Synthesis, Analysis, and Verification
Lecture 01

Introduction, Overview, Logistics

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Today

- Introduction and overview of topics
  - Analysis and Verification
  - Synthesis
- Course organization and grading

SAV in One Slide

We study how to build software
analysis, verification, and synthesis
tools that automatically
answer questions about software systems.

We cover *theory* and *tool building* through *lectures*, *exercises*, and *labs*.

Grade is based on

- quizzes
- home works (theory and programming)
- a mini project, presented in the class

Steps in Developing Tools

Modeling: establish precise mathematical meaning for: *software*, *environment*, and *questions* of interest

- discrete mathematics, mathematical logic, algebra

Formalization: formalize this meaning using appropriate representation of *programming languages* and *specification languages*

- program analysis, compilers, theory of formal languages, formal methods

Designing algorithms: derive algorithms that manipulate such formal objects - key technical step

- algorithms, dataflow analysis, abstract interpretation, decision procedures, constraint solving (e.g. SAT), theorem proving

Experimental evaluation: implement these algorithms and apply them to software systems

- developing and using tools and infrastructures, learning lessons to improve and repeat previous steps

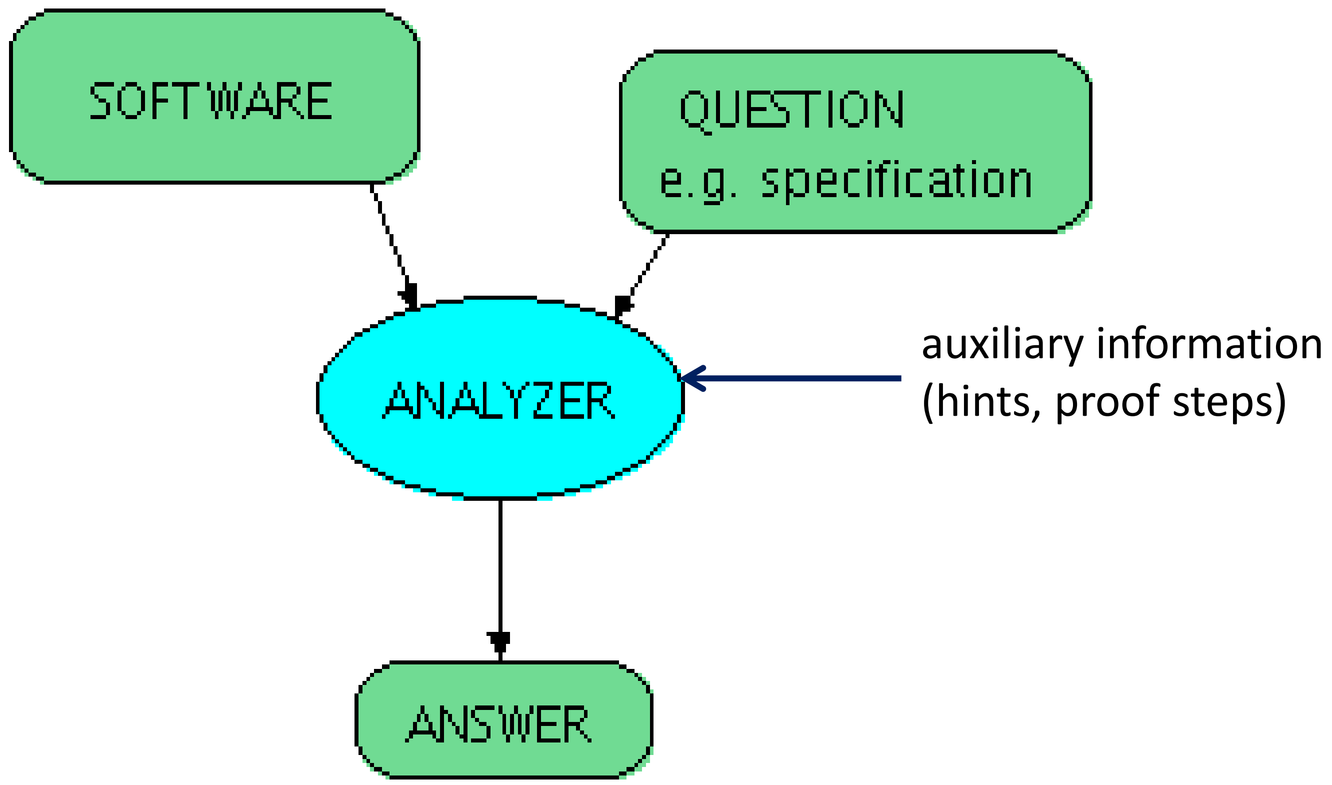
Comparison to other Sciences

Like science we model a part of reality (software systems and their environment) by introducing mathematical models. Models are by necessity *approximations* of reality, because 1) our partial knowledge of the world is partial and
2) too detailed models would become intractable for automated reasoning

Specific to SAV is the nature of software as the subject of study, which has several consequences:

- software is an engineering artifact: to an extent we can choose our reality through **programming language design** and **software methodology**
- software has complex **discrete**, **non-linear** structure: **millions of lines** of code, **gigabytes of bits** of state, one condition in if statement can radically change future execution path (non-continuous behavior)
- high standards of correctness: **interest in details** and exceptional behavior (bugs), not just in general trends of software behavior
- high standards along with large the size of software make manual analysis infeasible in most cases, and requires **automation**
- automation requires not just mathematical modeling, where we use everyday mathematical techniques, but also **formal modeling**, which requires us to specify the representation of systems and properties, making techniques from mathematical logic and model theory relevant
- automation means implementing **algorithms** for processing representation of software (e.g. source code) and representation of properties (e.g. formulas expressing desired properties), the study of these algorithms leads to questions of **decidability**, **computational complexity**, and **heuristics** that work in practice.

