University Karlsruhe
Research University · founded 1825

The Multicore Software Challenge

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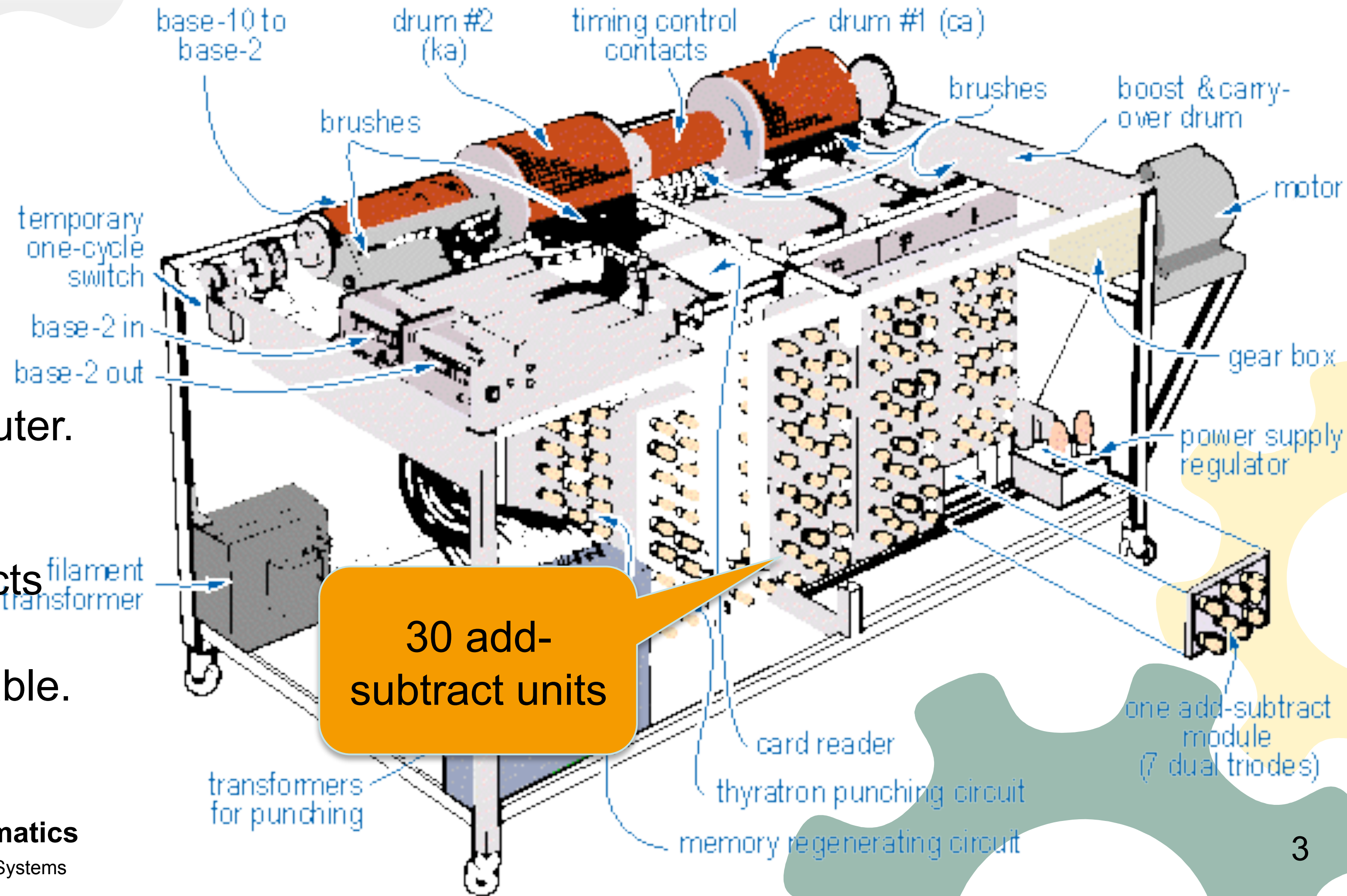
We´re Witnessing a Paradigm Shift in Computing

- For 60 years, the sequential computing paradigm was dominant.
- Parallelism occurred in niches only:
  - Numeric computing
  - Distributed computing (client/server)
  - Operating systems, data base mgmt systems
  - Instruction level parallelism
- With multi/manycore, parallel computers have become affordable to everyone, and they will be everywhere.
- It is already difficult to buy a computer with a single main processor.

Important Parallel Computers

Atanasoff-Berry-Computer (1942)

First digital, electonic computer.
Before ENIAC (1946).
30 adds/subtracts in parallel.
Not programmable.



Important Parallel Computers

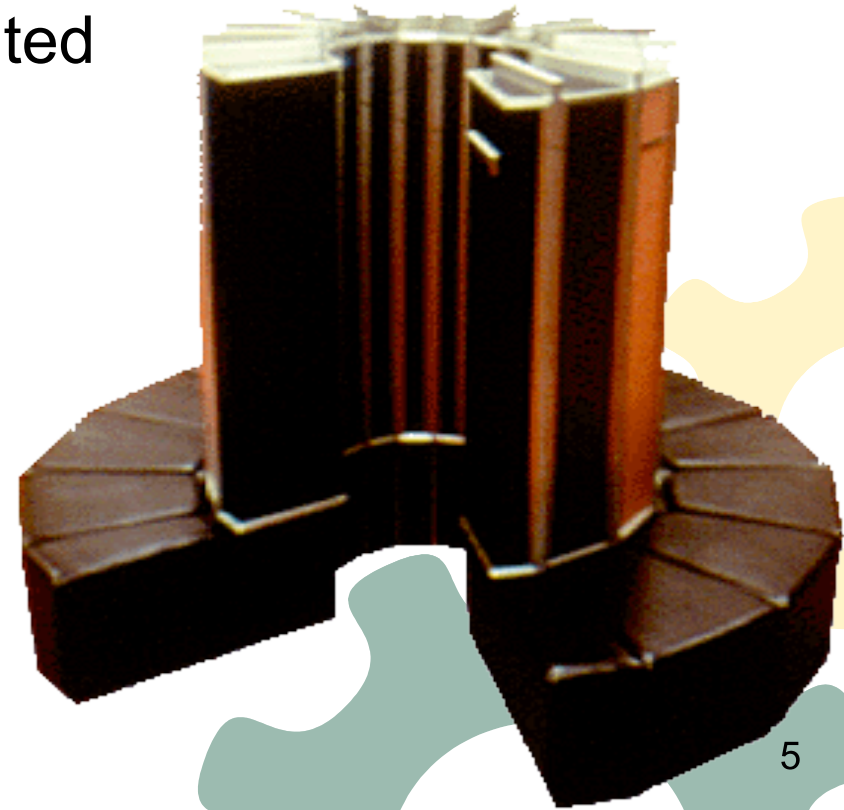
Illiac-IV: SIMD, distributed memory

- Only one built: 1976
  64 processors
- Worlds fastest
  computer until
  1981

Important Parallel Computers

Cray-1 vector computer

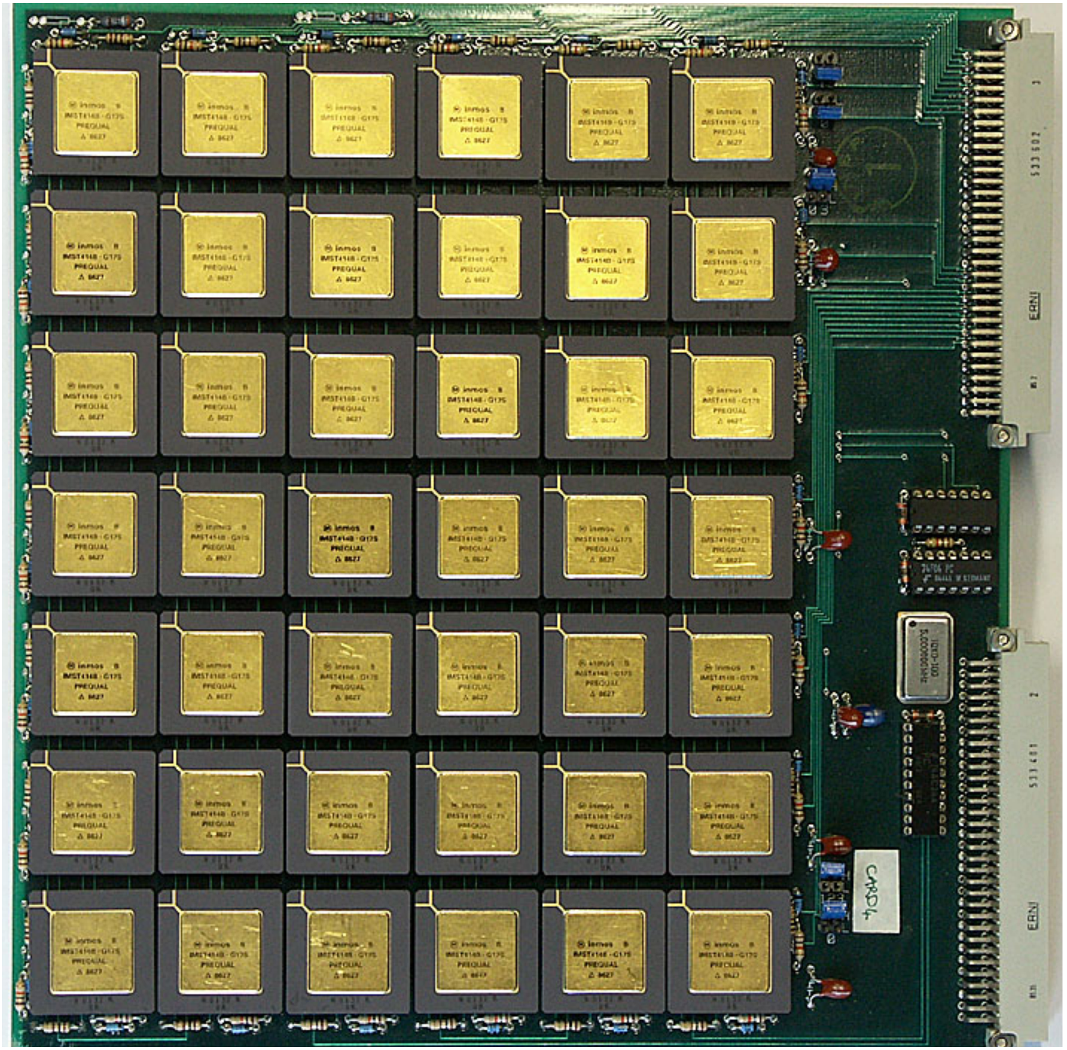
- Shared memory
- Vector registers with 64 elements
- Vector instructions implemented by pipelining.
- First delivery 1976
- Second fastest computer after Illiac-VI



