How to Write Fast Code

18-645, spring 2008

1st Lecture, Jan. 14th

Instructor: Markus Püschel

TAs: Srinivas Chellappa (Vas) and Frédéric de Mesmay (Fred)

Today

- Motivation and idea behind this course
- Technicalities
- Motivation: Concrete applications

Motivation and idea behind this course

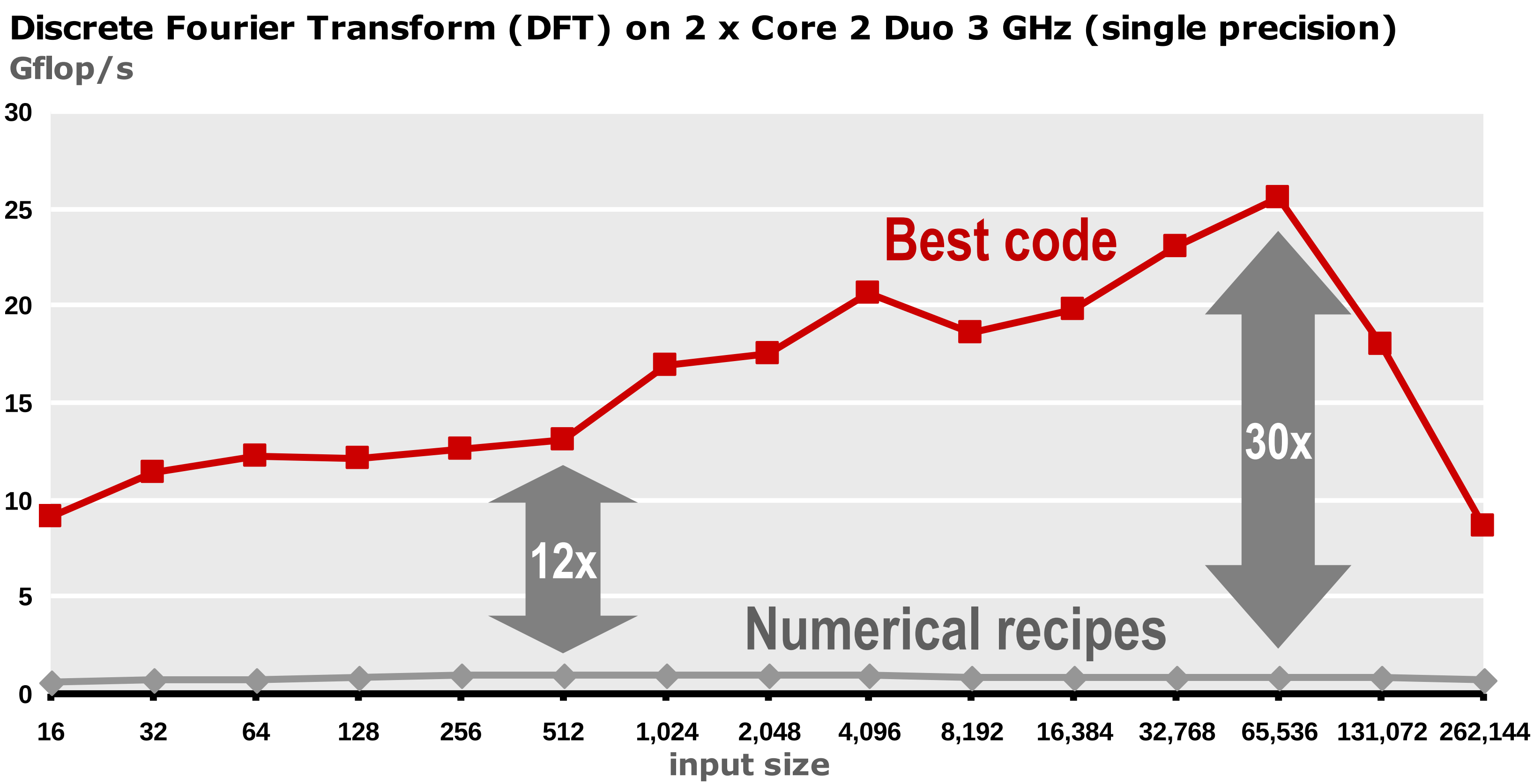
Scope

- Numerical computing: algorithms and implementation that are dominated by additions and multiplications, usually floating point
- Three domains of numerical computing:

Domain	Platform	Examples
Scientific computing	Large computer clusters	Climate modeling, Physics simulations
Consumer computing	Standard desktop	Adobe Photoshop, Audio/Video coding
Embedded computing	Small low-power processor	Signal processing, Control