Analysis and Verification



Questions of Interest

Example questions in analysis and verification (with sample links to tools or papers):

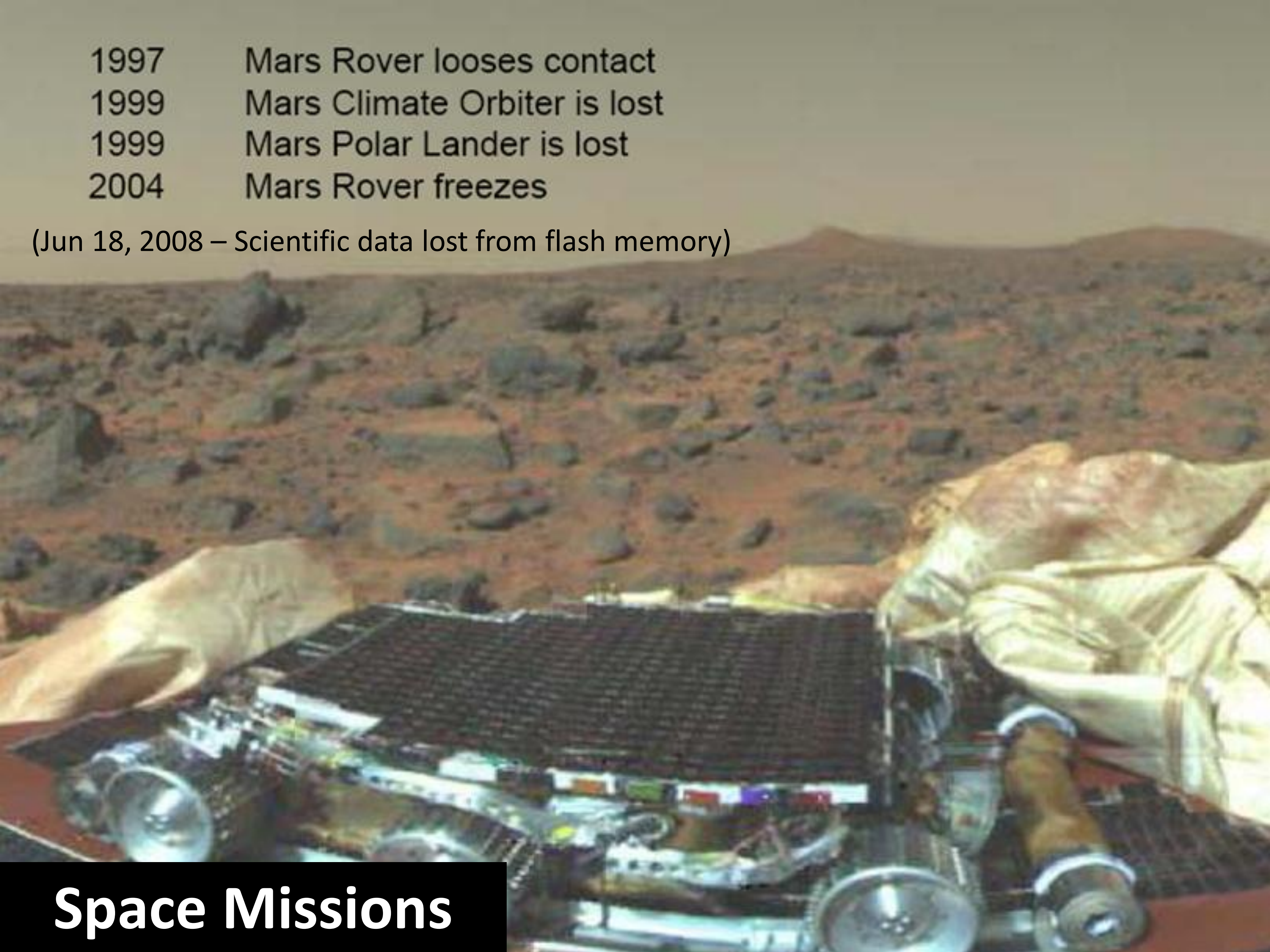
- Will the program crash?
- Does it compute the correct result?
- Does it leak private information?
- How long does it take to run?
- How much power does it consume?
- Will it turn off automated cruise control?

Viewer Discretion is Advised

French Guyana, June 4, 1996
t = 0 sec

t = 40 sec
$800 million software failure

Space Missions



1997	Mars Rover looses contact
1999	Mars Climate Orbiter is lost
1999	Mars Polar Lander is lost
2004	Mars Rover freezes

(Jun 18, 2008 – Scientific data lost from flash memory)

Space Missions

Boeing could not assemble and integrate the fly-by-wire system until it solved problems with the databus and the flight management software. Solving these problems took more than a year longer than Boeing anticipated. In April, 1995, the FAA certified the 777 as safe.

Total development cost:	$ 3 billion
Software integration and validation cost:	one third of total

Air Transport

August 2005

Gerardo Dominguez/zrh.airlinerpictures.net

As a Malaysia Airlines jetliner cruised from Perth, Australia, to Kuala Lumpur, Malaysia, one evening last August, it suddenly took on a mind of its own and zoomed 3,000 feet upward. The captain disconnected the autopilot and pointed the Boeing 777's nose down to avoid stalling, but was jerked into a steep dive. He throttled back sharply on both engines, trying to slow the plane. Instead, the jet raced into another climb. The crew eventually regained control and manually flew their 177 passengers safely back to Australia.

