Embedded Systems In the Real World

Introduction to Embedded Systems

Philip Koopman

January 14, 1999

Further Reading: **http://www.ices.cmu.edu/koopman/embedded.html**

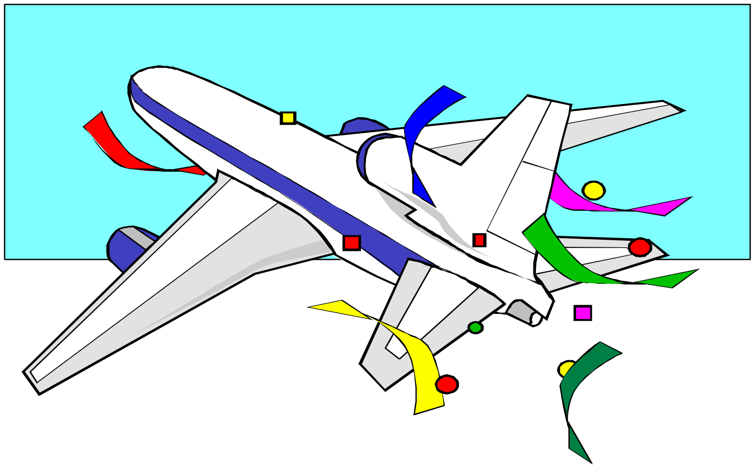
Carnegie Mellon

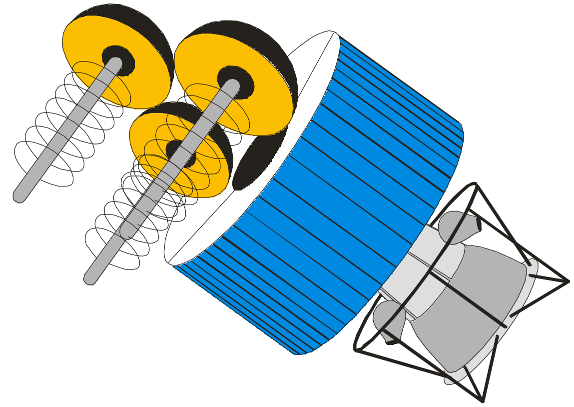
Preview

- **What is an embedded system?**
  - More than just a computer

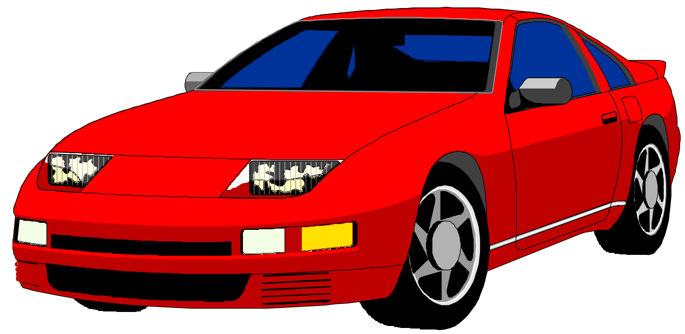
- **What makes them different?**
  - Real time operation
  - Many sets of constraints on designs

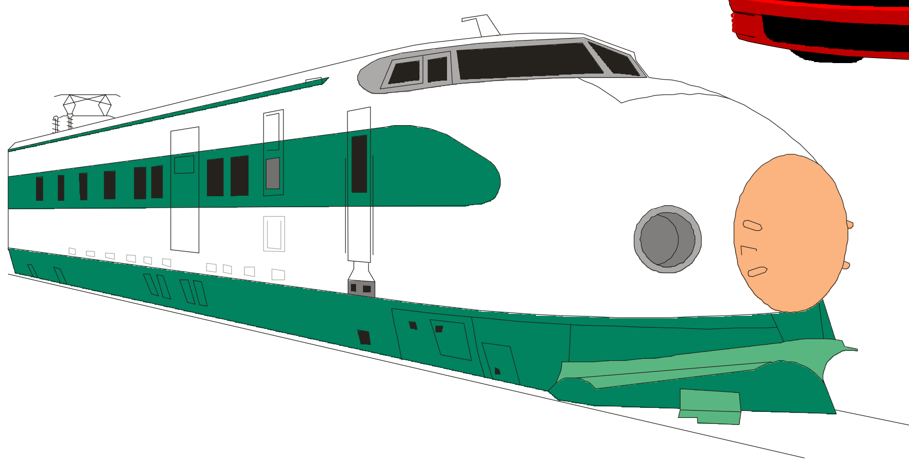
- **What embedded system designers need to know**
  - The big picture
  - Skills required to “play” in this area