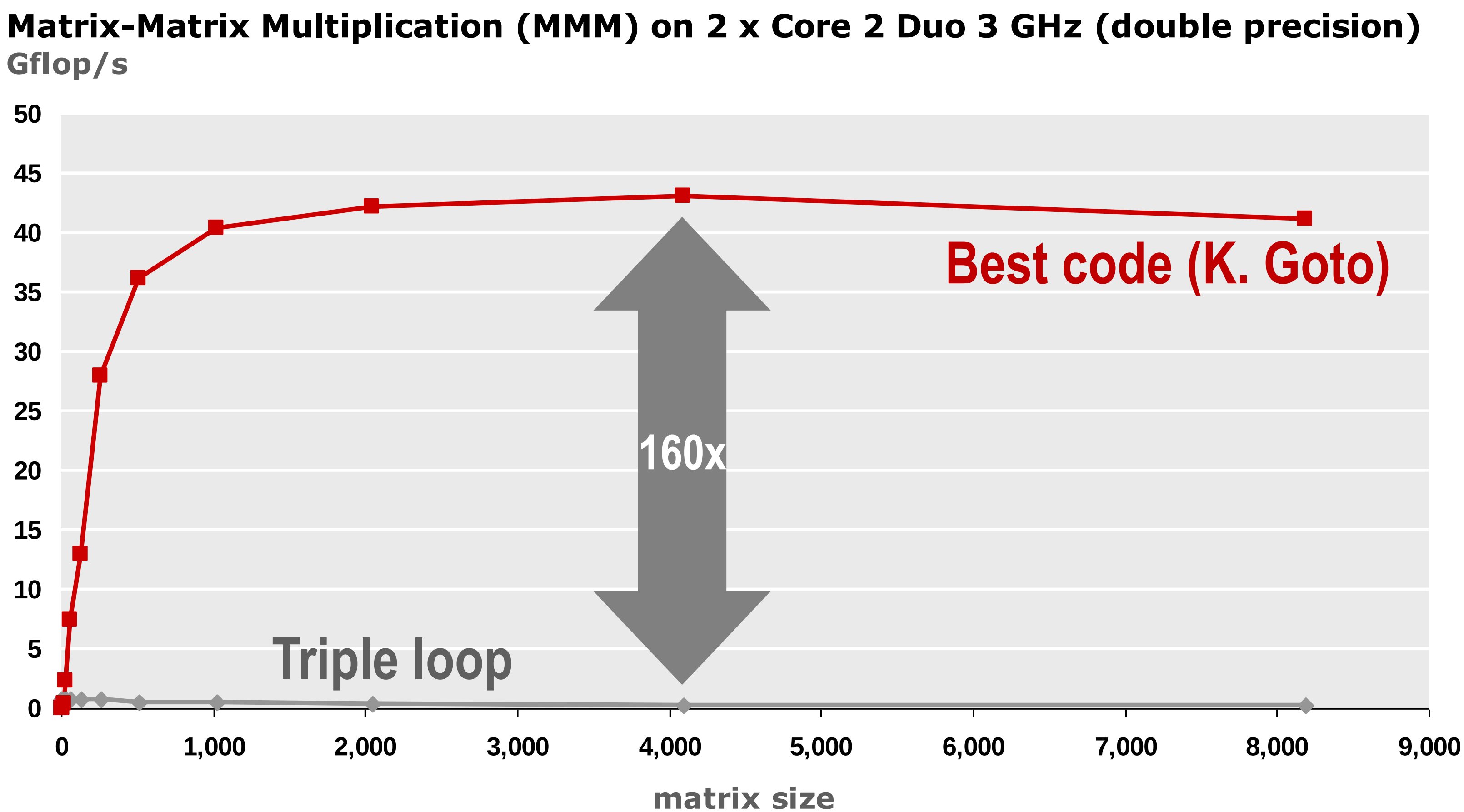
- Usually there is an unlimited need for performance
  large datasets, realtime

The Problem



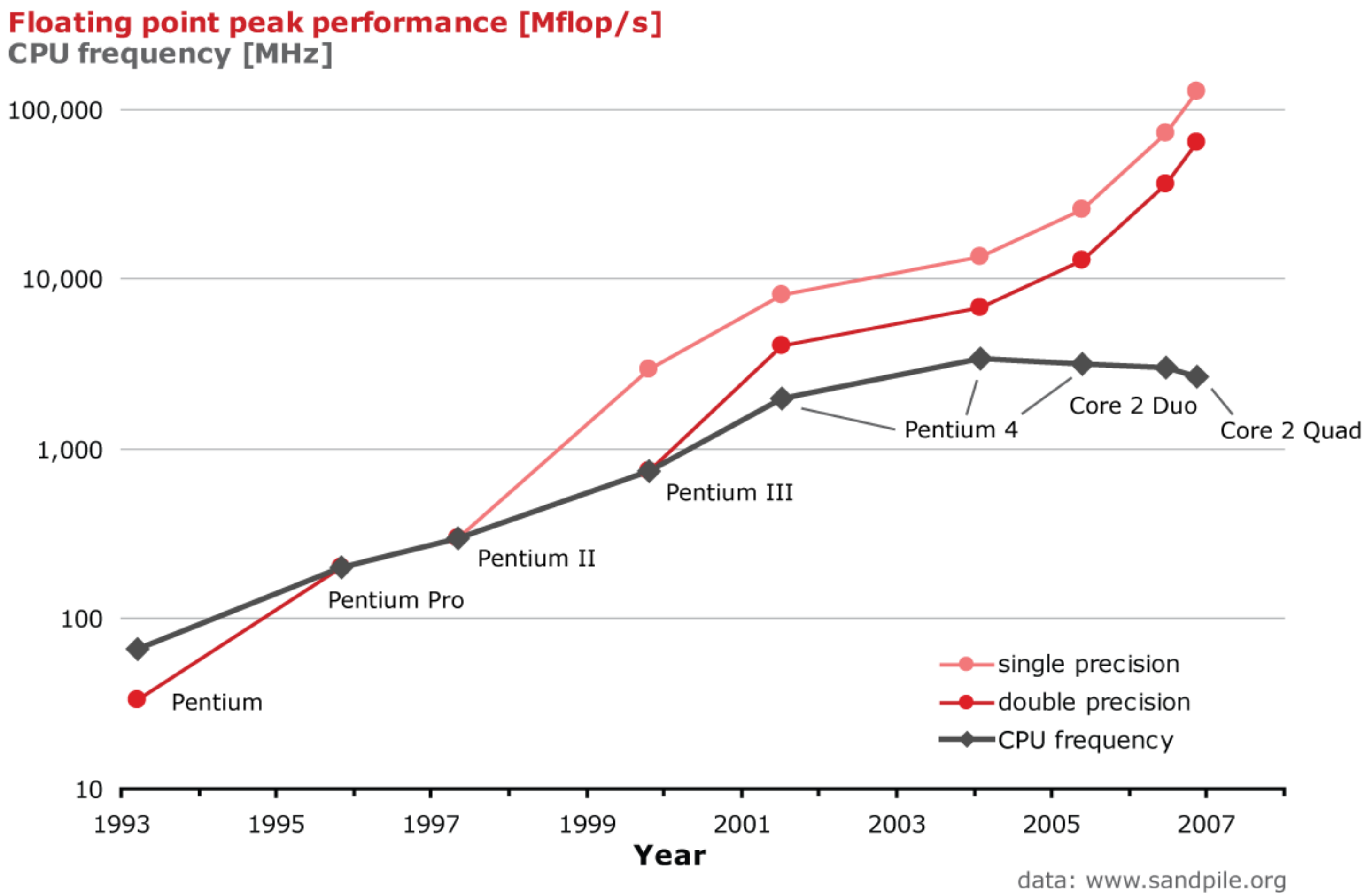
- Standard desktop computer, vendor compiler, using optimization flags
- All implementations have roughly the same operations count (~ $4n\log_2(n)$)
- *Maybe the DFT is just difficult?*