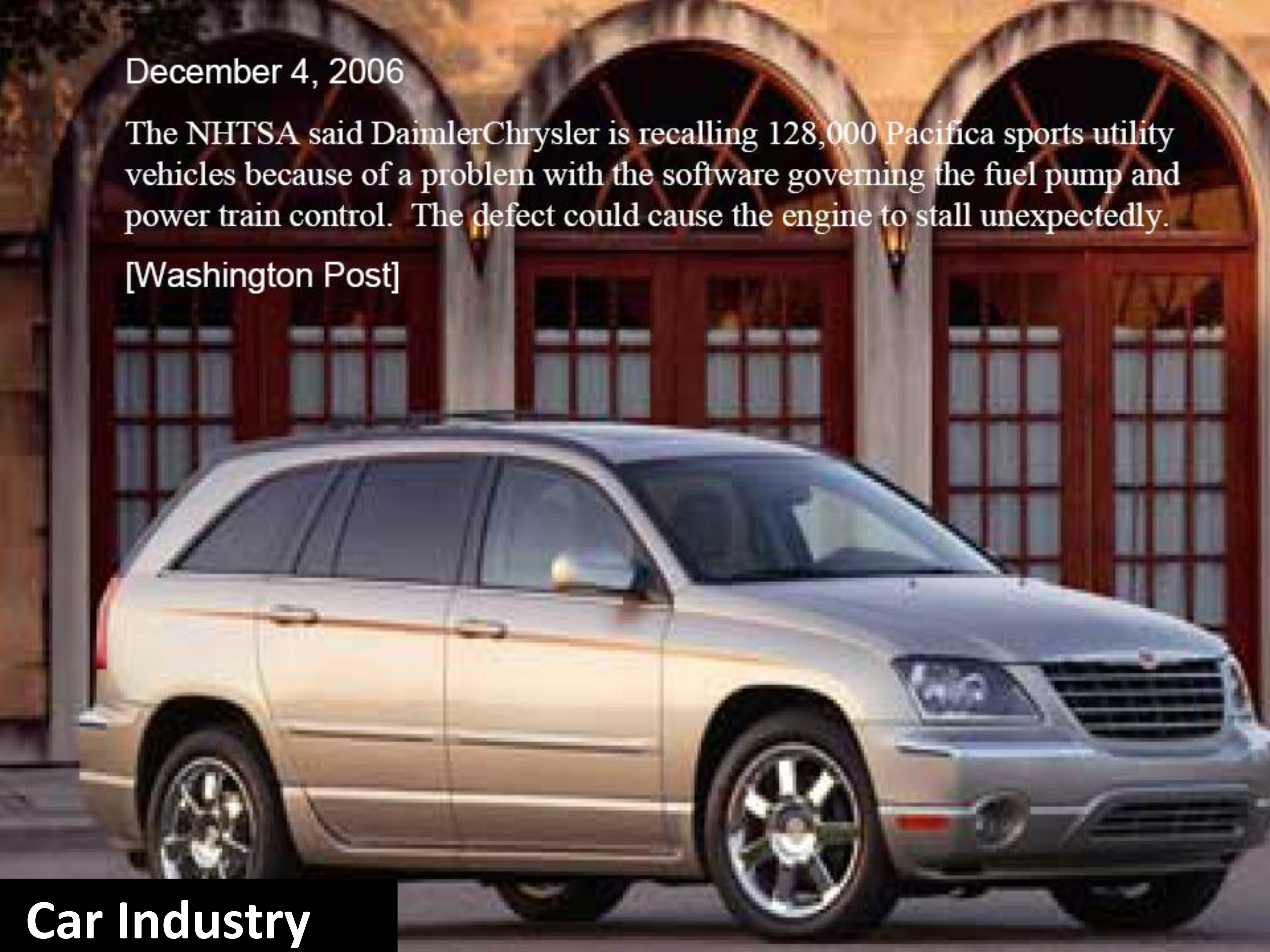
Investigators quickly discovered the reason for the plane's roller-coaster ride 38,000 feet above the Indian Ocean. A defective software program had provided incorrect data about the aircraft's speed and acceleration, confusing flight computers.

Air Transport

September 14, 2004

Without warning, at about 5 p.m. PDT, air traffic controllers lost contact with about 400 airplanes they were tracking over the southwestern US. A backup system that was supposed to take over in such an event crashed within a minute after it was turned on.