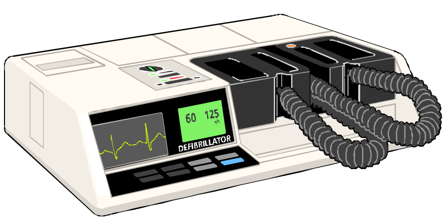




WHAT IS AN EMBEDDED SYSTEM?







Definition of an Embedded Computer

- **Computer purchased as part of some other piece of equipment**
  - Typically dedicated software (may be user-customizable)
  - Often replaces previously electromechanical components
  - Often no “real” keyboard
  - Often limited display or no general-purpose display device

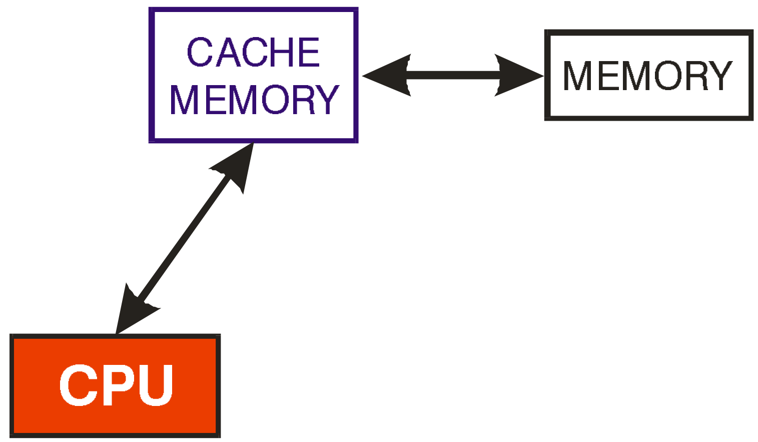
- **But, every system is unique -- there are always exceptions**