The Problem

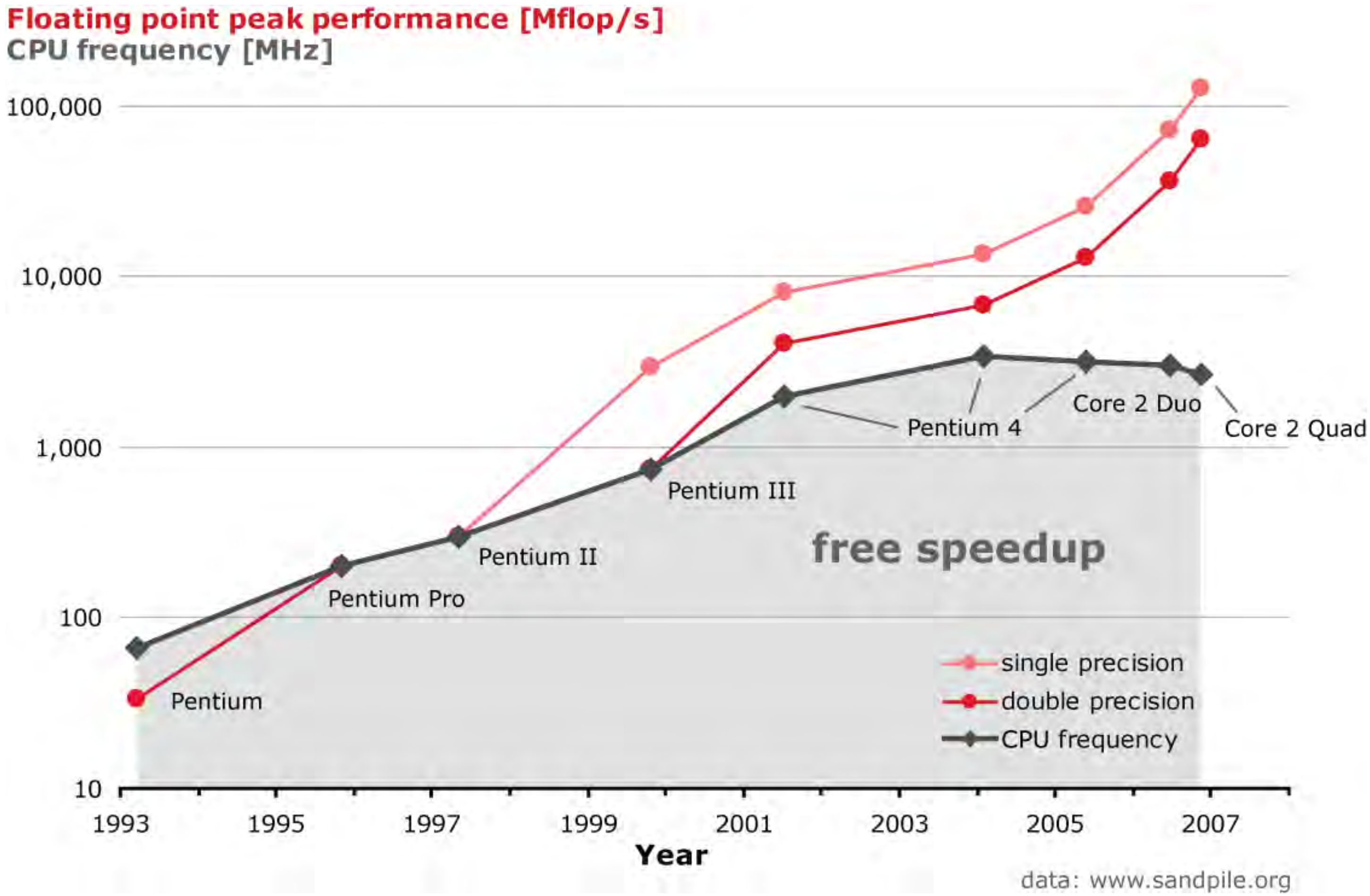


- Standard desktop computer, vendor compiler, using optimization flags
- All implementations have **exactly** the same operations count ($2n^3$)
- ***What is going on?***

