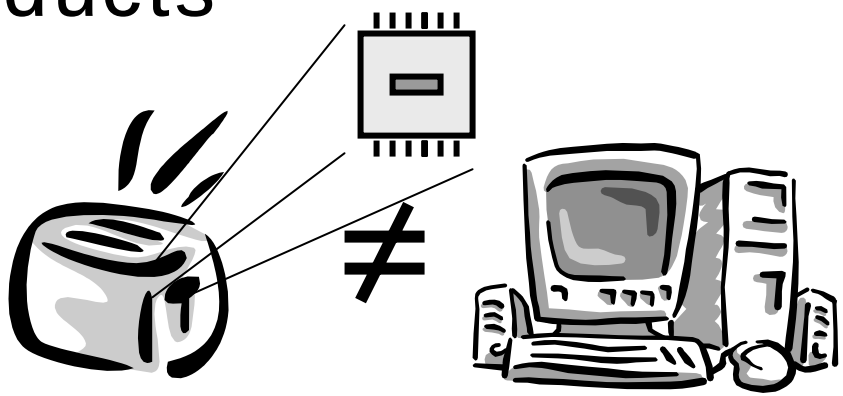
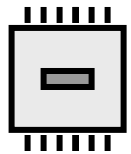
- “A computer that doesn’t look like a computer”
- Interacts with world
- Primitive or no user interface
- Part of other products



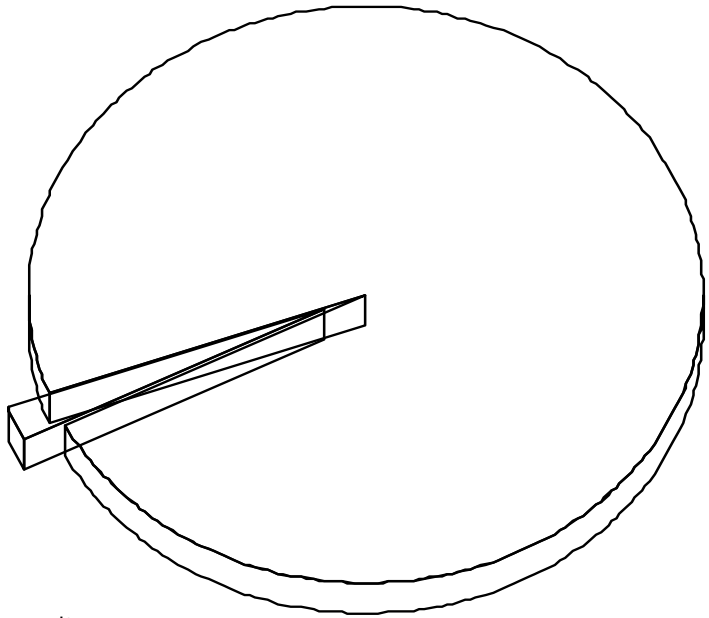
A product that contains a programmable processor

- Software programming is part of the design of the product



- Embedded = most processors!
  - 300 million PC and server
  - 9000 million embedded

"Desktop"
2%

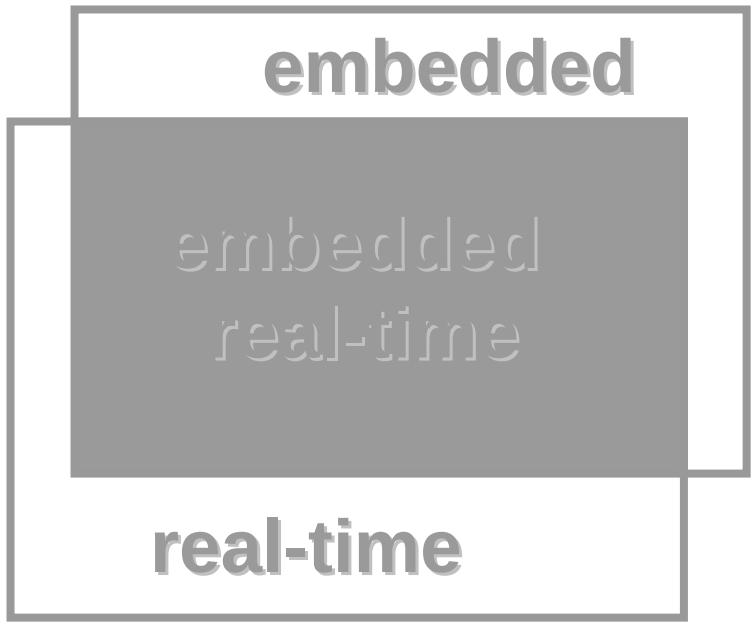


"Embedded"
98%

Embedded and Real-Time

- Synonymous?

- Most embedded systems are real-time
- Most real-time systems are embedded



- Single purpose products
  - Not *general purpose* like desktop PCs
  - Do one thing very efficiently
- Computer architecture
  - Tailor for a particular application niche
  - System applications known
    - Can select ”optimal” device
  - Specialization & workload knowledge!