An All-Too-Common View of Computing

- Measured by: Performance

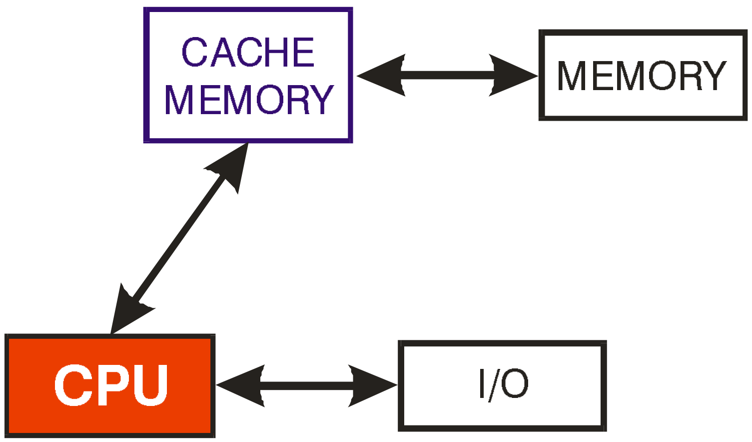
An Advanced Computer Engineer’s View

- **Measured by: Performance**
  - Compilers matter too…



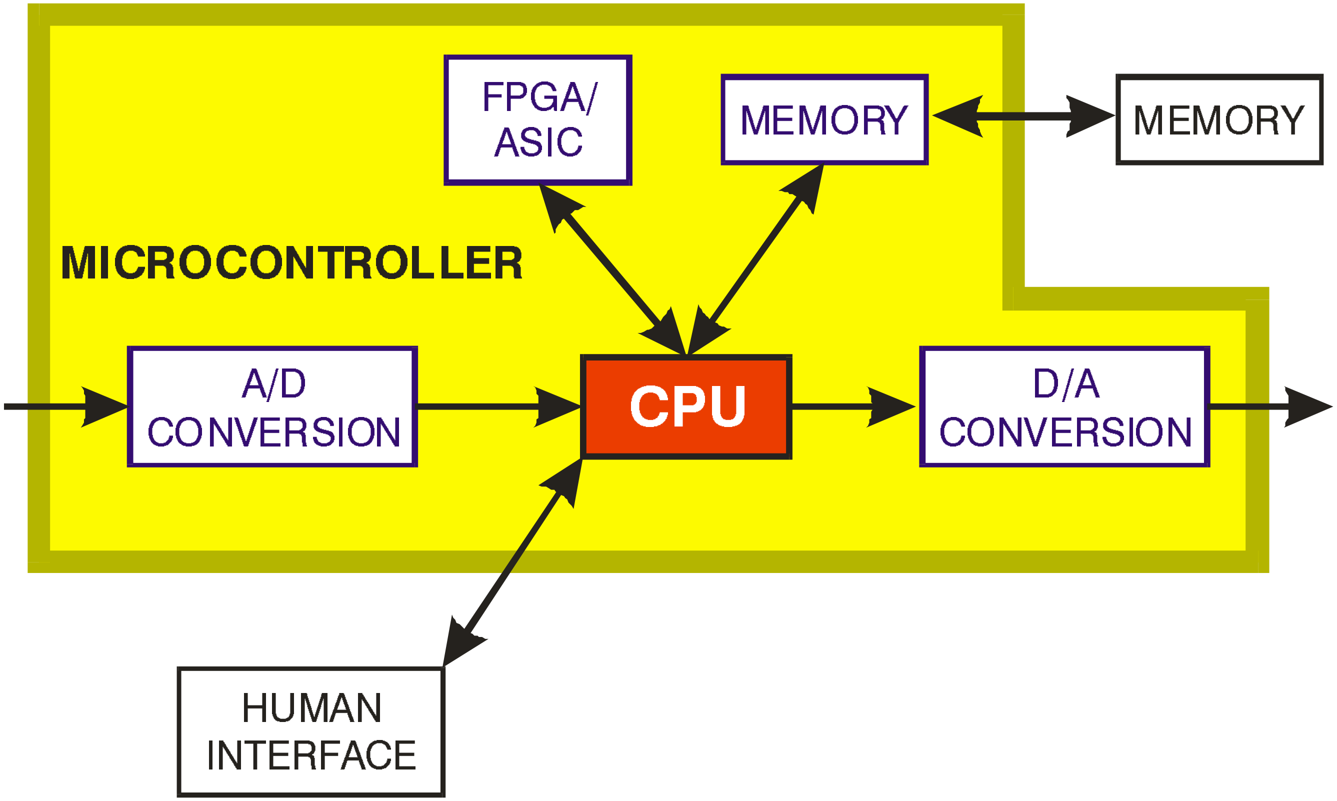
An Enlightened Computer Engineer's View

- **Measured by: Performance, Cost**
  - Compilers & OS matter



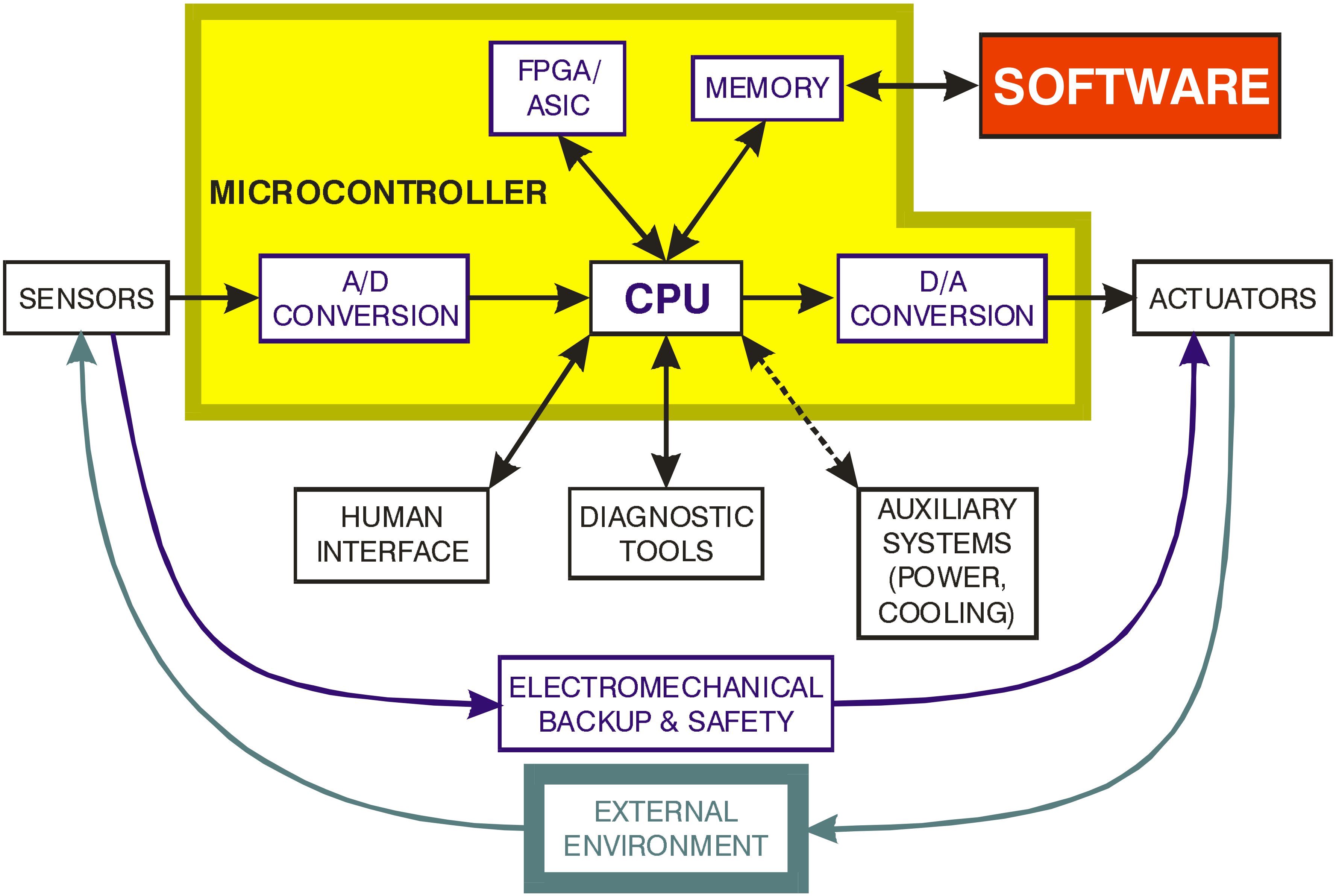
An Embedded Computer Designer's View

- **Measured by: Cost, I/O connections, Memory Size, Performance**