Air Transport



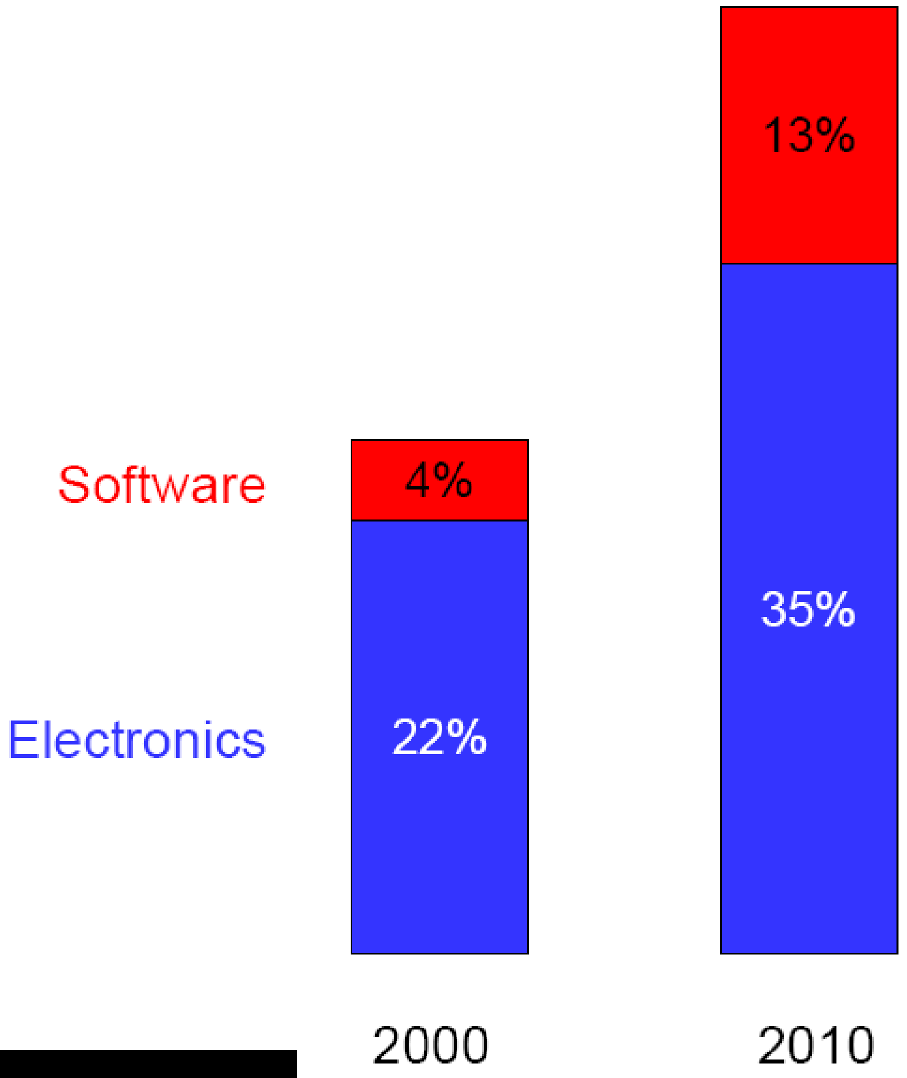
December 4, 2006

The NHTSA said DaimlerChrysler is recalling 128,000 Pacifica sports utility vehicles because of a problem with the software governing the fuel pump and power train control. The defect could cause the engine to stall unexpectedly.

[Washington Post]

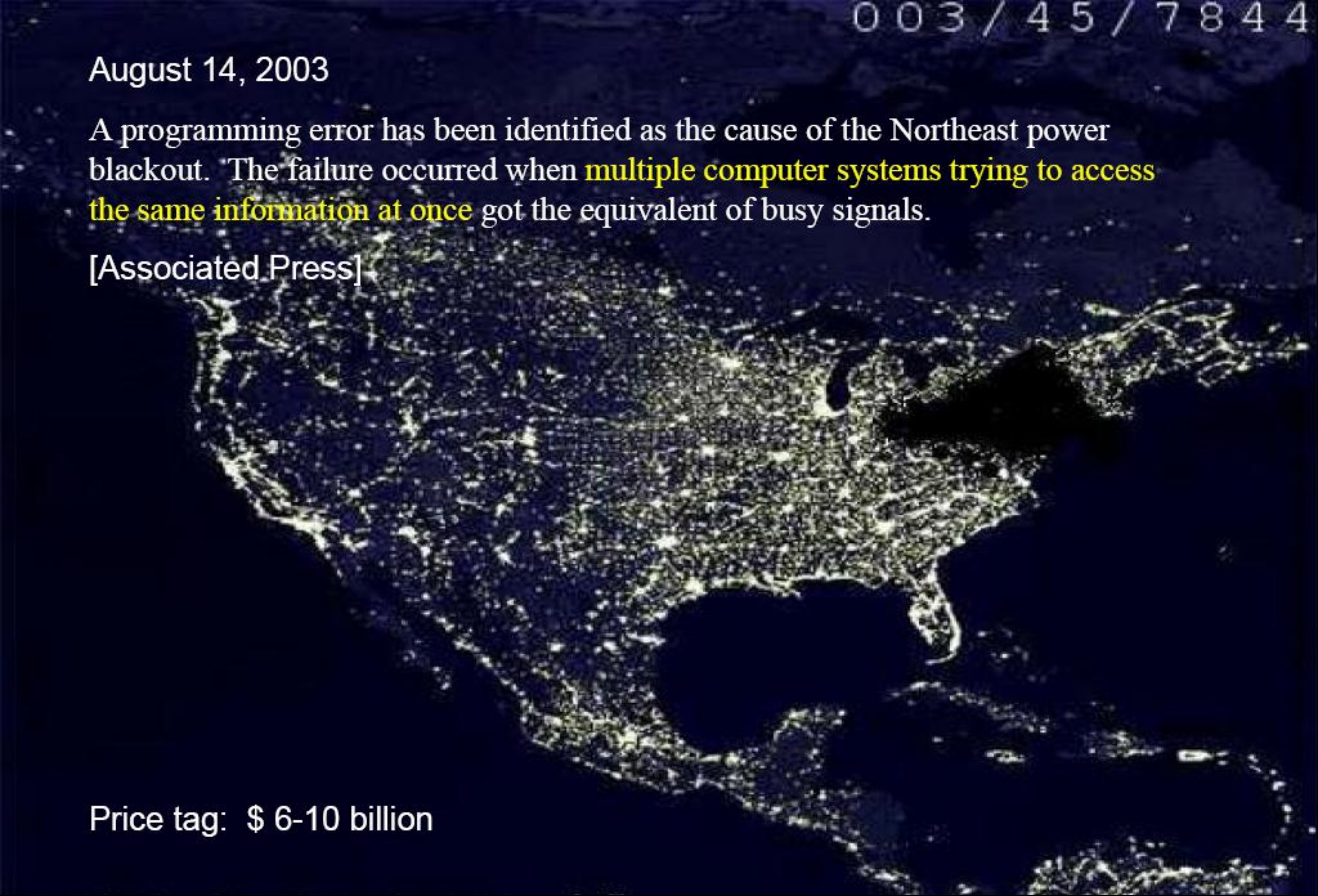
Car Industry

Production Cost of Automobiles



[MIT Tech Review]