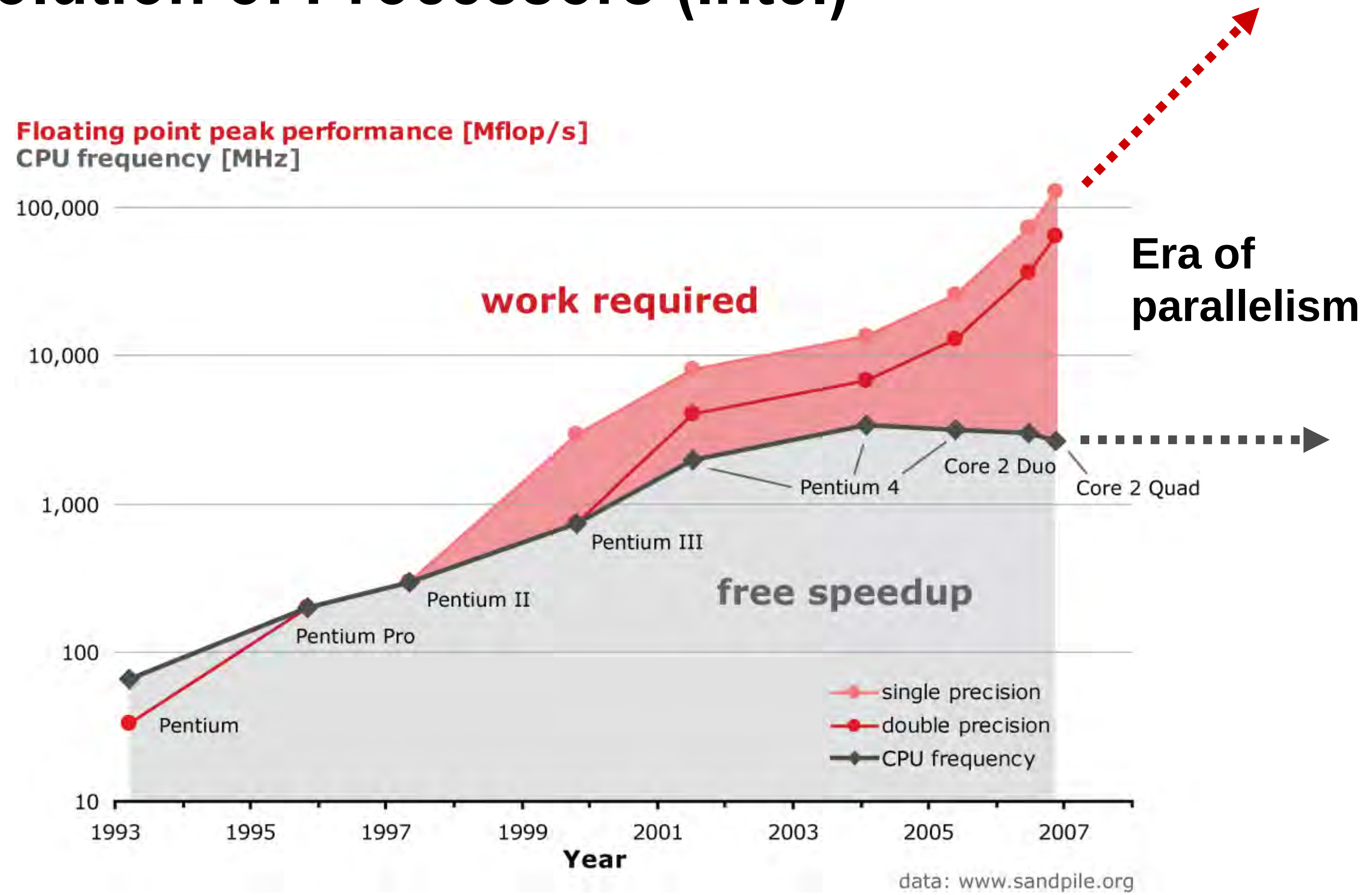
Evolution of Processors (Intel)



Evolution of Processors (Intel)