Software very important:

- Gives character to product
- Used to differentiate inside a “platform”
- Can be changed late
- Many vendors use same HW
- Processor cheaper than special HW
  - Replace relays with small processor!
- Dominates HW development cost

- 4-bit:
  - Very simple & slow
  - 1970s pocket calculators
- 8-bit:
  - Simple, slow, low-power
  - Immensely popular (4 G/year)
  - Early 1980s home computers

16-bit

- More power than 8-bit
- Mid-1980s home computers
- Very popular: 1.5G/year
- Threatened from the 32-bit processors

32 & 64-bit

- Old desktop & server chips
- New desktop & server chips
- Embedded-specific designs
- 30 to 3000 MHz
- About 1.5G units/year
  - Many more than PC & server market
- ARM sells 1.2G units in 2004!

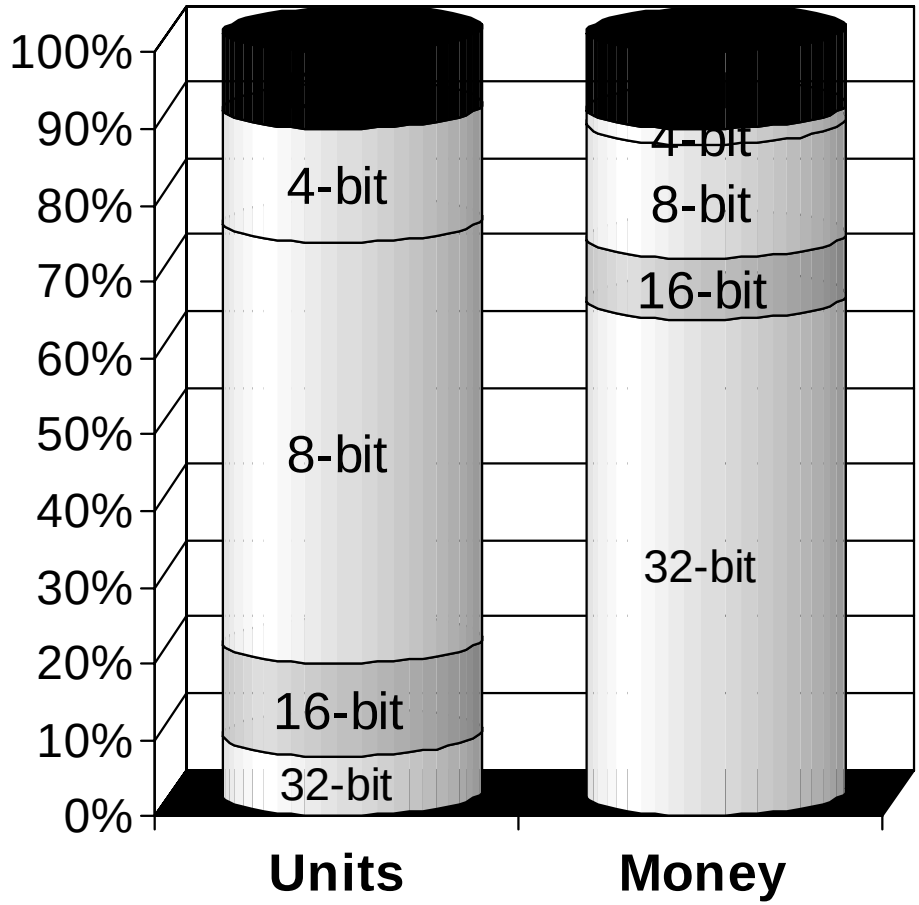
DSP: Digital Signal Processor

- Specialized for signal processing
  - Poor at general computing/control code
  - Poor interrupt handling
- High performance on DSP tasks
  - Low power, Low price
    - compared to regular processors of same capability
- Up to 1GHz clocks

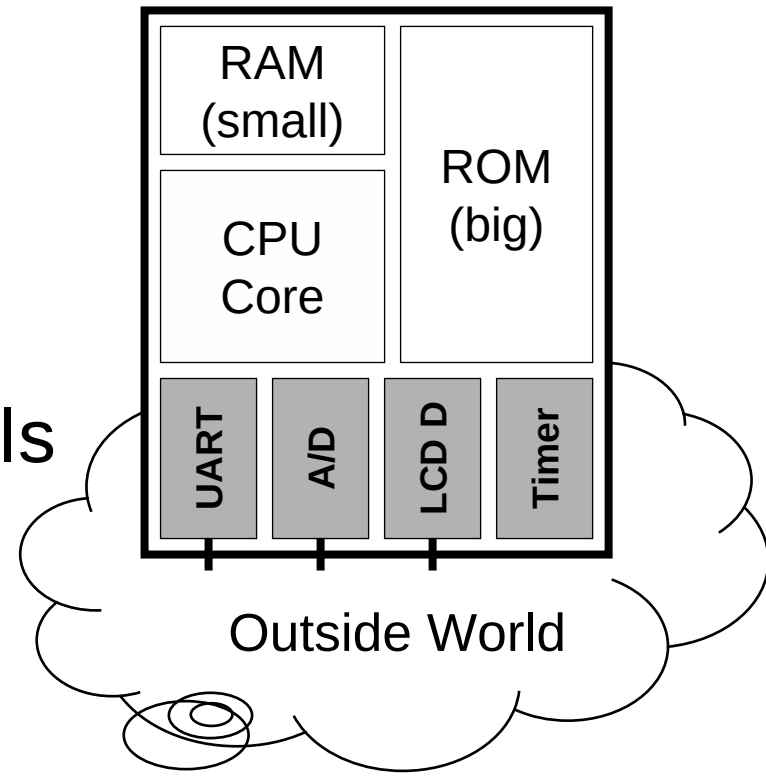
Processors:

- 50% of all semiconductor revenue
- Explains why everyone wants to do processors

- 32-bit dominant
  - 30% of total semiconductors
- PC processors:
  - 50% of CPU revenue
  - 15% of total semiconductors
  - AMD and Intel share it



- A single chip:
  - CPU Core
  - Integrated memory
  - Integrated peripherals
  - Integrated services
- Goal:
  - System on one chip
  - No external HW
  - Fit application “perfectly”



Interface with the world

- Digital inputs & outputs
  - 0/1 signals, like alarms & interrupts
  - Drive high/low outputs
- Analog inputs & outputs
  - Analog/Digital conversion
  - Digital/Analog conversion
  - Make signals digital, process, convert back to analog signals

Communications

- Standard networks
  - Ethernet, ATM, Sonet
  - Built for speed
- Control networks
  - CAN, Profibus, 1553
  - Built for predictability & efficiency
- Radio networks
  - WLAN, Zigbee, Bluetooth, DECT, GSM, ...
- Serial ports
- USB, FireWire

- Timers
  - Trigger interrupts
  - Keep track of real-world
    - Fuel injection & spark timing
  - Pulse-Width Modulation
- Watchdogs
  - Time out if not tickled
  - Watch that a system is alive

Graphics

- LCD drivers
- Graphics acceleration
- Camera drivers
- Video & image codecs in hardware

- Buses
  - On-chip between devices:
    - AMBA, OcEAN, CoreConnect
  - Off-chip:
    - PCI, HyperTransport, RapidIO, i2c, DDR

- Software dominates development
  - Hardware used to dominate
  - Software is now up to 85% of effort
  - Even when product is “full custom”
  - Especially in telecomm & datacomm
- Hardware is “under control”
  - Increasing use of standard components
  - Functionality moves to software

Talk by Lars Philipsson, LTH, 2004

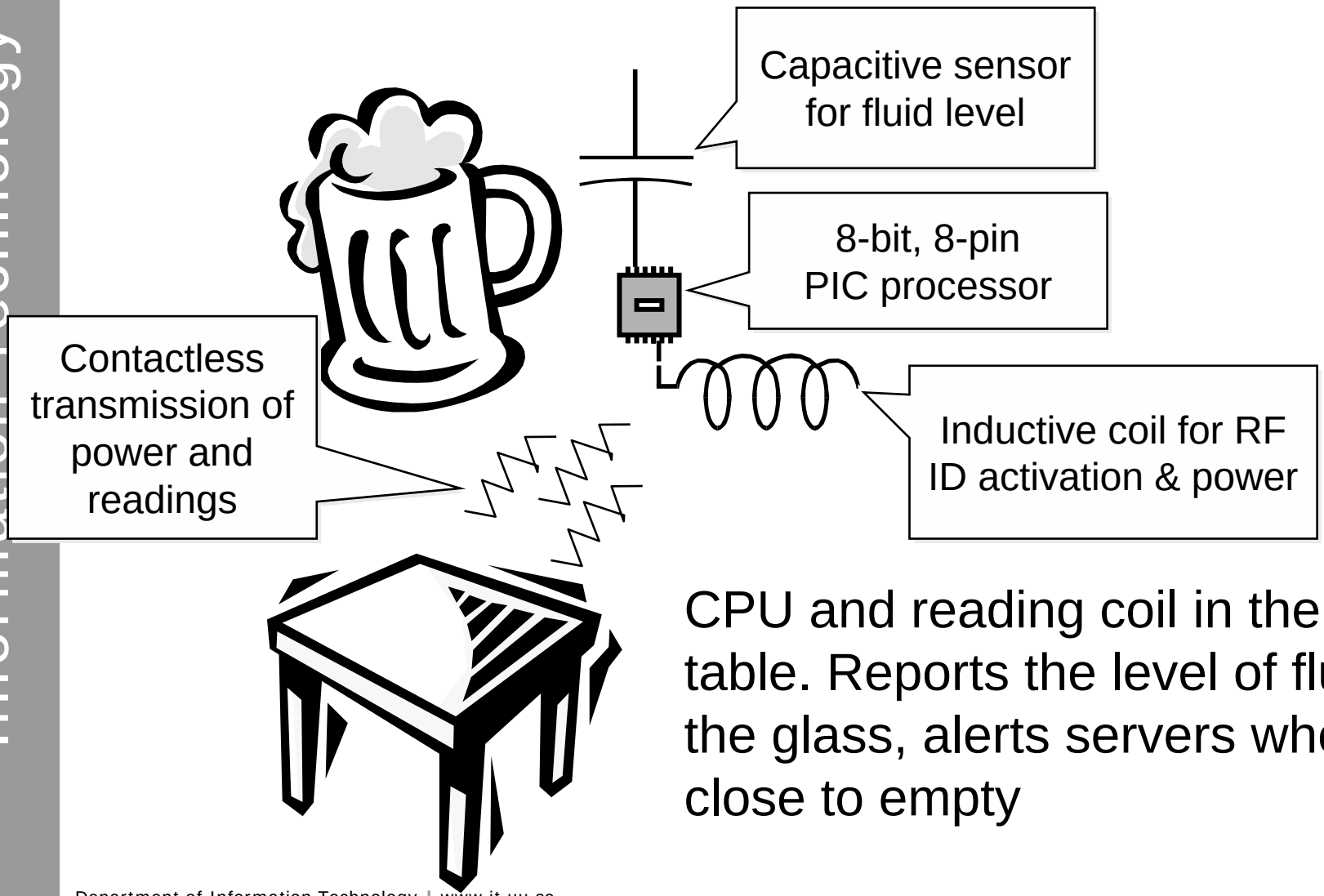
- What is the future of electrical engineering in Sweden?