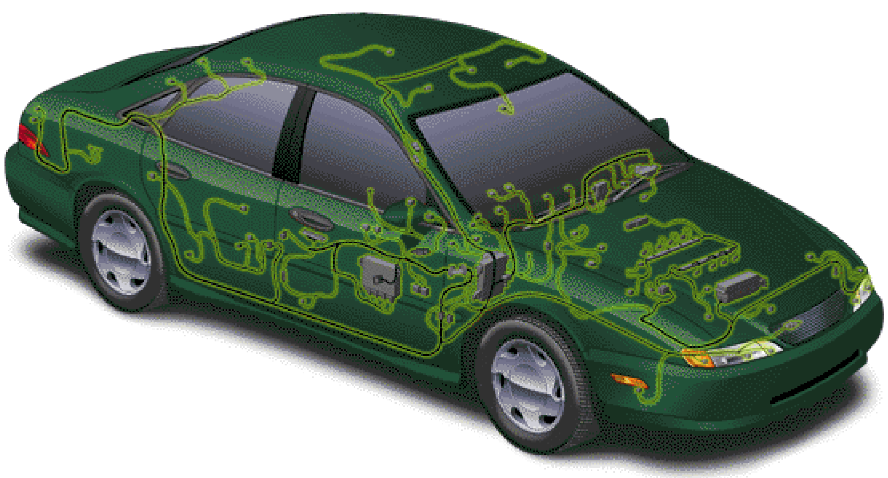
An Embedded Control System Designer's View

- **Measured by: Cost, Time-to-market, Cost, Functionality, Cost & Cost.**

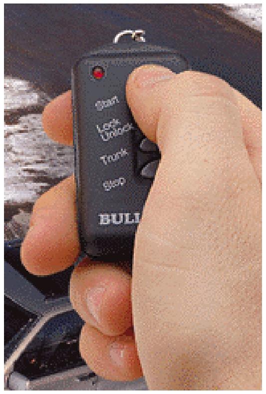


A Customer View

- **Reduced Cost**
- **Increased Functionality**
- **Improved Performance**
- **Increased Overall Dependability**
    - (Debatable, but can be true)



Three Embedded Examples



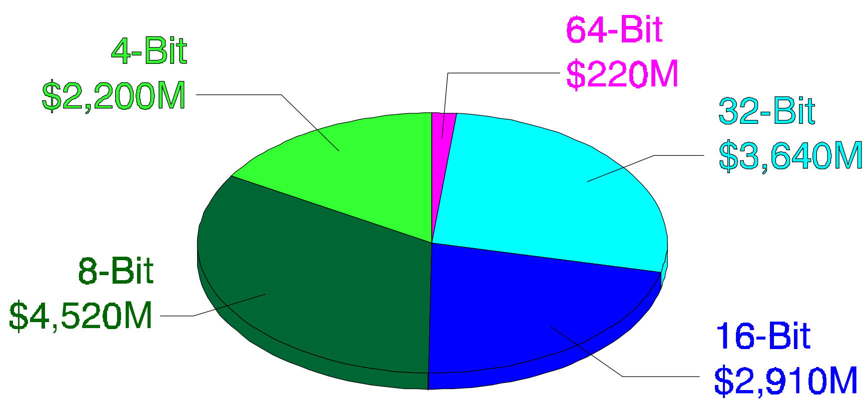
- **Pocket remote control RF transmitter**
  - 100 KIPS, water/crush-proof, fits in pocket, 5-year battery life
  - Software hand-crafted for small size (less than 1 KB)

- **Industrial equipment controller (e.g., elevator; jet engine)**
  - 1-10 MIPS for 1 to 10 CPUs, 1 - 8 MB memory
  - Safety-critical software; real-time control loops

- **Military signal processing (e.g., Radar/Sonar)**
  - 1 GFLOPS, 1 GB/sec I/O, 32 MB memory
  - Software hand-crafted for high performance