Car Industry



August 14, 2003

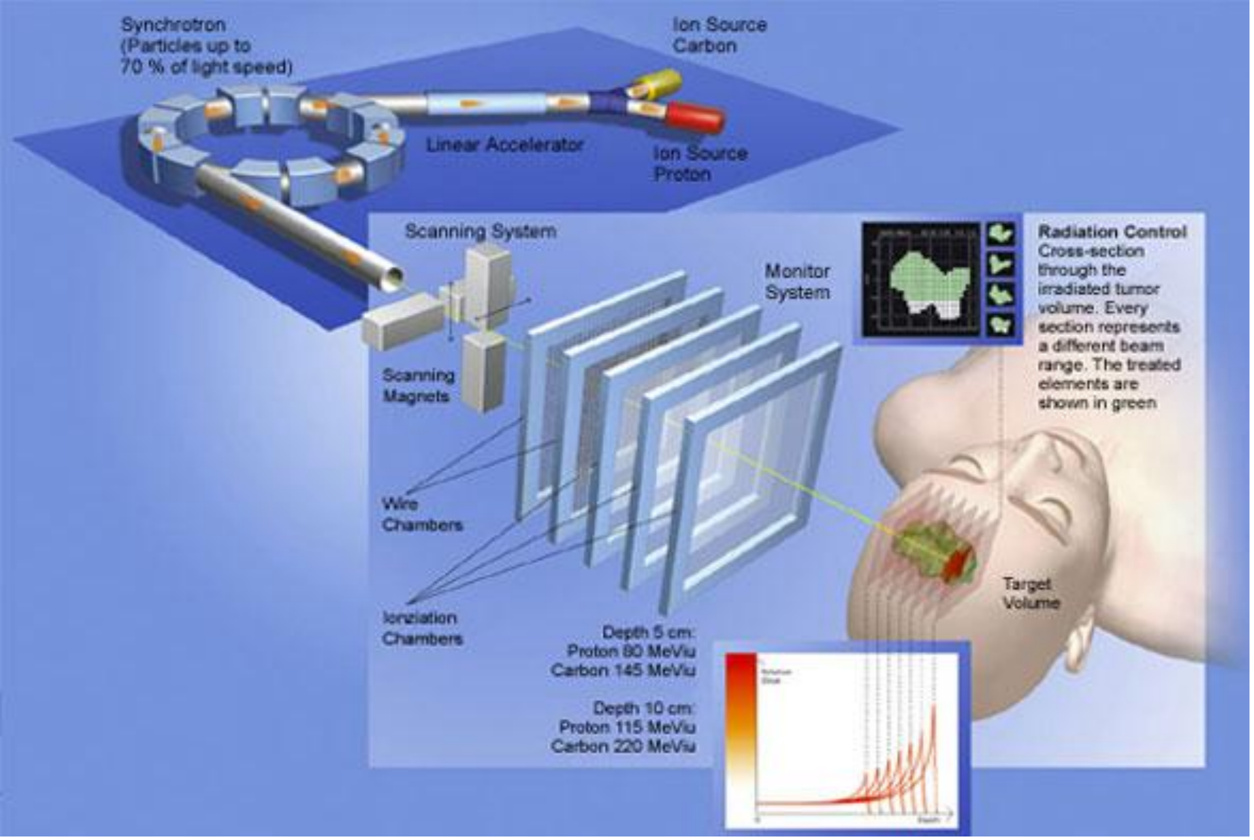
A programming error has been identified as the cause of the Northeast power blackout. The failure occurred when multiple computer systems trying to access the same information at once got the equivalent of busy signals.

[Associated Press]