- Answer:
  - Software work
    - Software replacing logic design
  - Some analog design work
    - Circuit-board design, high-speed circuits
  - Measuring technology

- Non-stop miniaturization and integration of computers
  - From one processor in a fridge
  - To thousands of processors on a chip
  - Steady trend over time
- One chip = one system
  - Processors, memories, electronics
    - Can be 100s of processors
  - “SoC”: System-on-a-Chip

Examples

Some embedded systems from real life



CPU and reading coil in the table. Reports the level of fluid in the glass, alerts servers when close to empty

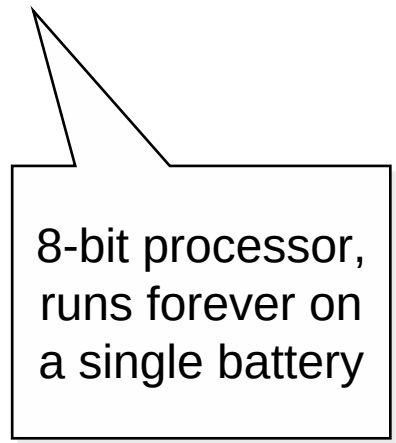
Typical embedded solution

- Integrates several technologies:
  - Radio transmissions
  - Sensor technology
  - Magnetic inductance for power
  - Computer used for calibration
- Impossible without the computer
- Meaningless without the electronics

Obvious computer work:

- Count steps
- Keep time
- Averages
- etc.

- Real computer task:
  - Sensor feels motion of device, not of user feet
  - Identify when a step is actually taken



Electronics control voltage & speed of wire feed

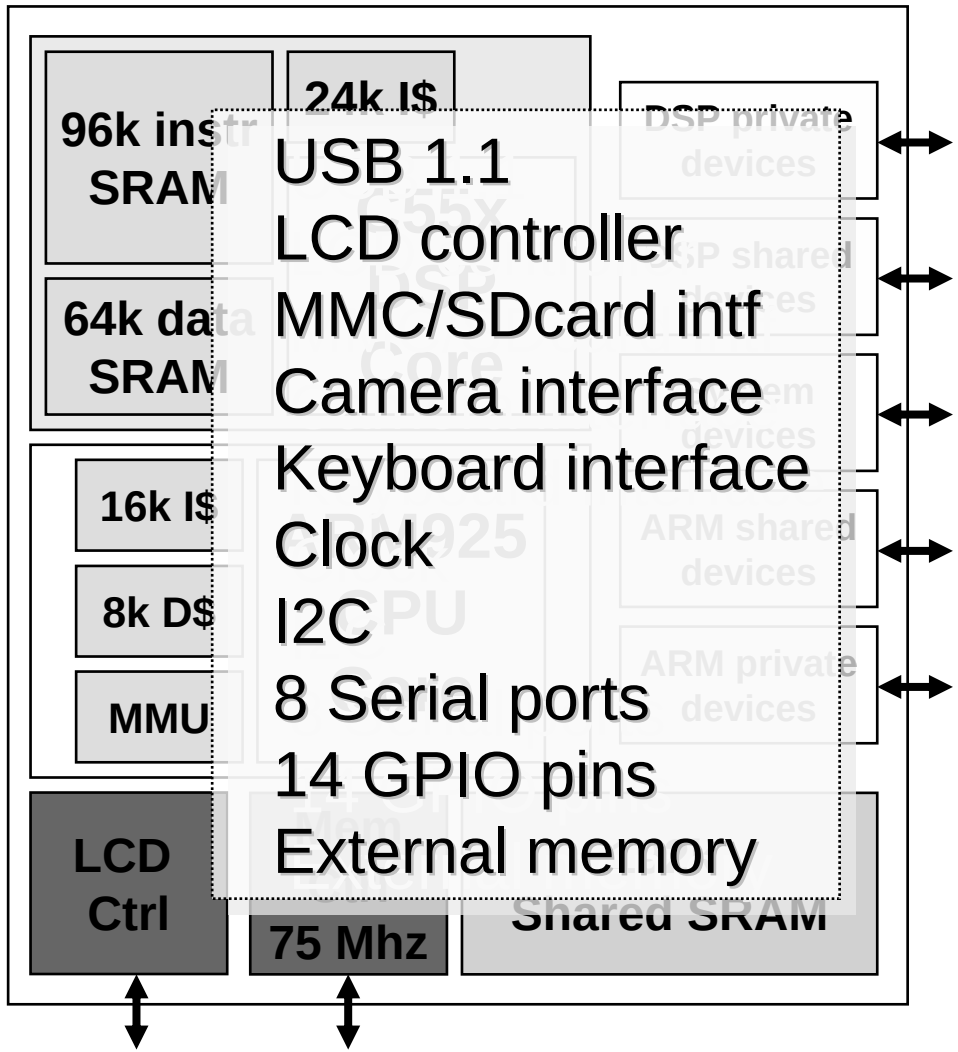
- Adjusts to operator
  - kHz sample rate
  - 1000s of decisions/second
- Perfect weld even for quite clumsy operators
- Easier-to-use product, but no obvious computer