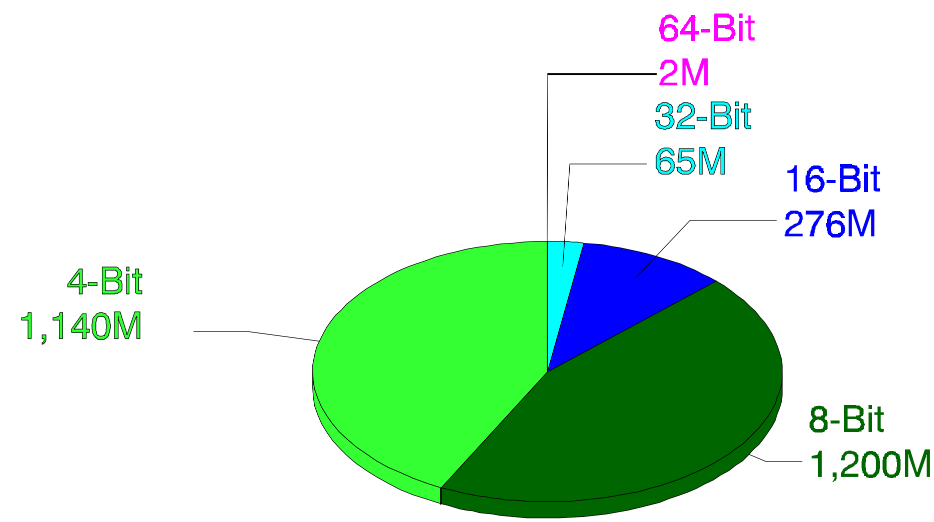
Small Computers Rule The Marketplace

- **~80 Million PCs vs. ~3 Billion Embedded CPUs Annually**
  - Embedded market growing; PC market mostly saturated



$13,490M Total

1994 Worldwide
Microcontroller Revenue
($Million U.S.)



2,683M Total

1994 Worldwide
Microcontroller Units
(Million Devices)

Approximated from EE Times, March 20, 1995
Source: The Information Architects

WHY ARE EMBEDDED SYSTEMS DIFFERENT FROM DESKTOP COMPUTERS?

Four General Embedded System Types

- **General Computing**
  - Applications similar to desktop computing, but in an embedded package
  - Video games, set-top boxes, wearable computers, automatic tellers
- **Control Systems**
  - Closed-loop feedback control of real-time system
  - Vehicle engines, chemical processes, nuclear power, flight control
- **Signal Processing**
  - Computations involving large data streams
  - Radar, Sonar, video compression
- **Communication & Networking**
  - Switching and information transmission
  - Telephone system, Internet

Types of Embedded System Functions

- **Control Laws**
  - PID control
  - Fuzzy logic, …
- **Sequencing logic**
  - Finite state machines
  - Switching modes between control laws
- **Signal processing**
  - Multimedia data compression
  - Digital filtering
- **Application-specific interfacing**
  - Buttons, bells, lights,…
  - High-speed I/O
- **Fault response**
  - Detection & reconfiguration
  - Diagnosis

Distinctive Embedded System Attributes

- **Reactive: computations occur in response to external events**
  - Periodic events (*e.g.*, rotating machinery and control loops)
  - Aperiodic events (*e.g.*, button closures)
- **Real Time: correctness is partially a function of time**
  - Hard real time
    - Absolute deadline, beyond which answer is useless
    - (May include minimum time as well as maximum time)
  - Soft real time
    - Approximate deadline
    - Utility of answer degrades with time difference from deadline
  - In general Real Time != "Real Fast"

Typical Embedded System Constraints

- **Small Size, Low Weight**
  - Hand-held electronics
  - Transportation applications -- weight costs money
- **Low Power**
  - Battery power for 8+ hours (laptops often last only 2 hours)
  - Limited cooling may limit power even if AC power available
- **Harsh environment**
  - Heat, vibration, shock
  - Power fluctuations, RF interference, lightning
  - Water, corrosion, physical abuse
- **Safety-critical operation**
  - Must function correctly
  - Must *not* function *in*correctly
- **Extreme cost sensitivity**
  - $.05 adds up over 1,000,000 units

A SAMPLING OF WHAT EMBEDDED DESIGNERS MUST DEAL WITH

Embedded System Design World-View

- **A complex set of tradeoffs**
  - Optimize for more than just speed
  - Consider more than just the computer
  - Take into account more than just initial product design