Price tag: $ 6-10 billion

Essential Infrastructure: Northeast Blackout

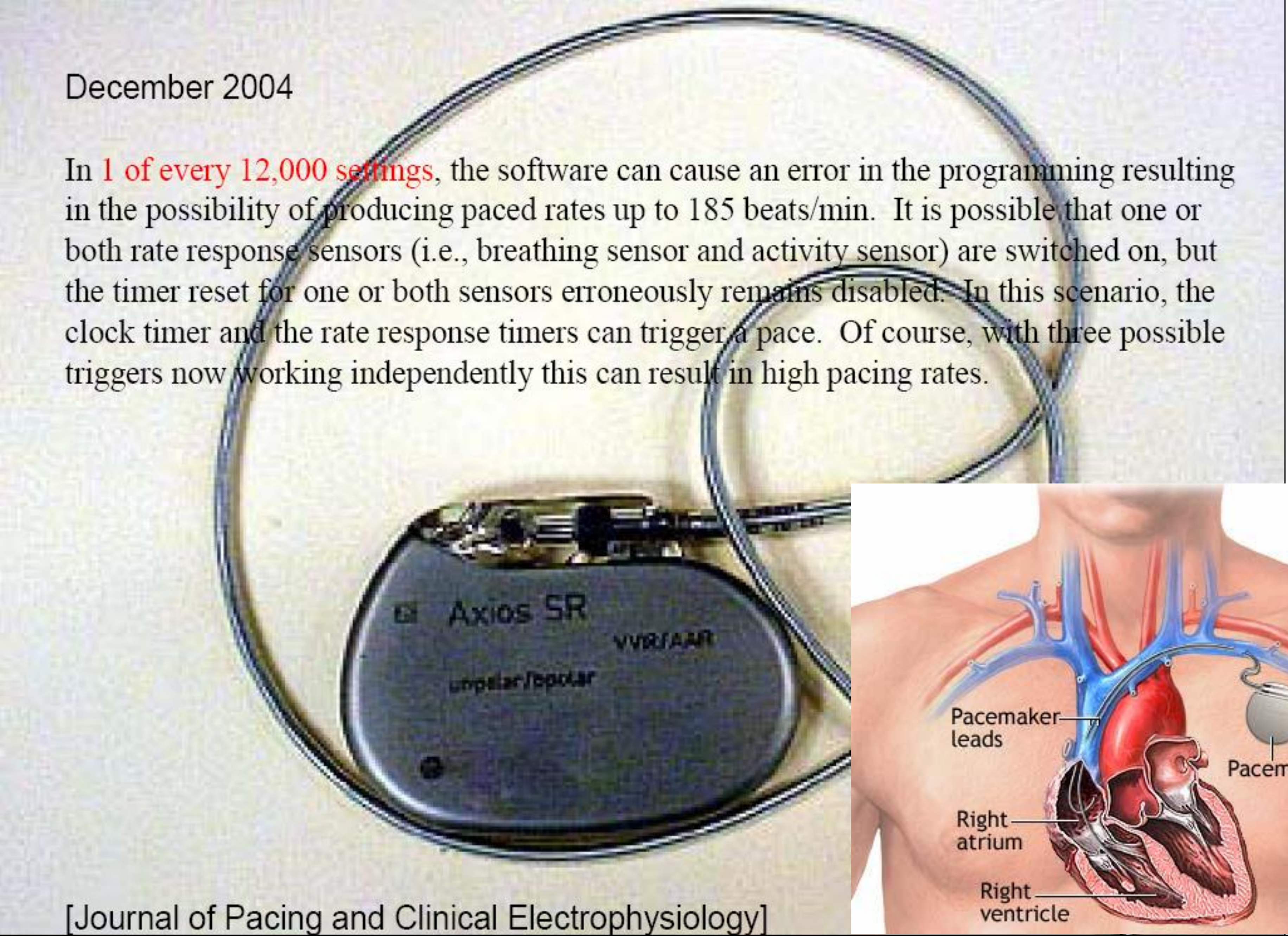
Radio Therapy


Synchrotron (Particles up to 70 % of light speed)
Ion Source Carbon
Linear Accelerator
Ion Source Proton
Scanning System
Monitor System
Radiation Control Cross-section through the irradiated tumor volume. Every section represents a different beam range. The treated elements are shown in green
Scanning Magnets
Wire Chambers
Ionization Chambers
Target Volume
Depth 5 cm: Proton 80 MeV/u Carbon 145 MeV/u
Depth 10 cm: Proton 115 MeV/u Carbon 220 MeV/u

Between June 1985 and January 1987, a computer-controlled radiation therapy machine, called the Therac-25, massively overdosed six people. These accidents have been described as the worst in the 35-year history of medical accelerators [6].

Nancy Leveson
Safeware: System Safety and Computers
Addison-Wesley, 1995

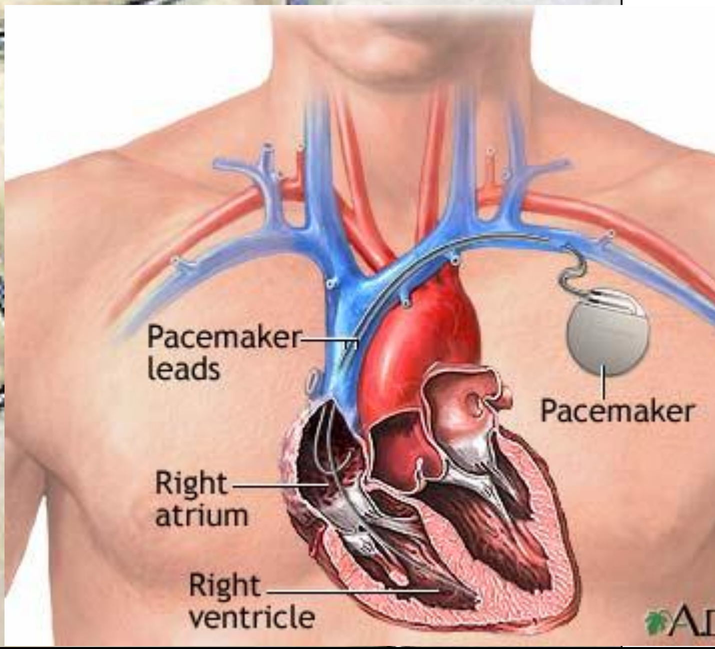
Life-Critical Medical Devices



December 2004

In 1 of every 12,000 settings, the software can cause an error in the programming resulting in the possibility of producing paced rates up to 185 beats/min. It is possible that one or both rate response sensors (i.e., breathing sensor and activity sensor) are switched on, but the timer reset for one or both sensors erroneously remains disabled. In this scenario, the clock timer and the rate response timers can trigger a pace. Of course, with three possible triggers now working independently this can result in high pacing rates.

[Journal of Pacing and Clinical Electrophysiology]



Life-Critical Medical Devices

Air-Traffic Control System in LA Airport

- *Incident Date: 9/14/2004*
- *(IEEE Spectrum) -- It was an air traffic controller's worst nightmare. Without warning, on Tuesday, 14 September, at about 5 p.m. Pacific daylight time, air traffic controllers lost voice contact with 400 airplanes they were tracking over the southwestern United States. Planes started to head toward one another, something that occurs routinely under careful control of the air traffic controllers, who keep airplanes safely apart. But now the controllers had no way to redirect the planes' courses.*
- *The controllers lost contact with the planes when the main voice communications system shut down unexpectedly. To make matters worse, a backup system that was supposed to take over in such an event crashed within a minute after it was turned on. The outage disrupted about 800 flights across the country.*
- *Inside the control system unit is a countdown timer that ticks off time in milliseconds. The VCSU uses the timer as a pulse to send out periodic queries to the VSCS. It starts out at the highest possible number that the system's server and its software can handle—2^{32}. It's a number just over 4 billion milliseconds. When the counter reaches zero, the system runs out of ticks and can no longer time itself. So it shuts down.*
- *Counting down from 2^{32} to zero in milliseconds takes just under 50 days. The FAA procedure of having a technician reboot the VSCS every 30 days resets the timer to 2^{32} almost three weeks before it runs out of digits.*