Important Parallel Computers

Transputer

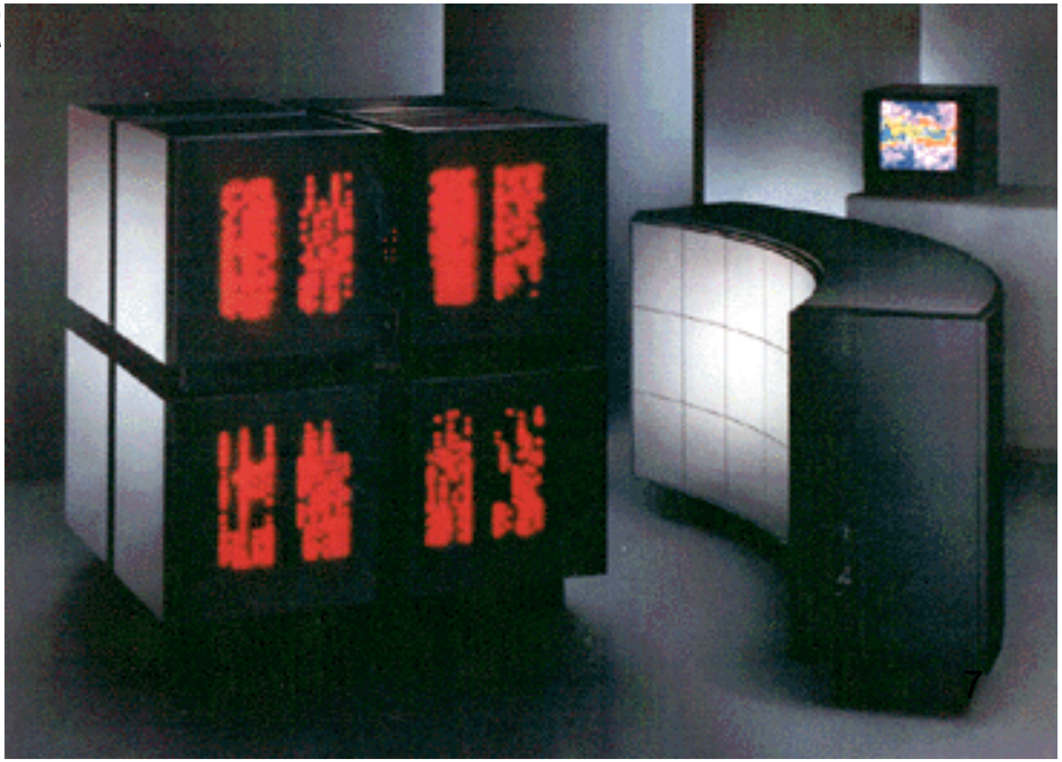
- MIMD computer,
- Distributed memory
- Processors with 4 fast connections
- First delivery 1984
- Up to 1024 processors
- Occam programming language
- Developed by Inmos, Bristol, GB



Important Parallel Computers

CM-1 Connection Machine

- SIMD
- Distributed memory
- 65.536 processors (1-Bit)
- Hypercube interconnect
- First delivery 1986
- First massively parallel computer



Important Parallel Computers

Computer Clusters

- Off-the-shelf PCs connected by off-the-shelf networks
- MIMD, distributed memory
- Low cost because of mass market parts
- Today´s fastest machines
- Hundreds of thousands of processors
- See top500.org

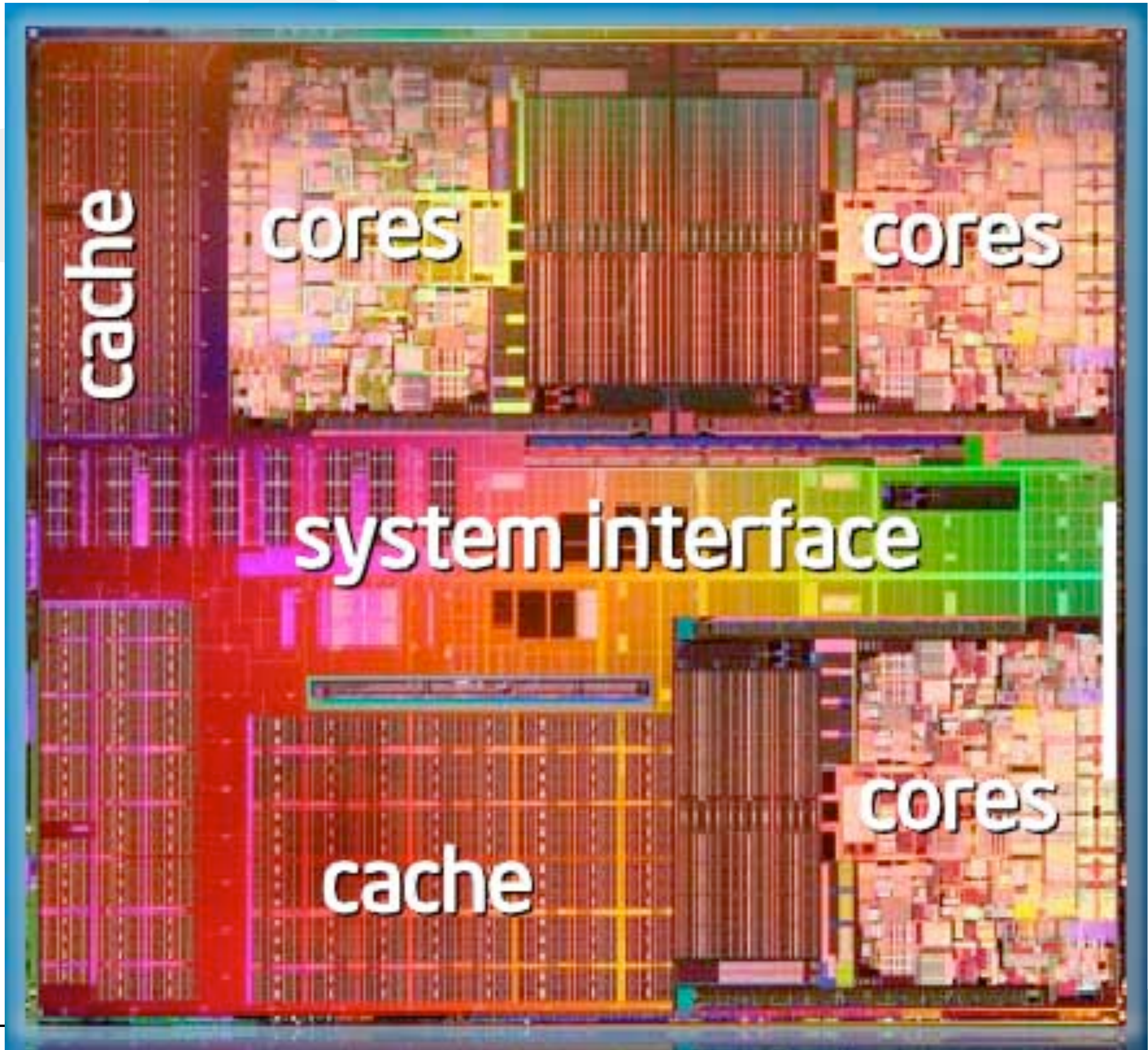
Nasa Avalon with 140 Alpha processors, 1998

Your Laptop—
a Parallel Computer?