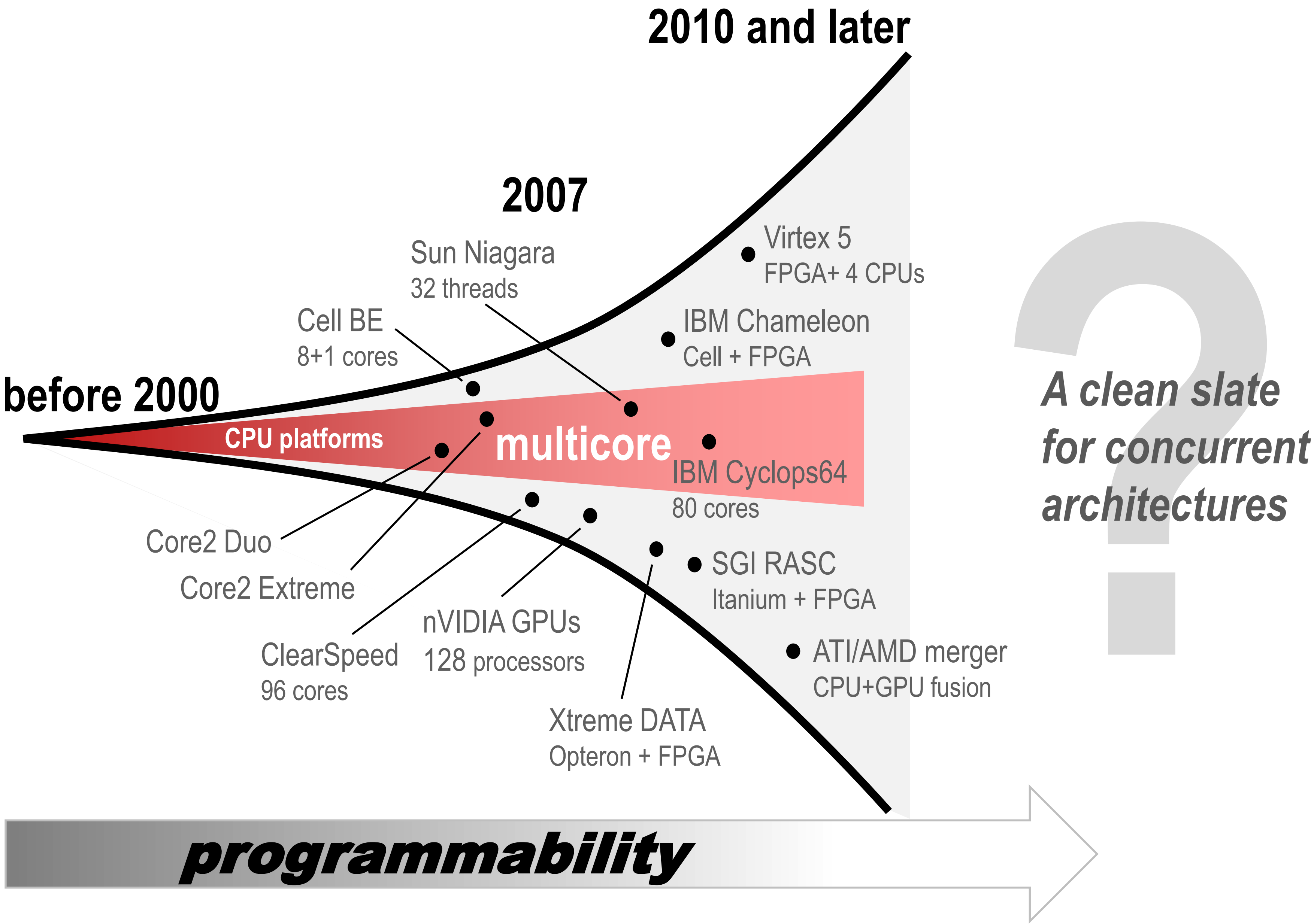


Evolution of Processors (Intel)