- User interface
  - Embroidery patterns
  - Touch-screen control
- ”Smart”
  - Sets pressure of foot depending on task
  - Raise foot when stopped
- New functions added by upgrading the software

- Multiprocessor
  - 8-bit/32-bit for UI
  - DSP for signals
  - 32-bit in IR port
  - 32-bit in Bluetooth
  - 100-200 MHz
  - Not shared memory
- 8-100 MB of memory
- All custom chips
- Power consumption & battery life depends on software

Texas Instruments

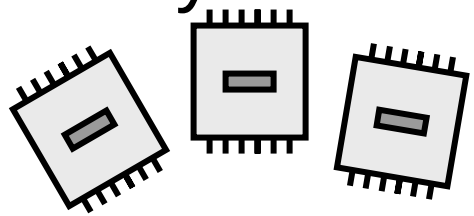
- Integrated solution for mobile phones
- Used by Nokia, Sony-Ericsson, etc.
- Dual-core chip
  - ARM925T 150 Mhz
  - TI C55 DSP 150 Mhz
- Power 230 mW
- Price 32 USD
- Competition:
  - Motorola
  - Infineon

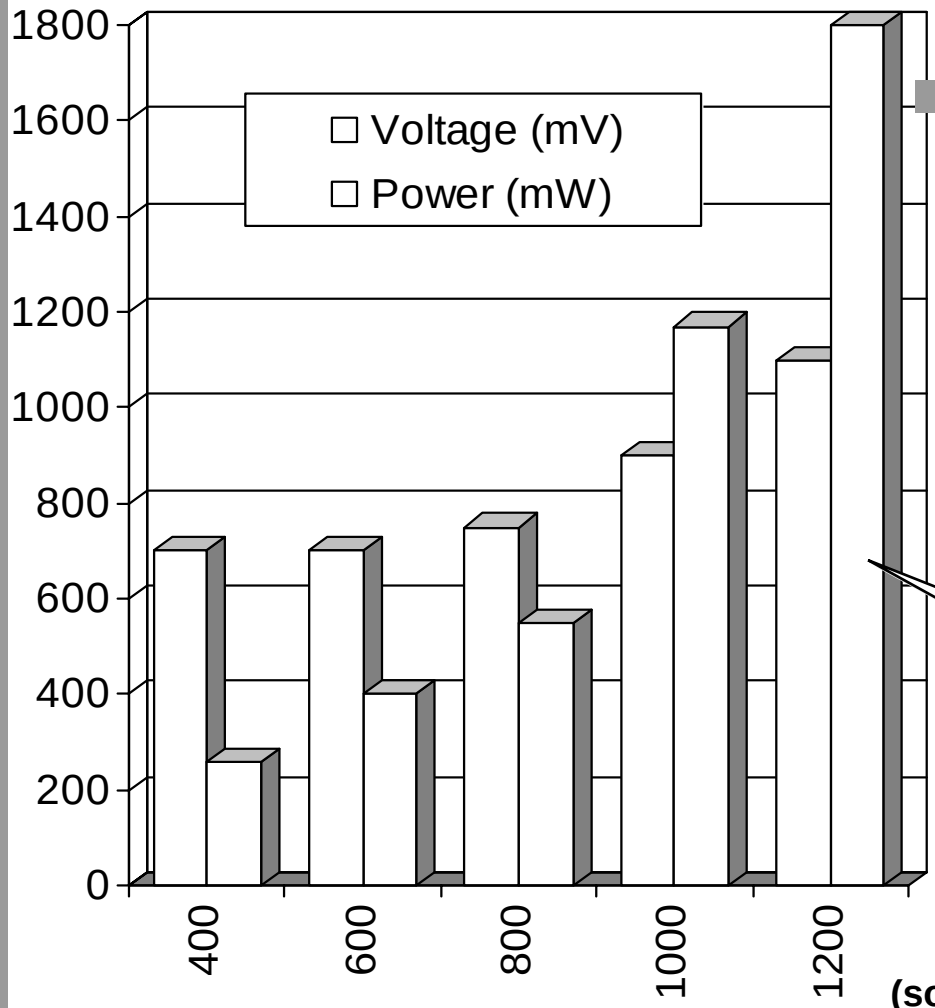


Clock and voltage related

- Higher operating frequency requires higher voltage

- Use lower clock speeds
  - Reduce speed until app barely works
- Use more processors
  - 1/2 speed = 1/4 power
  - 2 CPUs @ 100 Mhz = 1 CPU @ 200 Mhz, but requires half the power