Prices June 2007

Inspiron^{TM} 6400 15" Notebook für vielseitige Unterhaltung & 1 GB RAM.	**Inspiron^{TM} 1520** Stylischer Denker, der es geniesst seine Qualitäten zeigen zu können und gerne im Mittelpunkt steht.	**Inspiron^{TM} 1720** Unterhaltung & Spaß garantiert! Technologie genau angepasst für Ihren Lifestyle. Jetzt in 8 Farben.	**Inspiron^{TM} 1520** Schlank, elegant und noch etwas schlauer und stärker. Jetzt in 8 Farben.
~~729 €~~ 659 € inkl. MwSt., zzgl. 78 € Versand	~~999 €~~ 899 € inkl. MwSt., zzgl. 78 € Versand	1.049 € inkl. MwSt. und Versand	~~1.129 €~~ 1.079 € inkl. MwSt., zzgl. 78 € Versand
Prozessor Intel® Pentium® Dual-Core T2080 Prozessor (1,73 GHz, 533 MHz, 1 MB L2-Cache)	**Prozessor** Intel® Core™ 2 Duo T5450 Prozessor (1,66 GHz, 667 MHz, 2 MB L2-Cache)	**Prozessor** Intel® Core™ 2 Duo T5250 Prozessor (1,5 GHz, 667 MHz, 2 MB L2-Cache)	**Prozessor** Intel® Core™ 2 Duo T7100 Prozessor (1,8 GHz, 800 MHz, 2 MB L2-Cache)

Intel Dunnington
6 Processors on one Chip



3 x 2 Xeon Processors

(no HW multithreading)

2,6 GHz

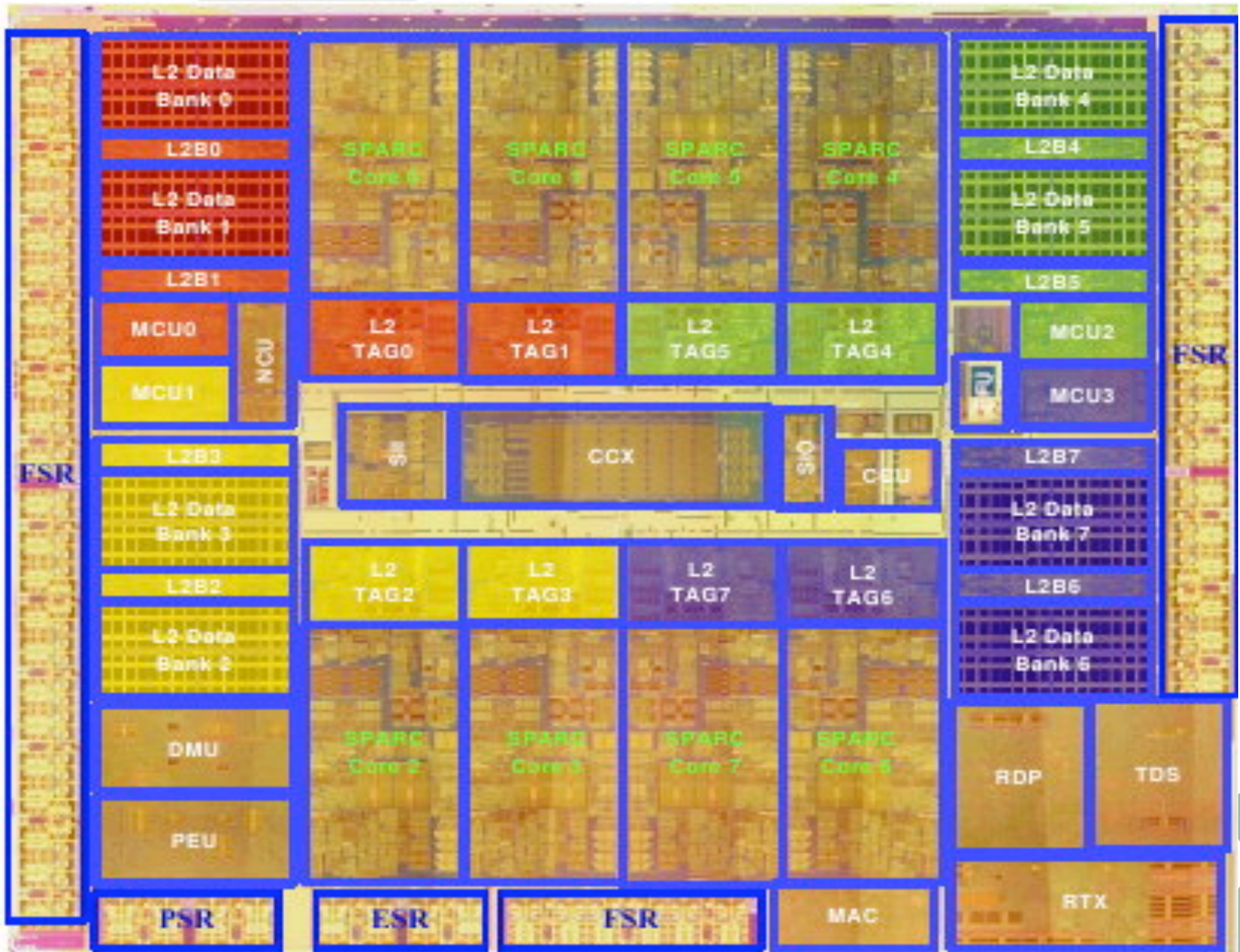
130 W

45nm technology

Up to 4 of those on one board

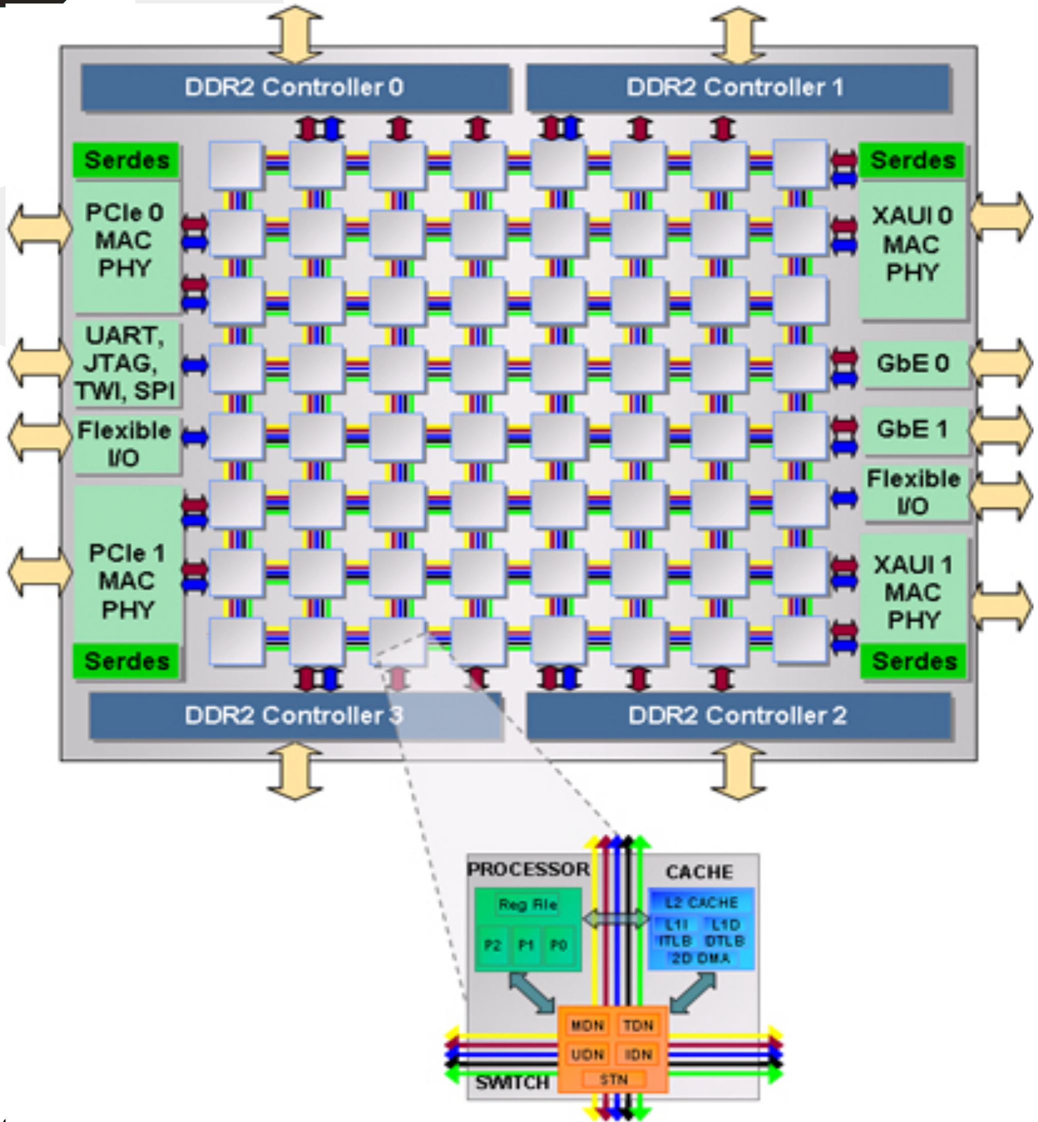
Available 2008

Sun Niagara 2: 8 Processors on 3,42 cm^2



- 8 Sparc Processors
- 8 HW-threads per processor
- 8x9 cross bar
- 1,4 GHz
- 75 W
- 65nm techology
- 4 per board
- Available 2007
- First Niagara 2005