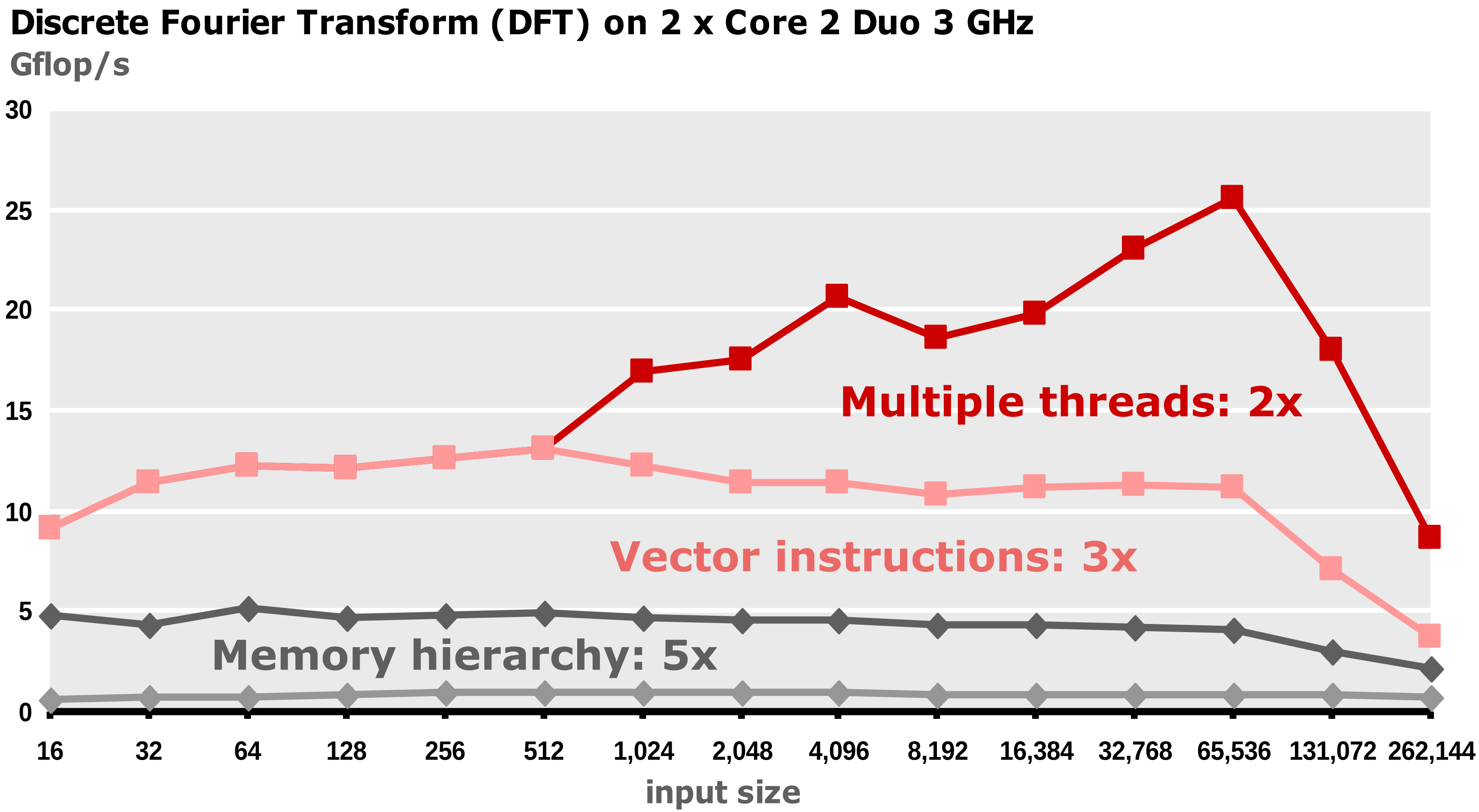


High performance software development becomes a nightmare

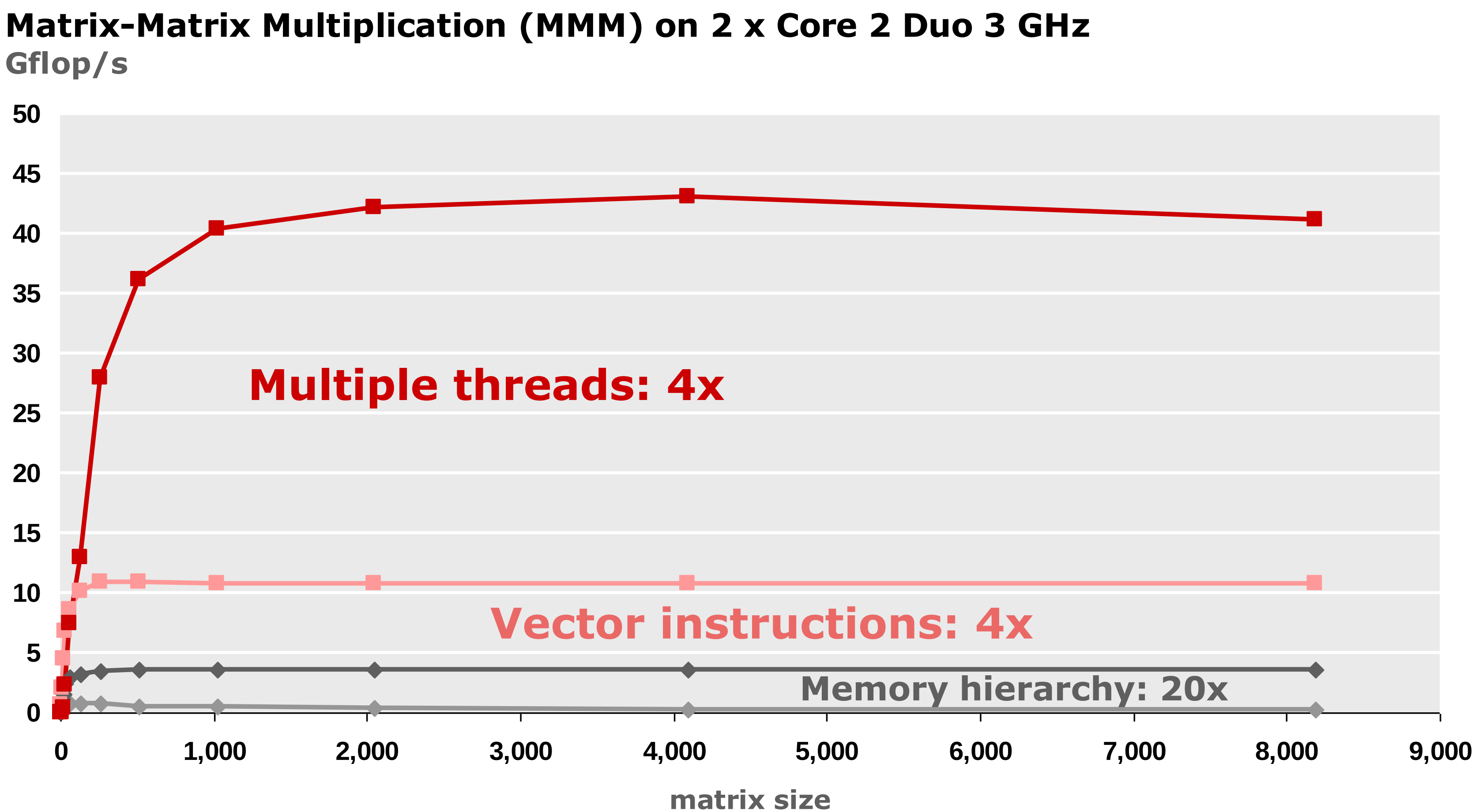
Evolution of Processors: The Future



DFT Plot: Analysis



MMM Plot: Analysis



Summary and Facts I

- **Implementations with same operations count can have vastly different performance (up to 100x and more)**
  - A cache miss can be 100x more expensive than an addition or multiplication
  - Vector instructions can perform 2 or 3 operations in parallel
  - All recent desktop computers have multiple cores = processors on one die
- **Minimizing operations count does not mean maximizing performance**
- **End of free speed-up: Legacy code will not get automatically faster anymore**
  - CPU frequency scaling has hit the power wall
  - Future performance gains through increasing parallelism
  - It is not clear how future platforms will look