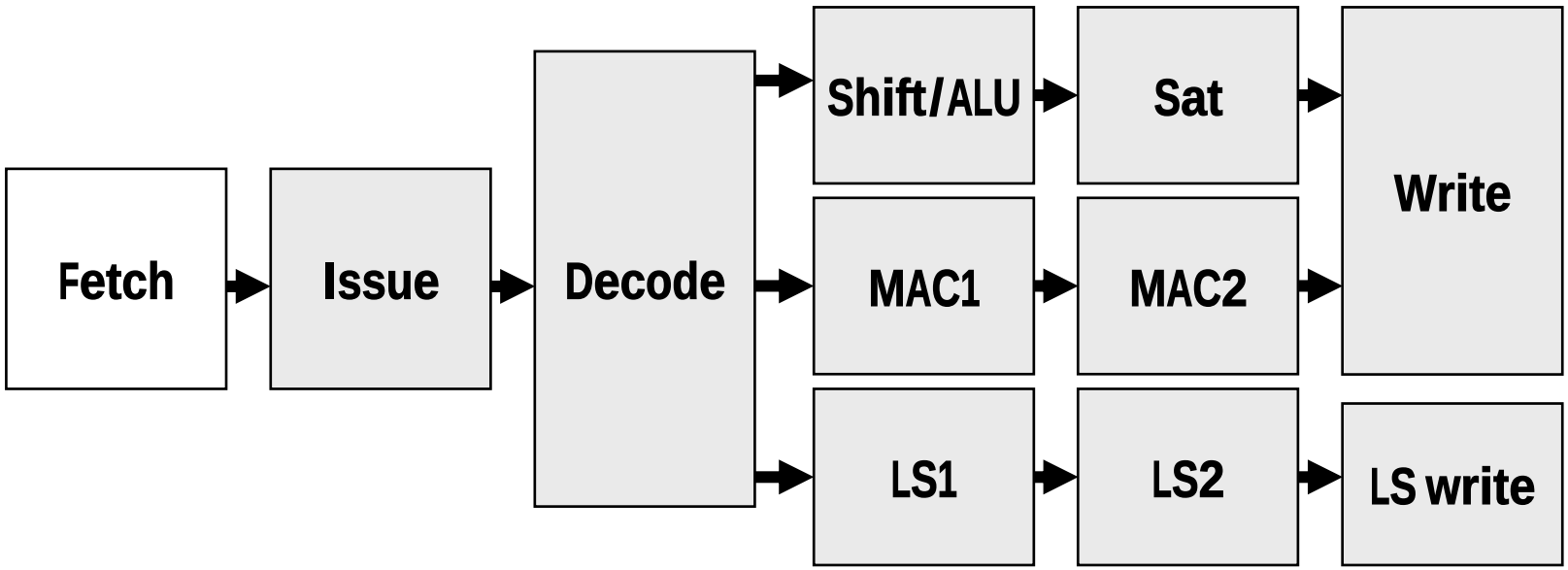
- Samsung Halla
  - ARM 1020E core
  - 6-stage pipeline (!)
  - 0.13 um process
  - Clock:
    400 Mhz to 1.2 Ghz

3x clock freq,
9x power!

(source: Microprocessor Report, Oct 16, 2002)

- ARM Thumb: fixed 16-bit size
  - Saves 28% compared to 32-bit ARM
  - Runs 20% slower than 32-bit ARM
- ARM Thumb 2: mixed 16/32
  - Saves 26% compared to 32-bit ARM
  - Runs 2% slower than 32-bit ARM
  - (Note that some new instructions are introduced)
- Conclusion: mixed length good!

Source: Microprocessor Report, June 2003


Fetch
Issue
Decode
Shift/ALU
Sat
Write
MAC1
MAC2
LS1
LS2
LS write

Assume very regular workloads
- Zero-overhead loop instructions

- Register sets
  - Accumulators (often 40 bits)
  - Data registers (often 16 bits)
  - Address registers (16 to 32 bits)
- Addressing modes
  - Index registers
  - Post & preincrement
  - Bit-reverse addressing
  - Goal: more parallelizable work per instruction

Example instructions fro

- ”Finite impulse response filter”
  - `FIRSADD Xmem, Ymem, Cmem, ACx, ACy`
  - Operation:
    - ACy = ACy + (ACx * Cmem)
    - ACx = (Xmem << #16) + (Ymem
- ”Conditional add or sub”
  - `ADDSUBCC Smem, ACx, TCx, ACy`
  - Operation:
    - If TCx = 1, then ACy = ACx + (Smem << #16)
    - If TCx = 0, then ACy = ACx - (Smem << #16)

Cmem, Xmem, Ymem: memory accesses + address updating

C55 DSP has three independent data buses, X, Y, and C

Special condition register

Massive signal processing

- Several processing tasks per connected mobile phone
- 1000s of independent parallel tasks = parallelizer's dream!