Tilera´s TILE64



64 VLIW processors plus grid on a chip

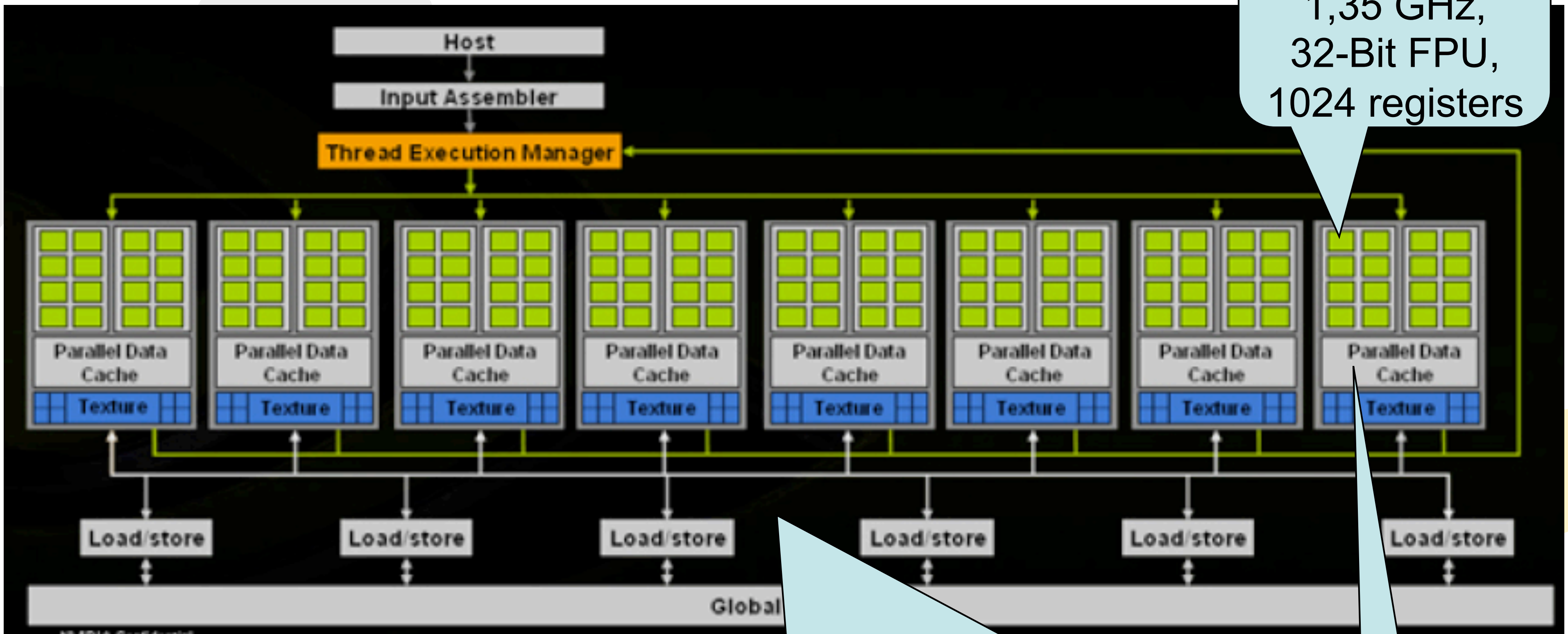
For network and video applications

700 MHz

22 W

Available 2007

Nvidia GeForce 8 Graphics Processing Unit



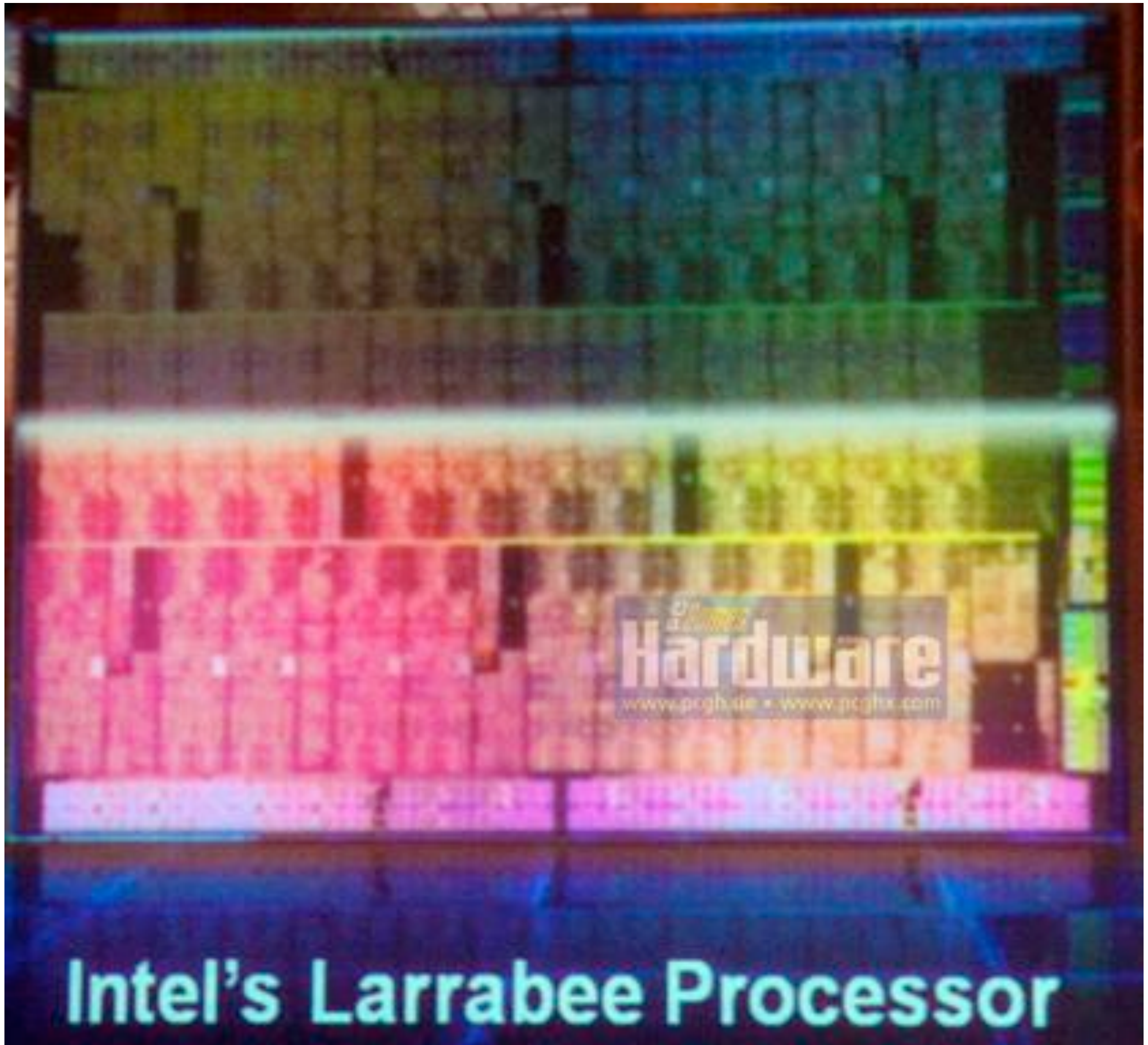
processor, 1,35 GHz, 32-Bit FPU, 1024 registers

16 KB

128 cores altogether, each with 96 threads in HW
Total of 12288 HW threads!
SIMD, distributed memory

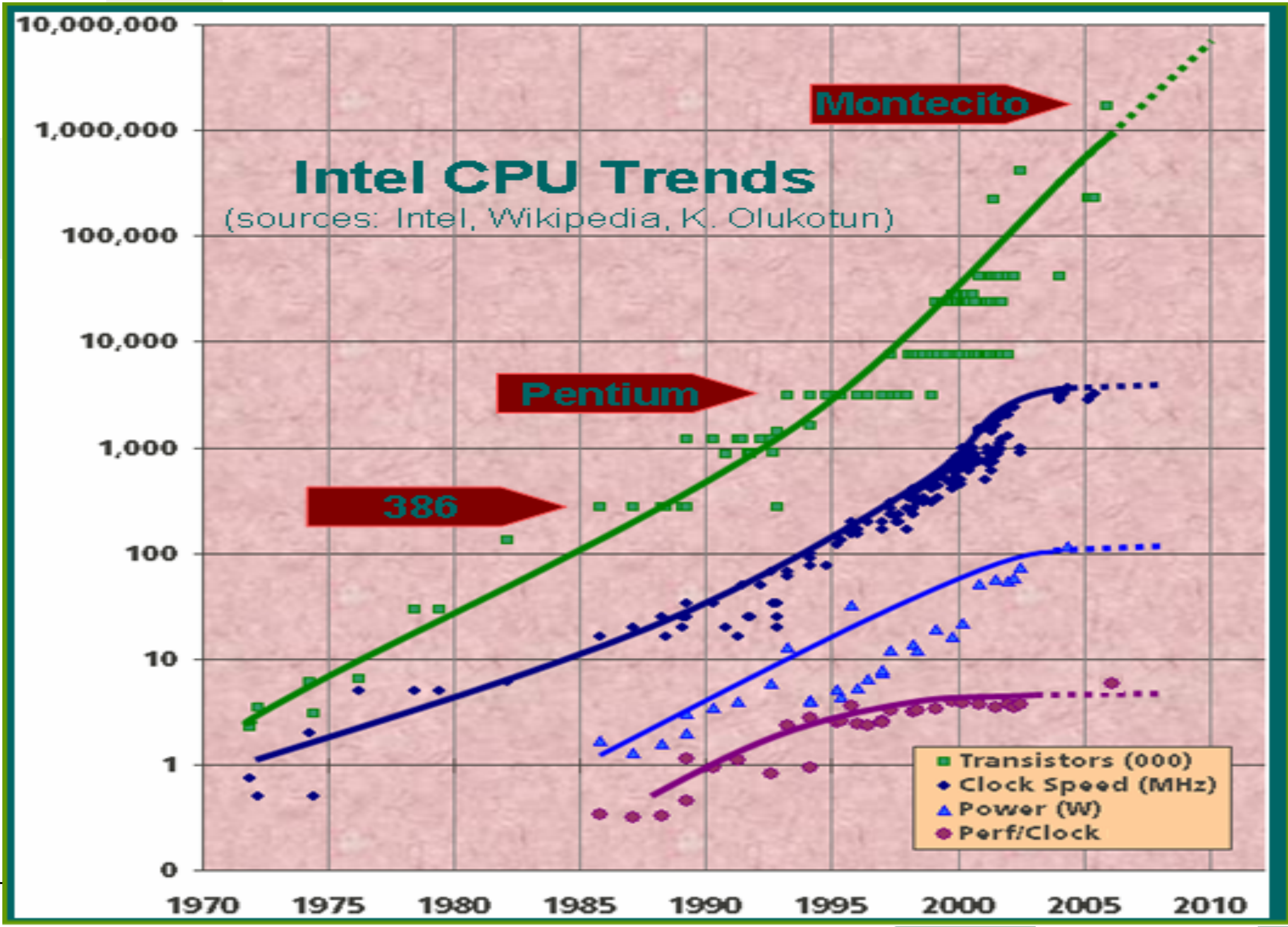
Intel´s Larrabee: 32 Pentiums on a Chip

- 32 x86 cores (45nm),
- (48 cores with 32 nm)
- Cache coherent,
- Ring interconnect
- 64 bit arithmetic
- 4 register sets per processor
- Special vector instructions for graphics
- Expected 2010



Source: www.pcgameshardware.com, May 12, 2009

What Happened?