Summary and Facts II

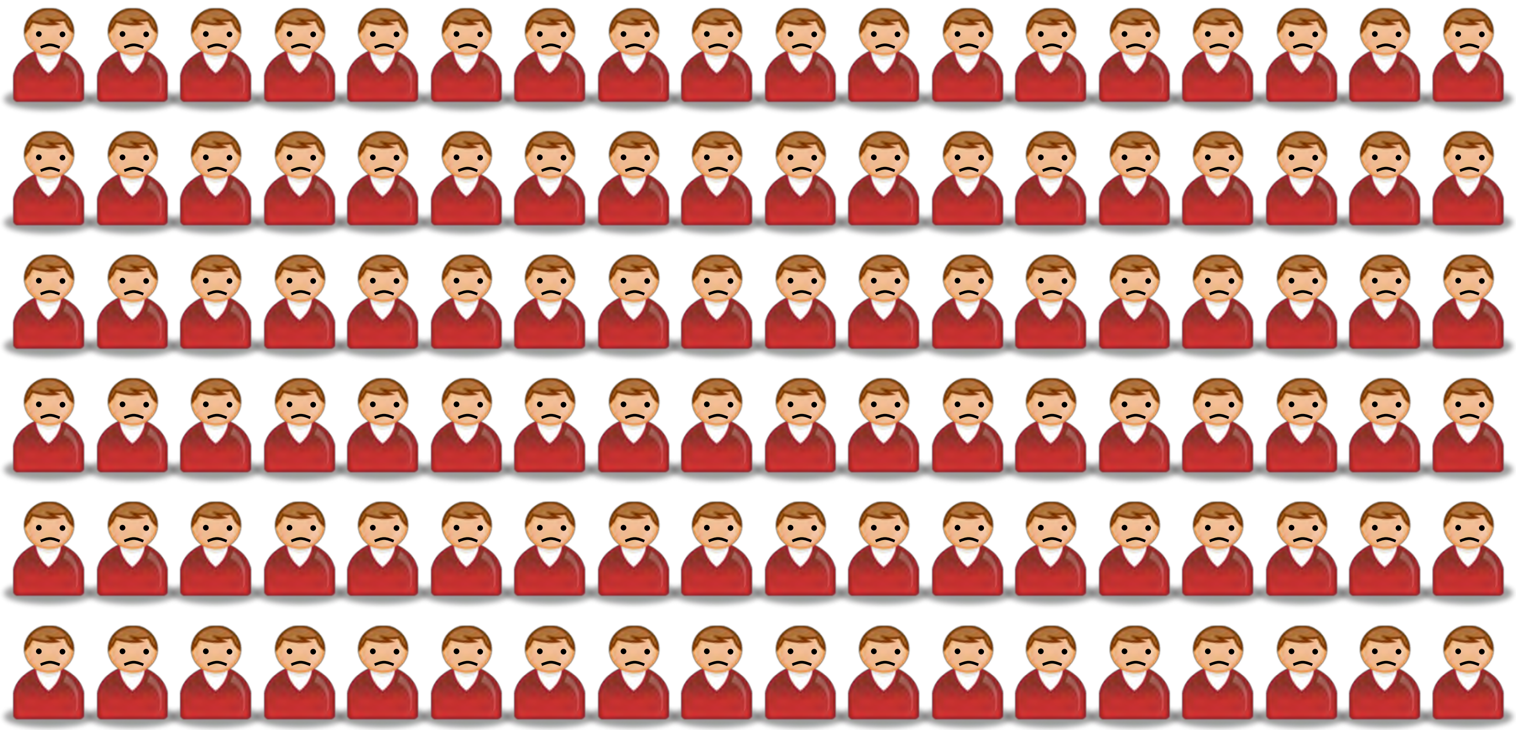
- **It is very difficult to write the fastest code**
  - Tuning for memory hierarchy
  - Efficient use of vector instructions
  - Efficient parallelization (multiple threads)
  - Requires expert knowledge in algorithms, coding, and architecture

- **Compilers can rarely perform the necessary optimization on numerical code**
  - Often intricate changes in the algorithm required
  - Automatic parallelization/vectorization still unsolved

- **Highest performance is in general non-portable**
  - Best code on one computer may be suboptimal on another
  - Best code is tuned to microarchitecture
  - Often assembly code is hand-written for optimal tuning

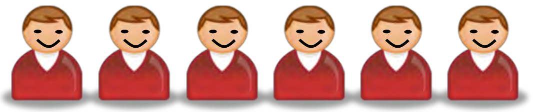
Current Practice

- **Legions** of programmers implement and optimize the **same** functionality for **every** platform and **whenever** a new platform comes out

