accident cause 1

- The operator erroneously enters X-ray mode, realizes the mistake, and switches back to electron mode – all within 8 seconds
- During that time window, the treatment phase task is ignoring the keyboard entry flag because it is delaying in a busy-wait loop while bending magnets are being set up. Thus the new mode is never copied over to the variable read by the gun emission control task
- The other tasks register the edit, though, so the turntable is moved and the screen updated accordingly
- This results in the patient being exposed to unshielded, high energy radiation, with no indication to the operator

Reconstructed accident cause 2

- When input parameters are unverified or inconsistent, the treatment monitor task periodically runs a procedure that increments a counter
- This counter is used as a flag by the housekeeping task, indicating whether gun firing should be enabled or not
- However, as the counter is only 8 bits, it will overflow every 256 ticks, and the "flag" will temporarily indicate a zero condition!
- If the "set" command is given at that instant, inconsistencies are not checked, and unshielded high-energy radiation may result

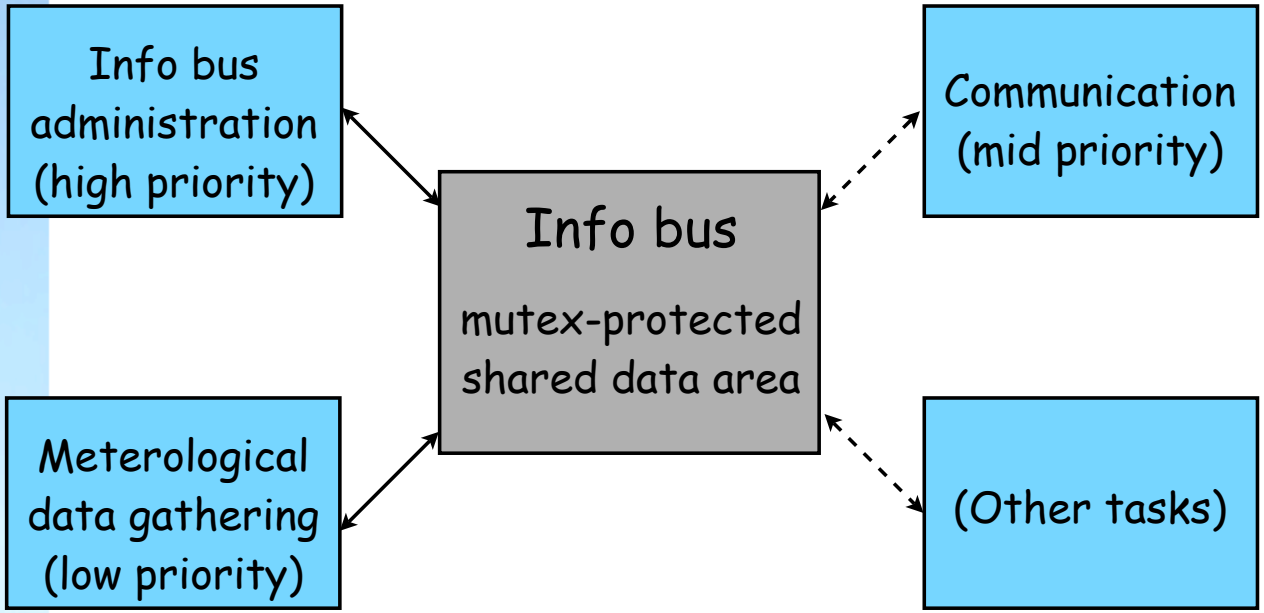
Additional facts

- The Therac-25 software was written in assembly language by a single person, who also wrote the context-switching "kernel"
- Few people seem to have had any clear idea of how the software really worked
- Safety analyses for the machine never took timing errors into account
- It turned out that the Therac-20 also contained the same bugs, but there hardware sensors and fuses were used as an extra safety net against high radiation
- Basic lesson: never synchronize using flags!