Moore´s Law, New Version

Doubling the numer of processors per chip with each chip-generation, at about the same clock rate.

Parallel computers will be everywhere in a short time.

What to do with all the Cores?

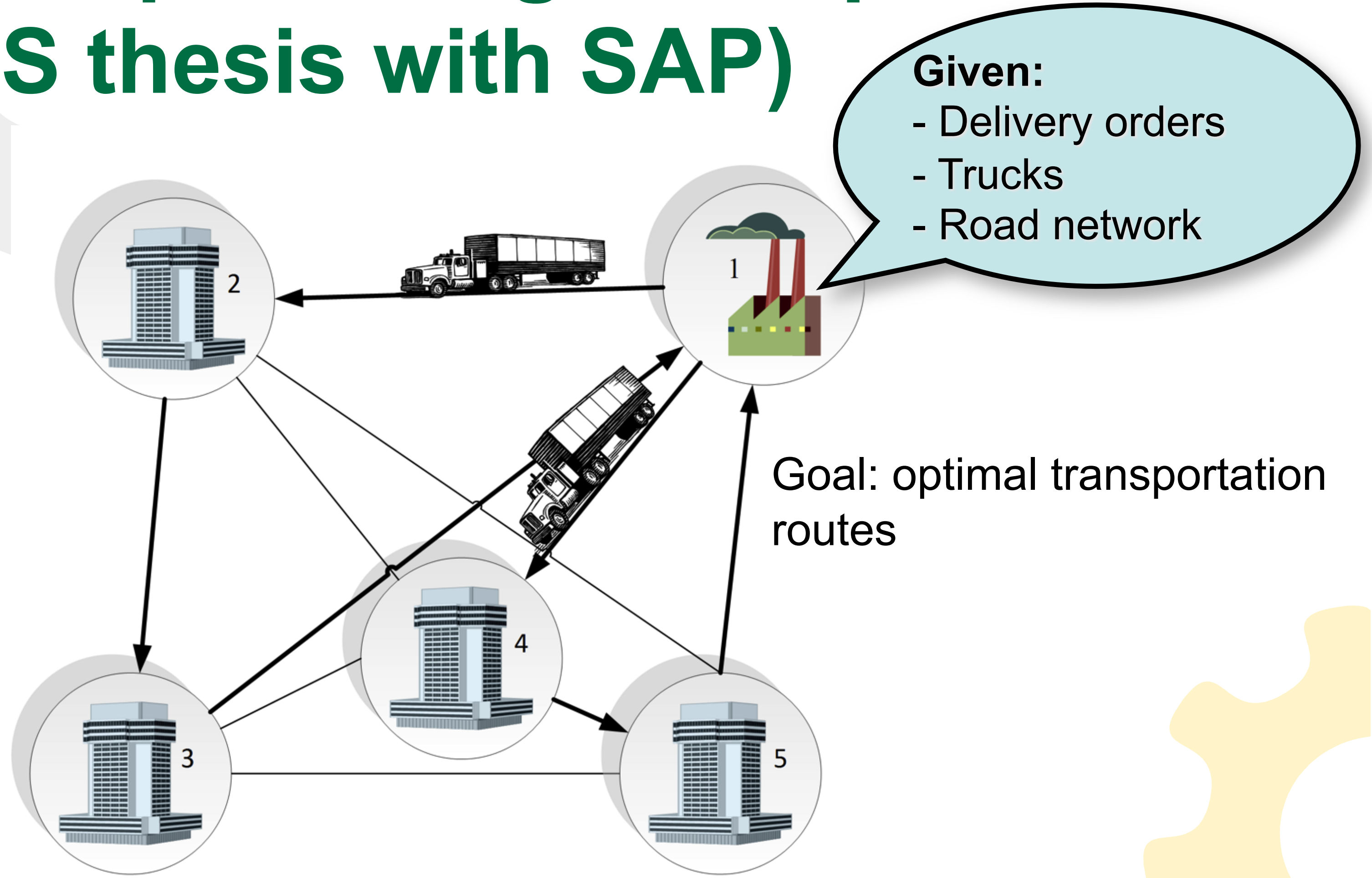
- „Who needs 100 processors for M/S Word?“
  - Lack of creativity, CS education?
  - Looking for applications that can use 100´s of cores.
- How could ordinary users of PCs, mobile phones, embedded systems benefit?
- Run faster!
- More compute intensive applications
- Speech and video interfaces
- Better graphics, games.
- Smart systems that model the user and environment and can predict what the user wants, therefore act more like a human assistant.

Example 1: Logistic Optimization (MS thesis with SAP)

Which deliveries?

On which trucks?

Which routes?



Goal: optimal transportation routes

Generalization of travelling salesman problem

Why parallelize?

Real logistics scenarios

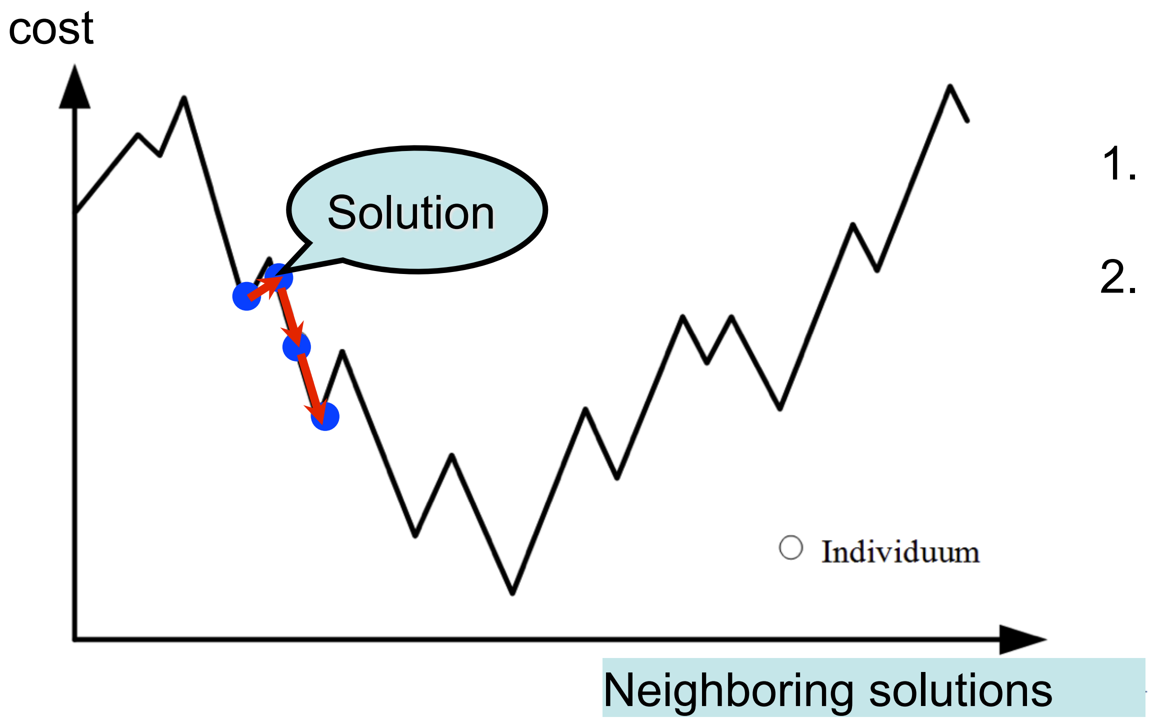
Scenario	1	2	3
Deliveries	804	1177	7040
Load dimensions	3	2	4
Loading stations	1	1	3
Delivery points	31	559	1872
Intermediate stations	0	5	0
Vehicles	281	680	2011
Vehicle types	7	3	10
Time window (days)	1	2	64

Also important:
Rest periods of drivers,
Time to load, trailers,
With/without refrigeration,
Ferry schedules, ships,....

Sequential implementation:
- -150.000 lines of C++
- -Evolutionary algorithm

Runs several hours for good solutions.