- Based on DSPs
  - Standard or custom
  - 500-1000 MHz
  - VLIW instruction sets
    - 4/8 way wide
  - 100s of processors
    - Serious supercomputer!

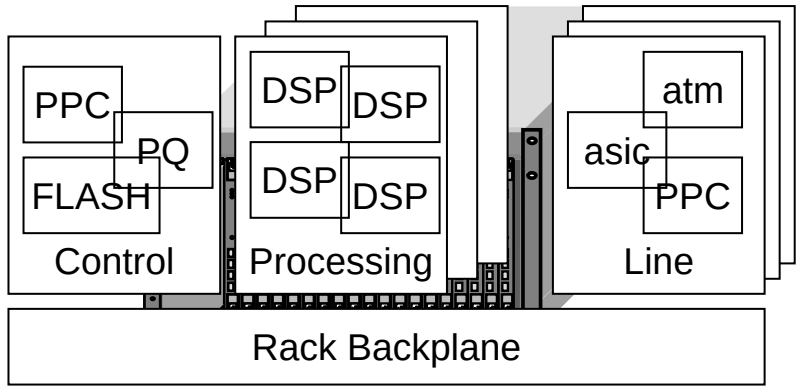
Core Network

- Optical & copper connections
- Digital & analog signals
  - Ethernet
  - ATM
  - Packet-over-Sonet
  - SS7
  - POTS

Rack-based systems

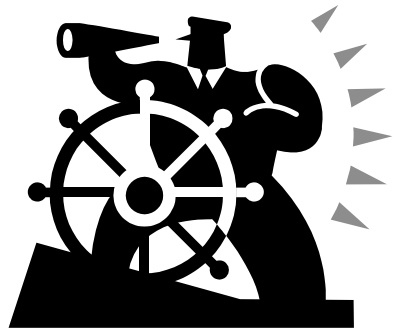
- 12-20 cards per shelf
- Many shelfs per rack
- 100s of CPUs

- Compute cards:
  - Run control code
  - 32-bit processors
- Processing cards:
  - Signal processing
  - DSP or 32-bit CPUs
- Line cards:
  - Interface to network
  - ASICs+32-bit CPUs

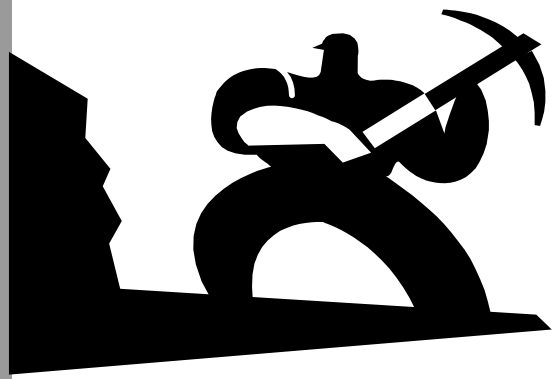


- Backplane:
  - ATM or Ethernet
  - Redundant network
  - Implemented by cards in the rack

- Control plane:
  - Decision-making
  - “Integer applications”
  - Call setup, services
  - General-purpose processors



- Data plane:
  - Move or process data
  - Signal processing
  - Media coding/decoding
  - Floating/fixed point
  - DSP & ASIC work



- One on each card in a telecomm rack
  - Data plane
  - Backplane
  - Very common
  - Sold by Freescale
- Processor
  - PowerPC e500
  - 666-1000 Mhz
  - 256 kB L2 cache
- Networking
  - CPM module
- 9 Ethernet lines!

Features	
Serial Communications Controller (SCC)	4
Fast Communications Controller (FCC)	3
Multi-Channel Controller (MCC2)	2
Serial Management Controller (SMC)	2
Serial Peripheral Interface (SPI)	1
I2C controller	1
DDR Memory controller	1
PCI-X/PCI controller	1
RapidIO controller	1
Ethernet 10/100/1000 controller	2
Capabilities	
Ethernet, 10 (from SCC)	4
Ethernet, 10/100 (from FCC)	3
Ethernet 10/100/1000	2
Utopia II ATM (from FCC)	2
Multichannel HDLC (from MCC2)	256