Zune 30 leapyear problem

- December 31, 2008
- "After doing some poking around in the **source code for the Zune's clock driver** (available free from the Freescale website), I found the root cause of the now-infamous Zune 30 leapyear issue that struck everyone on New Year's Eve. The Zune's real-time clock stores the time in terms of days and seconds since January 1st, 1980. When the Zune's clock is accessed, the driver turns the number of days into years/months/days and the number of seconds into hours/minutes/seconds. Likewise, when the clock is set, the driver does the opposite.
- The Zune frontend first accesses the clock toward the end of the boot sequence. Doing this triggers the code that reads the clock and converts it to a date and time..."
- "...The function keeps subtracting either 365 or 366 until it gets down to less than a year's worth of days, which it then turns into the month and day of month. Thing is, in the case of the last day of a leap year, it keeps going until it hits 366. Thanks to the if (days > 366), it stops subtracting anything if the loop happens to be on a leap year. But 366 is too large to break out of the main loop, meaning that the Zune keeps looping forever and doesn't do anything else."

http://www.zuneboards.com/forums/zune-news/38143-cause-zune-30-leapyear-problem-isolated.html

More Information

http://mtc.epfl.ch/~tah/Lectures/EPFL-Inaugural-Dec06.pdf

http://www.cse.lehigh.edu/~gtan/bug/softwarebug.html

Success Stories

ASTREE Analyzer

"In Nov. 2003, ASTRÉE was able to prove completely automatically the absence of any RTE in the primary flight control software of the Airbus A340 fly-by-wire system, a program of 132,000 lines of C analyzed in 1h20 on a 2.8 GHz 32-bit PC using 300 Mb of memory (and 50mn on a 64-bit AMD Athlon™ 64 using 580 Mb of memory)."

- http://www.astree.ens.fr/

AbsInt

- 7 April 2005. AbsInt contributes to guaranteeing the safety of the A380, the world's largest passenger aircraft. The Analyzer is able to verify the proper response time of the control software of all components by computing the worst-case execution time (WCET) of all tasks in the flight control software. This analysis is performed on the ground as a critical part of the safety certification of the aircraft.

Interactive Theorem Provers

- A Mechanically Checked Proof of IEEE Compliance of a Register-Transfer-Level Specification of the AMD K7 Floating Point Multiplication, Division and Square Root Instructions, doine using ACL2 Prover
- Formal certification of a compiler back-end, or: programming a compiler with a proof assistant. by Xavier Leroy

Coverity Prevent

- SAN FRANCISCO - January 8, 2008 - Coverity®, Inc., the leader in improving software quality and security, today announced that as a result of its contract with US Department of Homeland Security (DHS), **potential security and quality defects** in 11 popular open source software projects were **identified and fixed**. The 11 projects are **Amanda, NTP, OpenPAM, OpenVPN, Overdose, Perl, PHP, Postfix, Python, Samba, and TCL.**

Microsoft's Static Driver Verifier

Static Driver Verifier (SDV) is a thorough, compile-time, static verification tool designed for kernel-mode drivers. SDV finds serious errors that are unlikely to be encountered even in thorough testing. SDV systematically analyzes the source code of Windows drivers that are written in the C language. SDV uses a set of interface rules and a model of the operating system to determine whether the driver interacts properly with the Windows operating system.

SDV can verify device drivers (function drivers, filter drivers, and bus drivers) that use the Windows Driver Model (WDM), Kernel-Mode Driver Framework (KMDF), or NDIS miniport model. SDV is designed to be used throughout the development cycle. You should run SDV as soon as the basic structure of a driver is in place, and continue to run it as you make changes to the driver. Development teams at Microsoft use SDV to improve the quality of the WDM, KMDF, and NDIS miniport drivers that ship with the operating system and the sample drivers that ship with the Windows Driver Kit (WDK).

SDV is included in the Windows Driver Kit (WDK) and supports all x86-based and x64-based build environments.

Impact on Computer Science

Turing award is ACM's most prestigious award and equivalent to Nobel prize in Computing

In the next slides are some papers written by the award winners connected to the topics of this class

- A Basis for a Mathematical Theory of Computation by **John McCarthy**, 1961.

"It is reasonable to hope that the relationship between computation and mathematical logic will be as fruitful in the next century as that between analysis and physics in the last. The development of this relationship demands a concern for both applications and for mathematical elegance."

- Social processes and proofs of theorems and programs a controversial article by Richard A. De Millo, Richard J. Lipton, and Alan J. Perlis
- Guarded Commands, Nondeterminacy and Formal Derivation of Programs by Edsger W. Dijkstra from 1975, and other Manuscripts
- Simple word problems in universal algebras by D. Knuth and P. Bendix (see Knuth-Bendix_completion_algorithm), used in automated reasoning

- Decidability of second-order theories and automata on infinite trees by **Michael O. Rabin** in 1965, proving decidability for one of the most expressive decidable logics
- Domains for Denotational Semantics by **Dana Scott**, 1982
- Can programming be liberated from the von Neumann style?: a functional style and its algebra of programs by **John Backus**
- Assigning meanings to programs by R. W. **Floyd**, 1967
- The Ideal of Verified Software by **C.A.R. Hoare**
- Soundness and Completeness of an Axiom System for Program Verification by **Stephen A. Cook**
- An Axiomatic Definition of the Programming Language PASCAL by
  C. A. R. Hoare and **Niklaus Wirth**, 1973
- On the Computational Power of Pushdown Automata, by Alfred V. Aho, Jeffrey D. Ullman, **John E. Hopcroft** in 1970
- An Algorithm for Reduction of Operator Strength by **John Cocke**, Ken Kennedy in 1977