<u>Multi-Objective</u>

- Dependability
- Affordability
- Safety
- Security
- Scalability
- Timeliness

×

<u>Multi-Discipline</u>

- Electronic Hardware
- Software
- Mechanical Hardware
- Control Algorithms
- Humans
- Society/Institutions

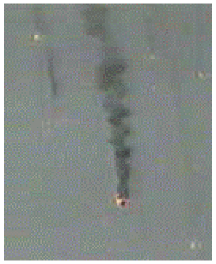
×

<u>Life Cycle</u>

- Requirements
- Design
- Manufacturing
- Deployment
- Logistics
- Retirement

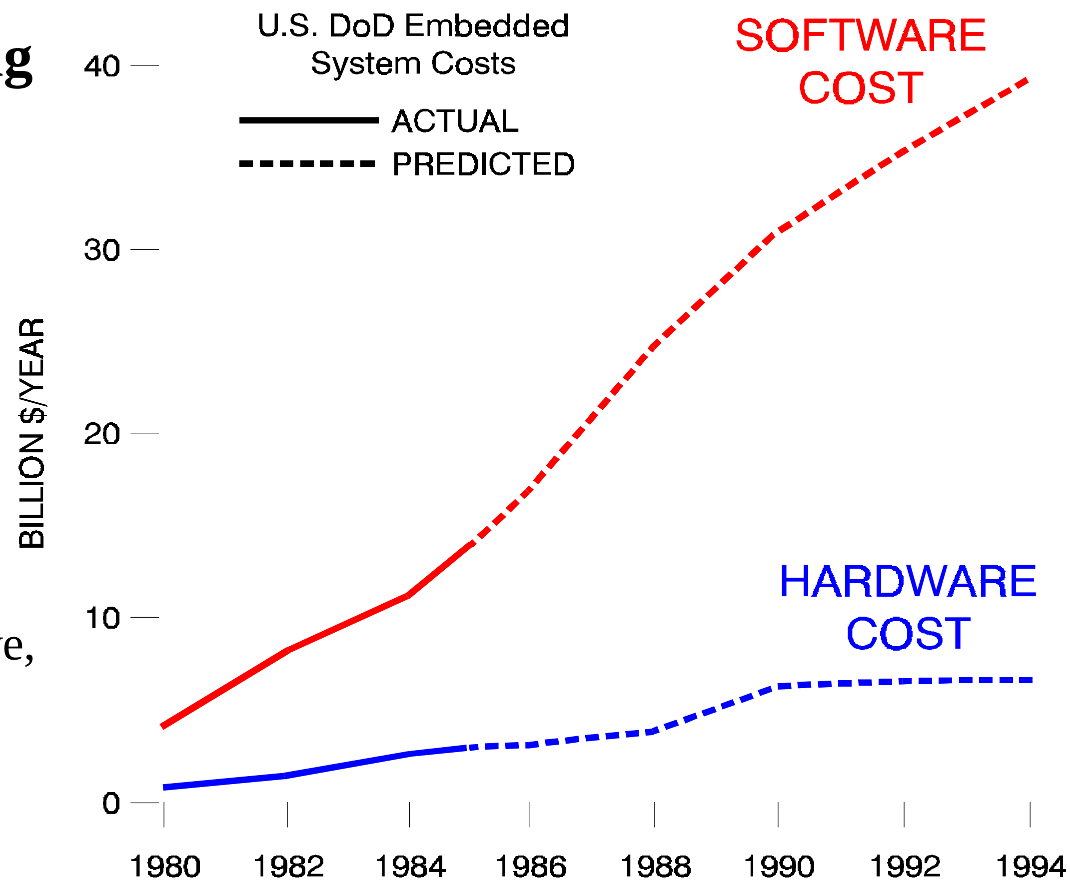
Mission-Critical Applications Require Robustness