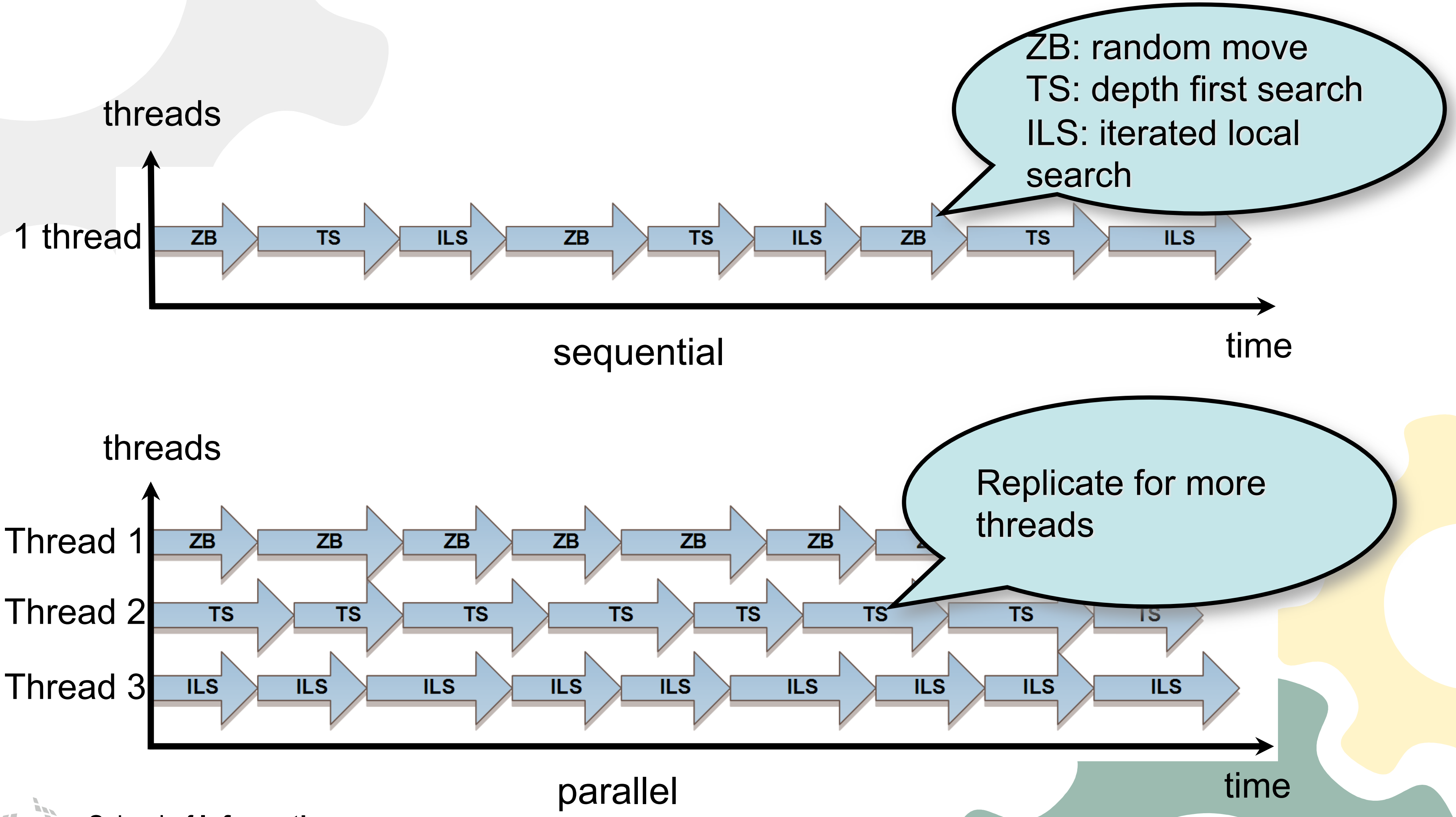
Search Algorithm



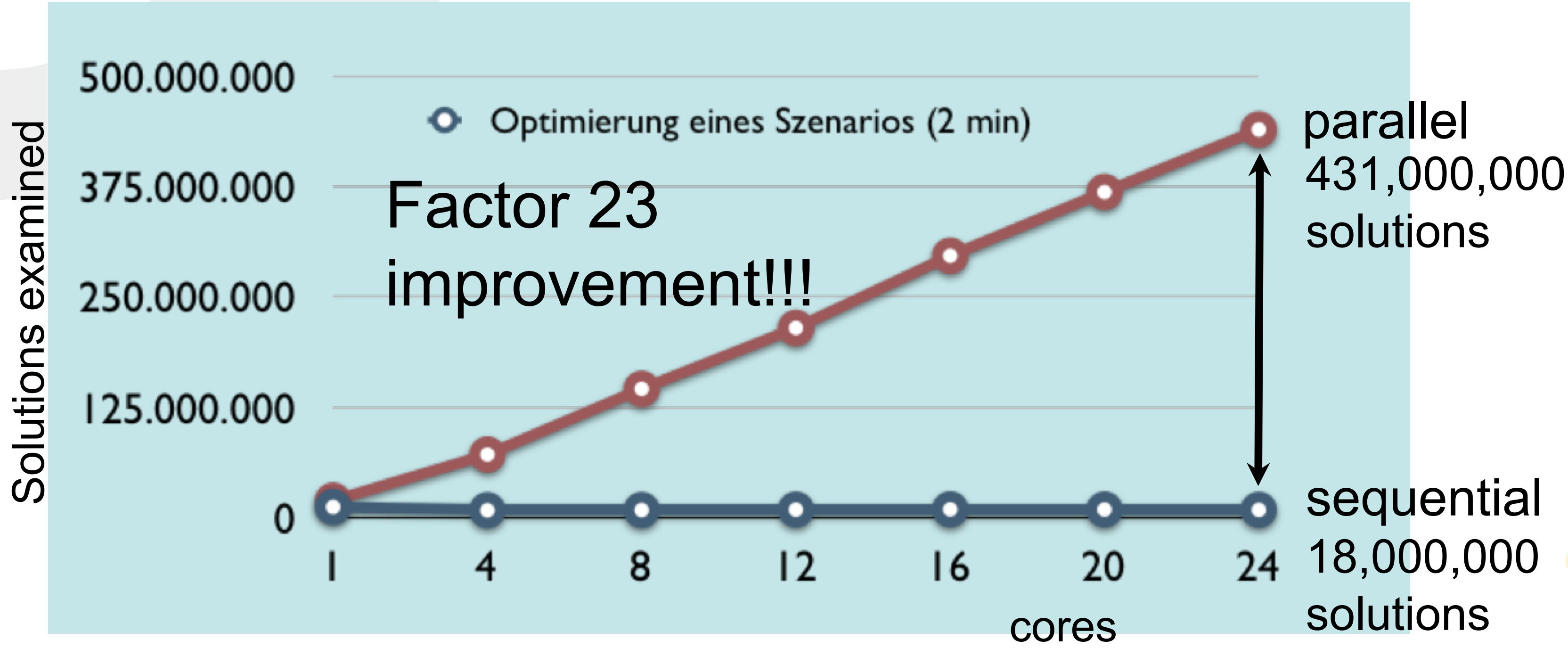
1. Start with initial solution

2. While cost bound not satisfied:
   - Improve solution with local changes
     (explore neighboring solutions)
   - Occasionally escape from local optimum with a jump in soution space

General Procedure

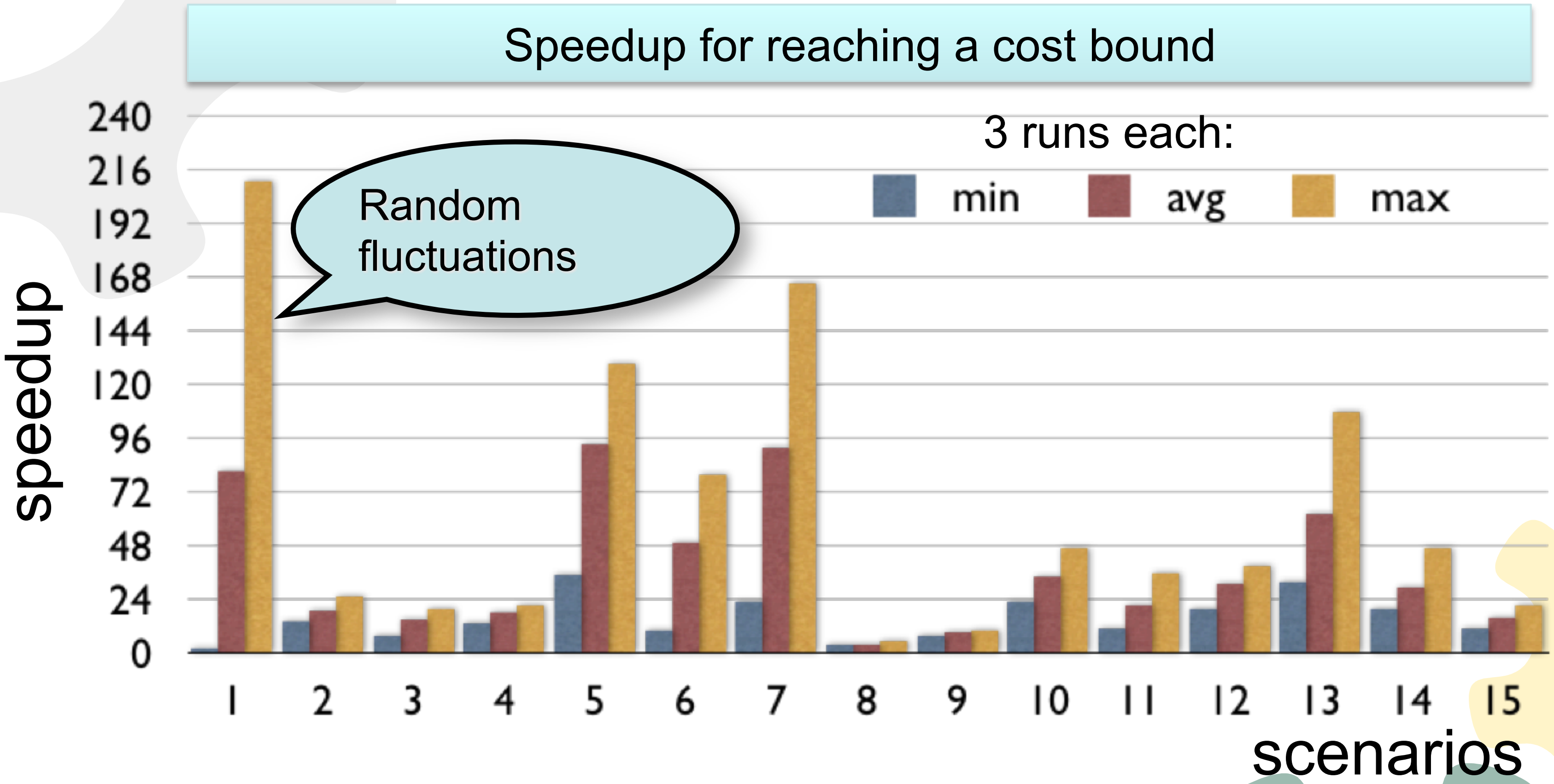


Solutions examined in 2 Min.