- A Metalanguage for Interactive Proof in LCF by Michael J. C. Gordon, **Robin Milner**, L. Morris, Malcolm C. Newey, Christopher P. Wadsworth, 1978
- Proof Rules for the Programming Language Euclid, by Ralph L. London, John V. Guttag, James J. Horning, **Butler W. Lampson**, James G. Mitchell, Gerald J. Popek, 1978
- Computational Complexity and Mathematical Proofs by **J. Hartmanis**
- Software reliability via run-time result-checking by **Manuel Blum**
- The Temporal Logic of Programs, by **Amir Pnueli** (see also the others of a few hundreds of publications)
- No Silver Bullet - Essence and Accidents of Software Engineering, by
  Frederick P. Brooks Jr., 1987

- Formal Development with ABEL, by **Ole-Johan Dahl** and Olaf Owe
- Abstraction Mechanisms in the Beta Programming Language, by Bent Bruun Kristensen, Ole Lehrmann Madsen, Birger Møller-Pedersen, **Kristen Nygaard**, 1983
- Formalization in program development, by **Peter Naur**, 1982
- Interprocedural Data Flow Analysis, by **Frances E. Allen**, 1974
- Counterexample-guided abstraction refinement for symbolic model checking by **Edmund Clarke**, Orna Grumberg, Somesh Jha, Yuan Lu, Helmut Veith, 2003
- Automatic Verification of Finite-State Concurrent Systems Using Temporal Logic Specifications by Edmund M. Clarke, **E. Allen Emerson**, A. Prasad Sistla
- The Algorithmic Analysis of Hybrid Systems by Rajeev Alur, Costas Courcoubetis, Nicolas Halbwachs, Thomas A. Henzinger, Pei-Hsin Ho, Xavier Nicollin, Alfredo Olivero, **Joseph Sifakis**, Sergio Yovine

How to prove programs

Proving Program Correctness

```
int f(int x, int y)
{
  if (y == 0) {
    return 0;
  } else {
   if (y % 2 == 0) {
     int z = f(x, y / 2);
     return (2 * z);
   } else {
     return (x + f(x, y - 1));
   }
  }
}
```

- What does ‘f’ compute?
- How can we prove it?

By translating Java code into math, we obtain the following mathematical definition of f:

$$f(x,y) = \begin{cases} 0, & \text{if } y = 0 \\ 2f(x, \lfloor \frac{y}{2} \rfloor), & \text{if } y > 0, \text{ and } y = 2k \text{ for some } k \\ x + f(x, y-1), & \text{if } y > 0, \text{ and } y = 2k+1 \text{ for some } k \end{cases}$$

By induction on y we then prove $f(x,y) = x \cdot y$.

- **Base case.** Let $y = 0$. Then $f(x,y) = 0 = x \cdot 0$
- **Inductive hypothesis.** Assume that the claim holds for all values less than y.
    - Goal: show that it holds for y where $y > 0$.
    - **Case 1:** $y = 2k$. Note $k < y$. By definition and I.H.

$$f(x,y) = f(x,2k) = 2f(x,k) = 2(xk) = x(2k) = xy$$

-
    - **Case 2:** $y = 2k+1$. Note $y - 1 < y$. By definition and I.H.

$$f(x,y) = f(x,2k+1) = x + f(x,2k) = x + x \cdot (2k) = x(2k+1) = xy$$

This completes the proof.

An imperative version

```
int fi(int x, int y)
{
    int r = 0;
    int i = 0;
    while (i < y) {
      i = i + 1;
      r = r + x;
    }
    return r;
}
```

- What does ‘fi’ compute?
- How can we prove it?

Preconditions, Postconditions, Invariants

```
void p()
/*: requires Pre
     ensures Post */
{
  s1;
  while /*: invariant 𝒥 */   (e) {
   s2;
  }
  s3;
}
```

Loop Invariant

$\mathcal{I}$ is a loop invariant if the following three conditions hold:

- $\mathcal{I}$ **holds initially**: in all states satisfying *Pre*, when execution reaches loop entry, $\mathcal{I}$ holds
- $\mathcal{I}$ is **preserved**: if we assume $\mathcal{I}$ and loop condition *(e)*, we can prove that $\mathcal{I}$ will hold again after executing *s2*
- $\mathcal{I}$ is **strong enough**: if we assume $\mathcal{I}$ and the negation of loop condition *e,* we can prove that *Post* holds after *s3*

Explanation: because $\mathcal{I}$ holds initially, and it is preserved, by induction from **holds initially** and **preserved** follows that $\mathcal{I}$ will hold in every loop iteration. The **strong enough** condition ensures that when loop terminates, the rest of the program will satisfy the desired postcondition.

Back to our Program: what is Invariant, Precondition, Postcondition

```
int fi(int x, int y)
{
    int r = 0;
    int i = 0;
    while (i < y) {
      i = i + 1;
      r = r + x;
    }
    return r;
}
```

- What does ‘fi’ compute?
- **How can we prove it?**

Bubbling up an Element in Bubble Sort (not shown)

```
int apartmentRents[];
int grades[];
...
void bubbleUp(int[] a, int from)
{
   int i = from;
   while (i < a.length) {




   }
}
```

Proving

- array indices are within bounds
- the element in a[from] is smaller than those stored after ‘from’
- property sufficient to prove correctness of bubble sort

How can we automate verification?

Important algorithmic questions:

- **verification condition generation**: compute formulas expressing program correctness
    - Hoare logic, weakest precondition, strongest postcondition
- theorem proving: prove verification conditions
    - proof search, counterexample search
    - decision procedures
- **loop invariant inference**
    - predicate abstraction
    - abstract interpretation and data-flow analysis
    - pointer analysis, typestate
- reasoning about numerical computation
- pre-condition and post-condition inference
- ranking error reports and warnings
- finding error causes from counterexample traces

Spec Sharp: the Movie

- See webcasts by Mike Barnett
  minutes 8 to 22