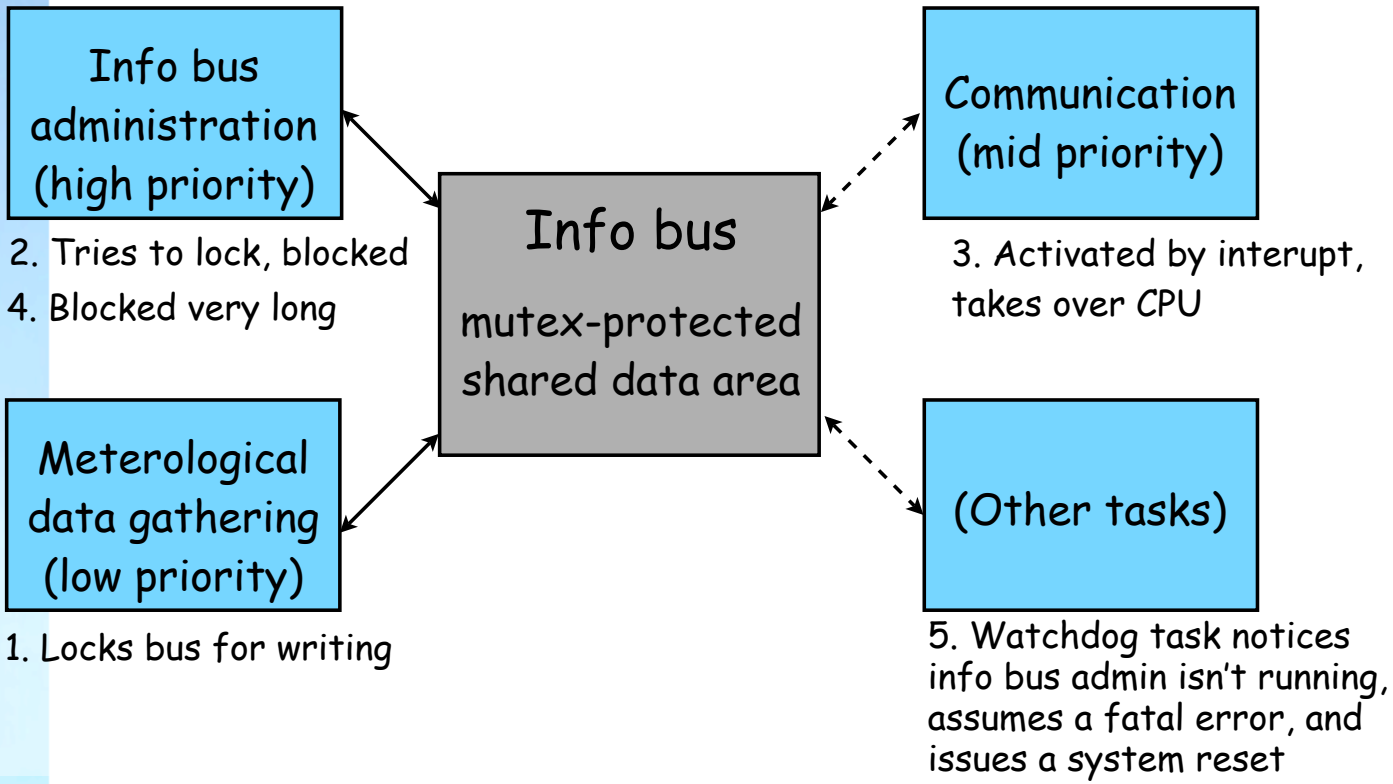
The Mars Pathfinder

- Unmanned spacecraft that landed on Mars in 1997
- Famous for its high-resolution panaorama pictures of the Mars surface
- Also famous for utilizing ballons in a "bouncing" landing procedure, and for deploying a surface vehicle on wheels
- Not so well-known: severe computer problems on the Pathfinder that resulted in frequent system resets and loss of data
- The cause: a classical example of priority inversion