Computer with 4 Intel Dunnington Chips
(4 * 6 cores)

Speedup with 24 Threads



Average speedup: 17,37

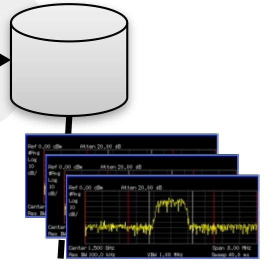
Super-linear speedups if good candidates are found early

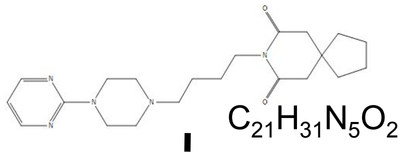
What is the Basic Challenge in Parallel Software?

- Speedup, programmer productivity, and software quality must be satisfactory simultaneously.
  - Parallelization only interesting if there is a speedup
  - Programmer productivy and software quality should not get any worse!
- Current languages and tools are unsatifactory (Thread ≅ Goto?)
- Most programmers are poorly prepared for parallelism.

Example 2: Metabolite Hunter

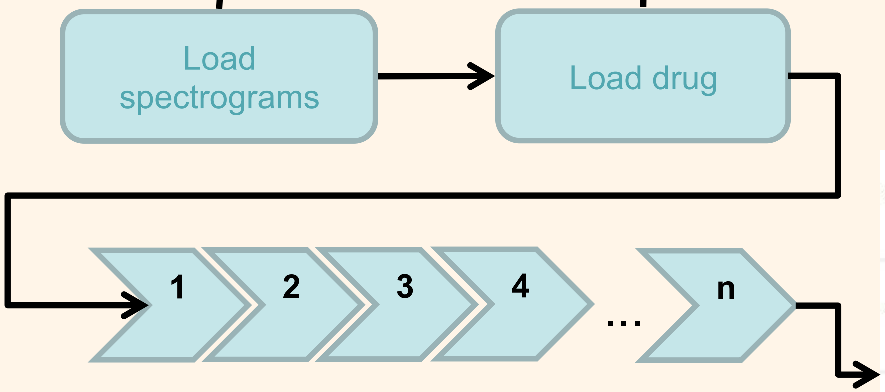
Mass spectrograms



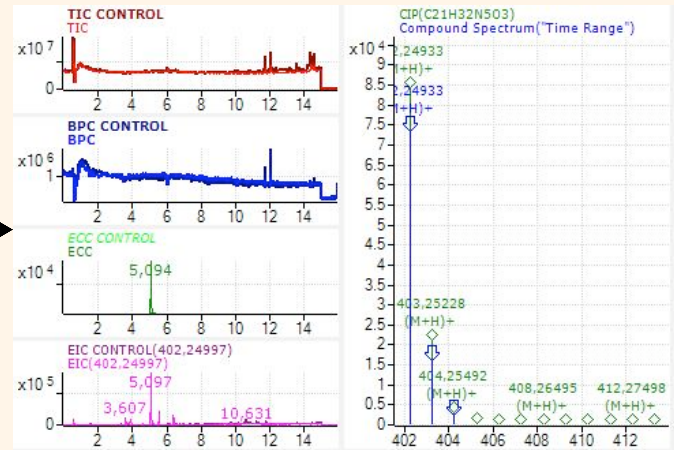


drug

Agilent Technologies



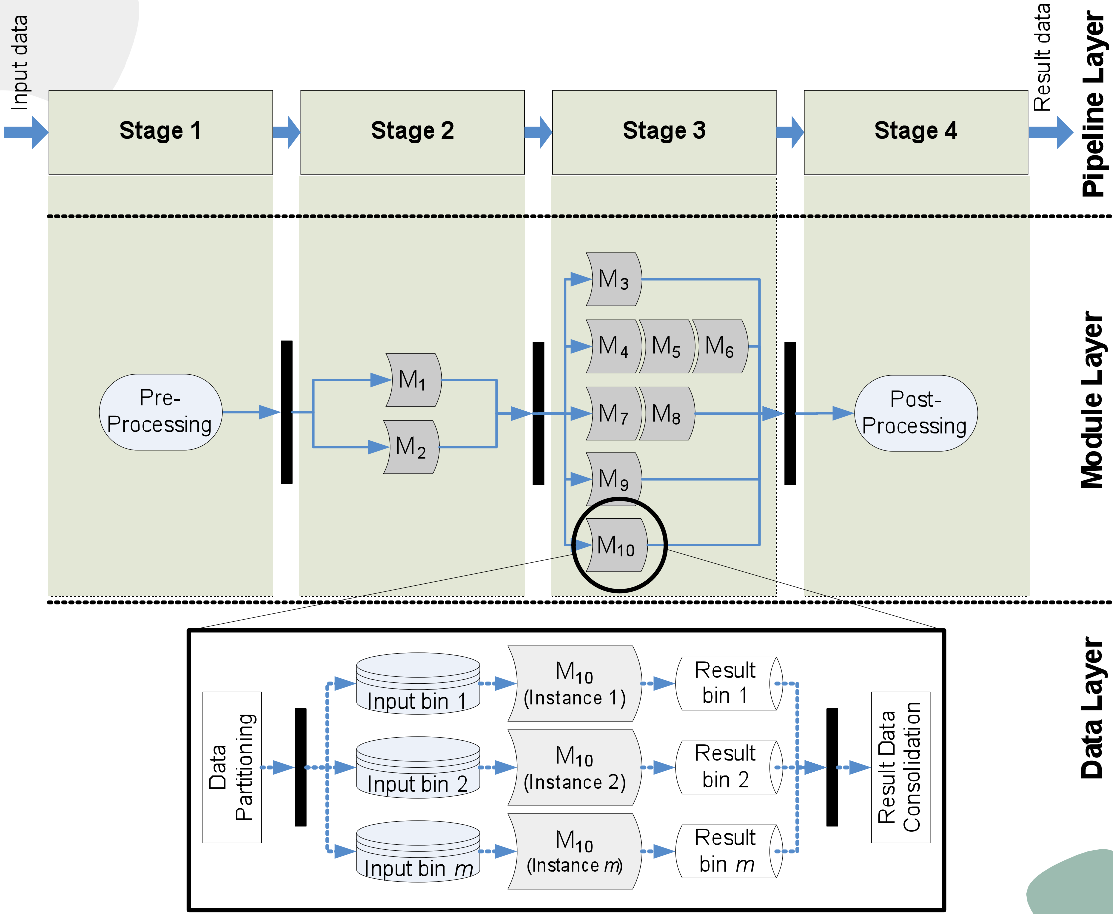
Algorithms pipeline
searches for metabolites in spectrograms.
Parallelization potential



Result: time-dependent graph of metabolites

Desktop application

Multi-Level Parallel Architecture



Auto-Tuning

- **Problem:** Find parameter configuration that optimizes performance.
- Parameters are platform and algorithm dependent
- Parameters:
  - number of cores,
  - number of threads,
  - parallelism levels,
  - number of pipeline stages, pipeline structure,
  - Number of workers in master/worker, load distribution
  - size of data partitions,
  - choice of algorithm
- Manual adjustment is too time-consuming
- Let the computer find the optimum!

Auto-Tuning (2)

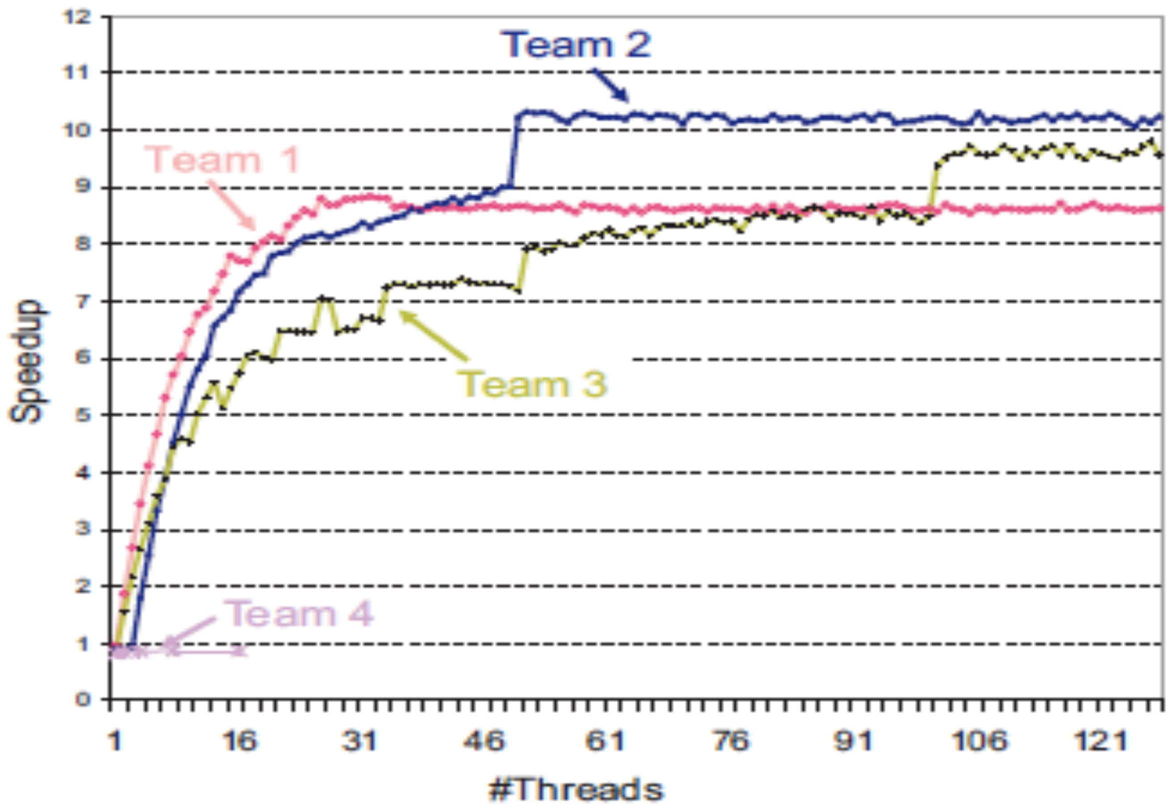
- **Solution:** *Atune* Parameter Optimizer
  - Library that searches for the optimum, given annotations about which parameters can be changed
    - specified with annotation language Atune-IL
  - Search space can be huge, so sampling, learning, and other optimization techniques need to be explored.
  - Difference between best and worst configuration in Metabolite Hunter: Factor of 1.9 (total speedup 3.1 on 8 cores)
  - Gene expression application: Auto-tuning contributes a Factor 4.2 to a total speedup of 7.7 on 8 cores.