8 clusters of 2 processors each

Total capacity: about 5 GOps, at 160 Mhz

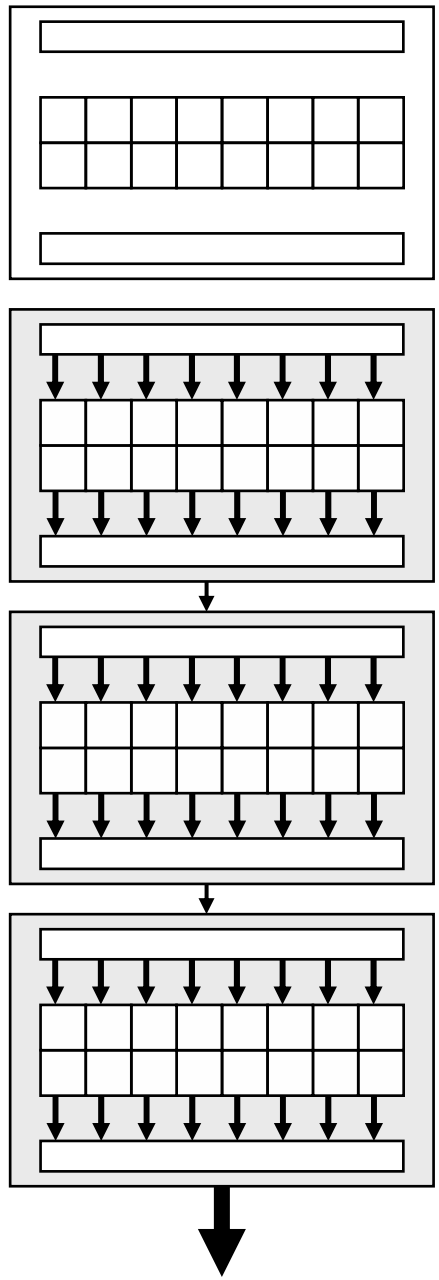
Each TMC is a VLIW machine with 74 bit instructions, 2k instructions in local memory

Two 32-bit ALUs and three control/data movement units per TMC

Image from Microprocessor Report, Oct 2002

Massive multiprocessing

- 16 cores on a chip
- 4 chips in serial
- Routing:
  - 10 Gbps
  - @ 20 Mpackets/s
  - 1000 ops per packet passing through



- Telecomm & datacomm tradition:
  - Distributed multiprocessing
  - No shared memory
  - Software assumes single processor
    - Especially operating systems
- Today: end-of-the-road
  - Future performance gains: CMP
  - Everybody has to use shared memory
- They need parallel programmers!

Multiple processors

- Networked
- Up to 100

Multiple networks

- Body, engine, telematics, media, safety

Functions by embedded processing:

- ABS: Anti-lock braking systems
- ESP: Electronic stability control
- Airbags
- Efficient automatic gearboxes
- Theft prevention with smart keys
- Blind-angle alert systems
- ... etc ...

- Large diversity in processor types:
  - 8-bit – door locks, lights, etc.
  - 16-bit – most functions
  - 32-bit – engine control, airbags
- Form follows function
  - Processing where the action is
  - Sensors and actuators distributed
  - Massive distributed system

- Networked computer system
  - Controlling arms & tools
  - Navigating the forest
  - Recording the trees harvested
  - Crucial to efficient work
- Computer
  - 16-bit C167 processors in a CAN network
- Tough environment
  - -40°C at startup, +100°C when running
  - Network cables in bends – wireless useful!

- Infineon
- Target Market
  - Automotive control
- Processing
  - 16-bit C16x core
  - 4-stage simple pipeline
  - 40 Mhz operation
  - 16 MB memory space, including ROM, RAM, devices
- 144 pin package
  - Tolerates -40 to +125 C
- About 25 USD

Devices	
CAN 2.0b controllers	2
General-Purpose Timers (GPT)	5
Watch-Dog Timer (WDT)	1
Pulse-Width Modulator (PWM)	1
Analog-Digital Converter Channels	24+8
USART	1
Synchronous Serial Comms (SSC)	1
Capture/Compare Channels	2x16
External Ports	
CAN interfaces	2
8-bit ports from devices	8
16-bit ports from devices	1
Memory	
ROM	32 kB
Fast General Internal RAM (IRAM)	3 kB
Extension Internal RAM (XRAM)	8 kB

- Embedded PC
  - Graphical display
  - Touch panel
  - Joystick
  - Buttons
  - Keyboard
- Regular PC arch
- But tough enough to be “out in the woods”

Functions requiring computers:

- Radar
- Weapons
- Damage control
- Navigation
- basically everything

- Computers:
  - Large servers
  - 1000s of processors

- Custom processors
  - Graphics, sound
- 32-bit processors
  - IR, Bluetooth
  - Network, WLAN
  - Harddisk
  - RAID controllers
- 8-bit processors
  - USB
  - Keyboard, mouse

- Lego mindstorms robotics kit
  - Standard controller
    - 8-bit processor
    - 64 kB of memory
  - Electronics to interface to motors and sensors
- Good way to learn embedded systems

Swedish Business Perspective

All advanced products contain embedded systems today

- Software is the key driver for new functions & special characteristics

Core Swedish industry

- Very large companies
- Builds end-user products

- Ericsson
- ABB
- Volvo
- Volvo Cars
- Saab
- Scania
- SonyEricsson
- SKF
- Silva
- Huskvarna

- Tool providers
  - IAR Systems
  - Telelogic
  - Nohau
  - Virtutech
  - Volcano
  - Arcticus
  - Enea
- Solution providers
  - CC-Systems
  - ConnectBlue
- Component companies
  - Xelerated
  - Switchcore
- Consultants
  - TietoEnator
  - Teleca
  - ÅF
  - Saab Combitech
  - + many many more