- **June, 1996 loss of inaugural flight**
  - Lost $400 million scientific payload (the rocket was extra)
- **Efforts to reduce system costs led to the failure**
  - Re-use of Inertial Reference System software from Ariane 4
  - Improperly handled exception caused by variable overflow during new flight profile (that wasn't simulated because of cost/schedule)
    - 64-bit float converted to 16-bit int assumed not to overflow
    - Exception caused dual hardware shutdown (because it was assumed software doesn't fail)
- **What really happened here?**
  - The narrow view: it was a software bug -- fix it
  - The broad view: the loss was caused by a lack of system robustness in an exceptional (unanticipated) situation
- **Many embedded systems must be *robust***



Software Drives Designs

- **Hardware is mostly a recurring cost**
  - Cost proportional to number of units manufactured
- **Software is a "one-time" non-recurring engineering design cost (NRE)**
  - Paid for "only once"
    - But bug fixes may be expensive, or impossible
  - Cost is related to complexity & number of functions
  - Market pressures lead to feature creep
  - ***SOFTWARE Is Not FREE!!!!!***

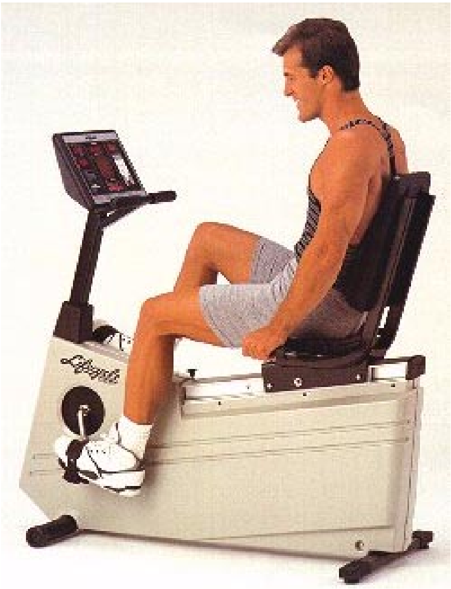


Source: *Software Requirements: objects, functions, states; Davis, 1993.*

Life-Cycle Concerns Figure Prominently

- **"Let's use a CAD system to re-synthesize designs for cost optimization"**
  - Automatically use whatever components are cheap that month
  - Would permit quick responses to bids for new variants
  - Track record of working fine for PC motherboards

- **Why wouldn't it work for an automotive application?**
  - Embedded system had more analog than digital -- mostly digital synthesis tool
  - Cost of re-certification for safety, FCC, warrantee repair rate
  - Design optimized for running power, not idle power
    - Car batteries must last a month in a parking lot
  - Parts cost didn't take into account life-cycle concerns
    - Price breaks for large quantities
    - Inventory, spares, end-of-life buy costs
  - Tool didn't put designs on a single sheet of paper
    - Archive system paper-based -- how else do you read 20-year-old files?



Embedded System Designer Skill Set

- **Appreciation for multi-disciplinary nature of design**
  - Both hardware & software skills
  - Understanding of engineering beyond digital logic
  - Ability to take a project from specification through production

- **Communication & teamwork skills**
  - Work with other disciplines, manufacturing, marketing
  - Work with customers to understand the real problem being solved
  - Make a good presentation; even better -- write “trade rag” articles

- **And, by the way, technical skills too…**
  - Low level: Microcontrollers, FPGA/ASIC, assembly language, A/D, D/A
  - High level: Object-oriented Design, C/C++, Real Time Operating Systems
  - Meta level: Creative solutions to highly constrained problems
  - Likely in the future: Unified Modeling Language, embedded networks
  - Uncertain future: Java, Windows CE

REVIEW

Review

- **What is an embedded system?**
  - More than just a computer -- it's a system

- **What makes embedded systems different?**
  - Many sets of constraints on designs
  - Four general types:
    - General Purpose
    - Control
    - Signal Processing
    - Communications

- **What embedded system designers need to know**
  - **Multi-objective:** cost, dependability, performance, *etc.*
  - **Multi-discipline:** hardware, software, electromechanical, *etc.*
  - **Life cycle:** specification, design, prototyping, deployment, support, retirement