Tested on 2x Intel Xeon E5320 Quad-Core 1,86 GHz

Example: BZip2

- BZip2
  - Compression program
  - Used on many PCs worldwide
  - 8000 LOC, open source
- Parallelized in student competition
  - 4 teams of 2 students each
  - Preparation in 3 month lab course on OpenMP and Posix threads
  - Competition in the final 3 weeks (course project)

Speedup



Winners reached a ten-fold speedup on Sun Niagara T1 (8 processors, 32 HW-threads).

How did they do it?

- Massive restructurings of the code
  - Teams who invested little in restructuring were unsuccessful.
  - Winners parallelized only on the day before submission; they spent the preceding 3 weeks on refactoring to enable parallelization.
  - Dependencies, side effects, sequential optimizations needed to be removed before parallelization became possible.

What did not work?

- Adding parallelization incrementally did not work for any team.
- Parallelizing the critical path only was not enough.
- Parallelizing inner loops did not work.
  - Parallel steps must encompass larger units (coarse grained parallelization)
- BZip2 contains specialized algorithms, so help from algorithms libraries is unlikely.

The Good News: Parallelization is not a Black Art

- Have a plan. Trial and error does not work.
- Develop hypothesis were parallelization might produce the most gains.
- Consider several parallelization levels.
- Use parallel design patterns.
  - Producer/consumer, pipeline, domain decomposition, parallel divide and conquer, master/worker.
- Don't despair while refactoring!
- Build tools that help.

How Can We Use all this Computing Power?

- Intuitive interfaces with speech and video,
- Applications that anticipate what users will do and assist them,
- Extensive modeling of users, their needs, and their environments for truly smart applications,
- New types of applications that are too slow today,
- Improved reliability and security
  - Run all kinds of checks in parallel with applications

Some Research Topics for Parallel Software Engineering

- Better programming languages for clear and explicit expression of parallel computations
- Compilation techniques
- Processor/process scheduling
- Parallel design patterns and architectures
- Parallel algorithms and libraries
- Testing, debugging
  - Automated search for data races, synchronization bugs.
- Performance prediction for parallel architectures
- Auto-tuning, auto-scaling, adaptability
- Tools for sequential-to-parallel refactoring
- New classes of applications
- Your favorite research topic/technique/expertise applied to parallel software.

XJava: Parallelism Expressed Compactly

Operator „=>“ links processes in pipeline, as in Unix

```
compress(File in, File out) {
  read(in)  =>  compress()  =>  write(out);
}
```

Reads file, outputs blocks

Buffered stream

Reads blocks, compresses them

Buffered stream

Writes blocks in file

All filters run in parallel, until end of input.
Streams are typed and typesafe.
Also suitable for master/worker, producer/consumer

XJava

Operator „|||“ runs processes in parallel:

```
compress(f1, f1out) ||| compress(f2, f2out);
```

Methods executed by their own threads,
implicit barrier at the end.

For process and data parallelism.
Multilevel (nested) parallelism.

Master/Worker in XJava

Input type
=>
Output type

- One master, three workers:

```
void => X master() { /* master*/ }
X => void w()      { /* worker*/ }
X => void gang()   { w() ||| w() ||| w(); }
```

- i workers (dynamic):

```
X => void gang()   { w():i; }
```

- **`master() => gang()`**
  `master` passes Elements of type X to workers in round-robin fashion.
- **`master() =>* gang()`**
  broadcasts elements to all workers.

XJava Extensions

- Easy to understand
- Fully integrated in Java
- Typesafe
- Easier to handle than threads or libraries
- Less code, fewer „opportunities“ for bugs
- Specialized autotuning possible
  - Example: tune stages in a pipeline in such a fashion that they take about the same time.

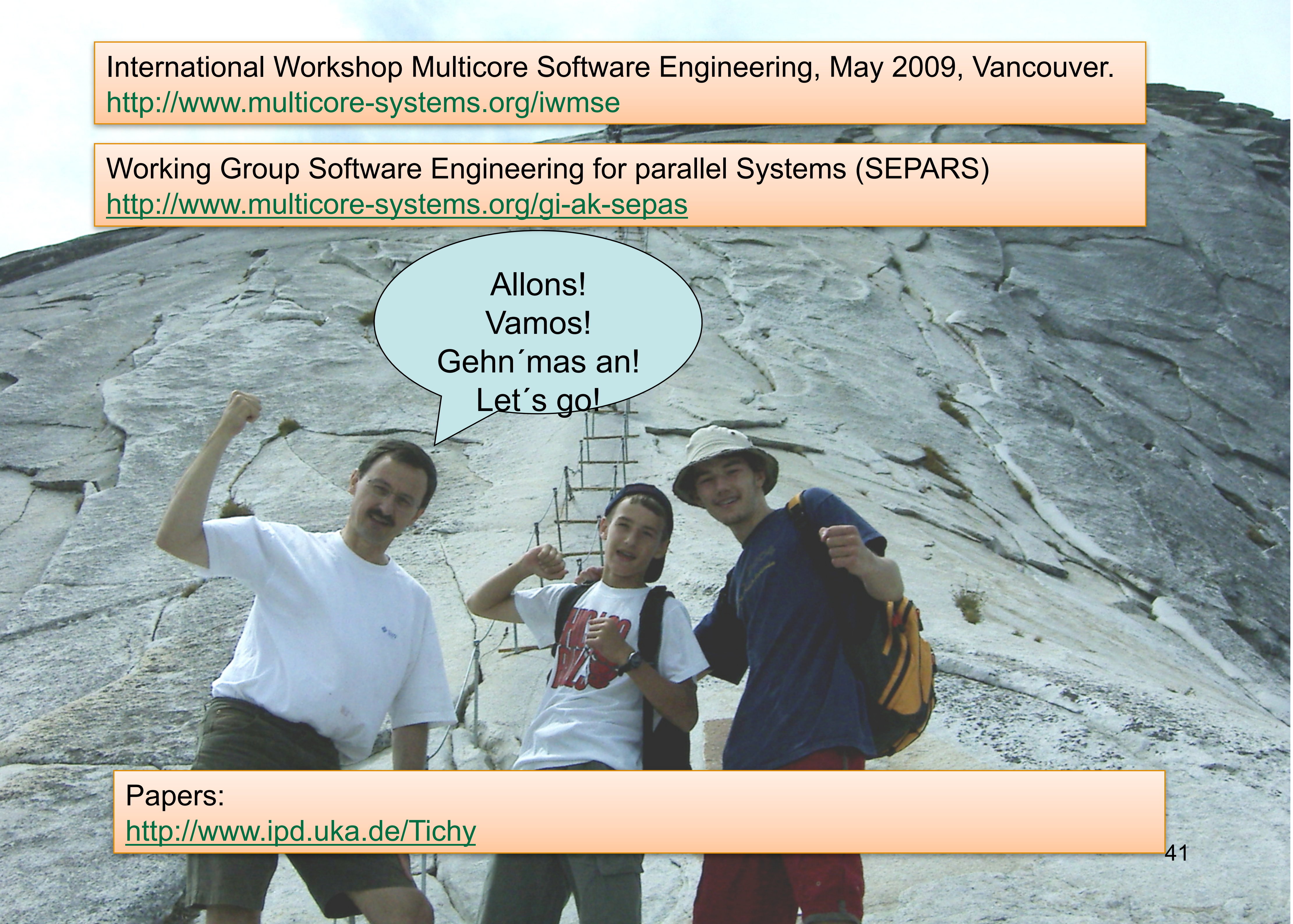
Summary

- Future performance gains by parallelism
- Goal: Faster, intelligent applications
- … of the same quality and at the same programmer productivity as sequential applications now.
- … while the number of processors per chip doubles every two years.
- Lots of the basics of computer science need to be reinvented.

„Reinventing Software Engineering“

International Workshop Multicore Software Engineering, May 2009, Vancouver.
http://www.multicore-systems.org/iwmse

Working Group Software Engineering for parallel Systems (SEPARS)
http://www.multicore-systems.org/gi-ak-sepas



Papers:
http://www.ipd.uka.de/Tichy