Pathfinder software design



The priority inversion problem



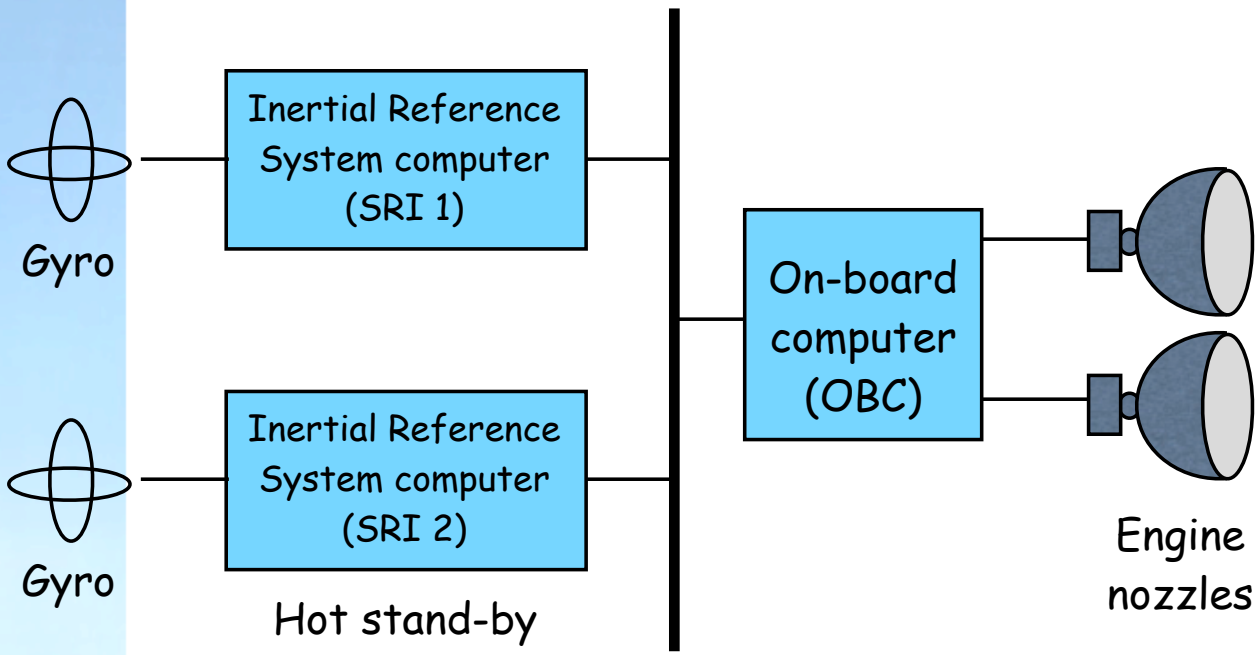
Additional facts

- The Pathfinder software ran under the VxWorks RTOS
- VxWorks can be run with a tracing option, which records every activity within in the kernel
- During simulations on an exact replica of the Pathfinder, engineers were able to reproduce the resets, and the problem was identified
- Fortunately, a C interpreter had been left in the Pathfinder's version of VxWorks, and a fix could be uploaded that turned on priority inheritance for the info bus mutex
- (The mutex in question was actually hidden within a higher-level synchronization construct, that didn't offer any priority inheritance option!)

The Ariane-5 blow-up

- Launch of Ariane-5 took place in French Guyana, June 4 1996
- The rocket contained a fairly sophisticated, fault-tolerant computer system, with software written in Ada
- About 40 seconds after take-off, the rocket self-destructed at an altitude of approximately 4000 meters
- Telemetry data, and memory readouts from computer units recovered from the debris, enabled the cause of events to be determined at a high level of detail

Part of the Ariane-5 design



Reconstructed event-chain

- The rocket started to disintegrate at 39 s after lift-off, which caused automatic self-destruction
- Disintegration was the result of an angle-of attack of more than 20°, which in turn was caused by full nozzle deflections on all engines
- Nozzle deflections were commanded by the OBC software on basis of data transmitted by SRI2
- SRI2 was actually not transmitting inertial data, but bit-patterns corresponding to post-mortem debug information
- SRI2 had aborted because of an unhandled floating-point exception, and so had SRI1 one cycle earlier

Reconstructed event-chain

- The FP exception was due to an error fitting a 64-bit floating-point value into a 16-bit integer
- Exception handling for this conversion had been turned off in order to squeeze CPU utilization below 80% (as dictated by RM analysis)
- The unexpected value occurred in a task used for guiding the rocket while still at the launch pad
- This task was left running for 40 s after lift-off, due to extra time allocated in case of short pauses during countdown (to avoid realigning the gyros)
- The analysis that outruled exceptional values for the variable after lift-off was most likely based on trajectory data for Ariane-4!

Conclusions

- If something can go wrong in a real-time concurrent system, it will eventually go wrong
- Because of the time dimension, the argument "it works now" has little value for a real-time system
- Corrrectness of a real-time system should ideally be established by some form of formal verification, with clearly stated assumptions (including timing)
- Current technology only allows us to go a few steps in this direction
- Extensive testing can find many errors, but never give full correctness guarantees
- We as programmers can help by choosing program structures that are clearly correct by construction