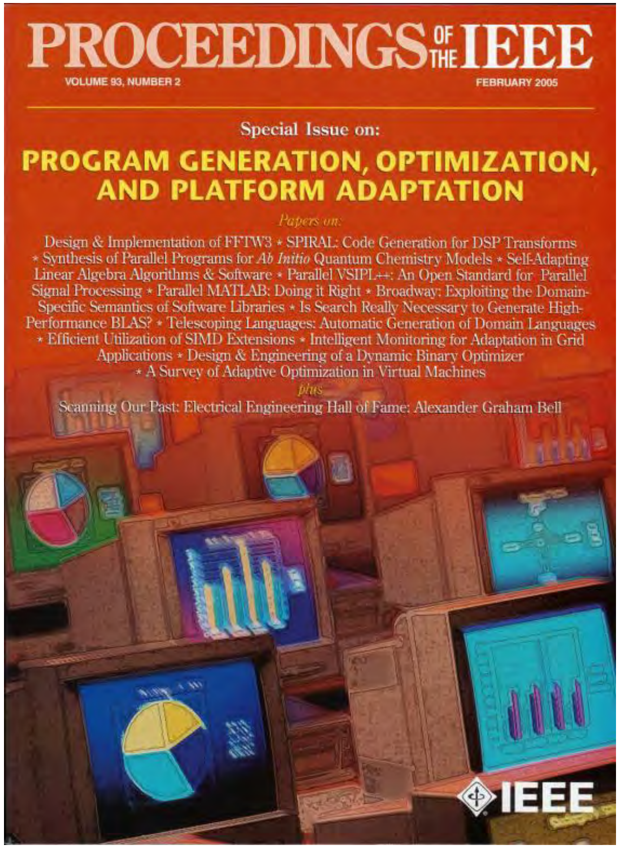


Current Research: Automatic Performance Tuning

- **Automate (parts of) the implementation or optimization**



- **Research efforts**
  - Linear algebra: Phipac/ATLAS, LAPACK, Sparsity/Bebop/OSKI, Flame
  - Tensor computations
  - PDE/finite elements: Fenics
  - Adaptive sorting
  - Fourier transform: FFTW
  - Linear transforms: Spiral
  - …others
  - New compiler techniques

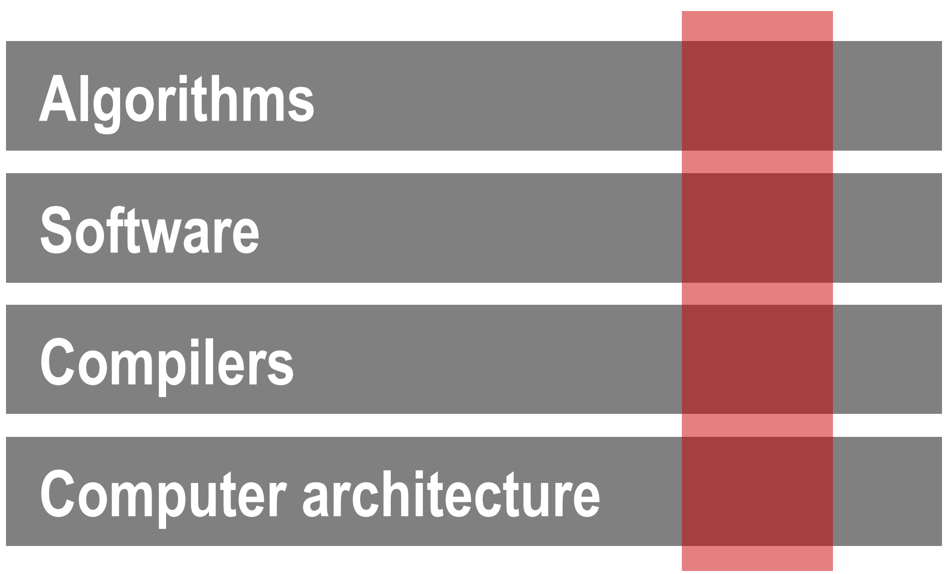


Proceedings of the IEEE special issue, Feb. 2005

This Course

- **Learn how to write fast code for numerical problems**
  - Requires multi-disciplinary knowledge
  - Principles studied using important examples
  - Applied in homeworks and a semester-long research project

Fast implementations of numerical problems



This Course cont'd

- **Background**
  - Algorithm analysis
  - Compilers
  - Computer architecture

- **Performance optimization**
  - Benchmarking, optimization techniques (memory hierarchy, vector instructions, multithreading)
  - Case studies: important numerical kernels (transforms, linear algebra, filters, convolution, …)
  - Automatic performance tuning (state-of-the-art research)

- **Other knowledge**
  - History, tips for publishing and presenting, …

About this Course

- **Requirements**
  - solid C programming skills
  - matrix algebra
  - senior or above
- **Grading**
  - 40% research project
  - 15% midterm
  - 35% homework
  - 10% class participation
- **No textbook**
- **Office Hours: yet to be determined**
- **Website: www.ece.cmu.edu/~pueschel → teaching → 18-645**

Research Project

- Team up in pairs
- Topic: Very fast implementation of a numerical problem
- Jan 28th: suggest to me a problem or I give you a problem
  Tip: pick something from your research (for PhD students)
- Show “milestones” during semester
- Write 4 page standard conference paper (template will be provided)
- Give short presentation end of semester

Midterm

- Mostly about algorithm analysis
- Some multiple-choice

Final Exam

- There is no final exam

Homework

- **Exercises on algorithm analysis (Math)**

- **Implementation exercises**
  - Concrete numerical problems
  - Study the effect of program optimizations, use of compilers, use of special instructions, etc. (Writing C code + creating runtime/performance plots)
  - Some templates will be provided

- **Homework scheduled to leave time for research project**

Classes/Class Participation

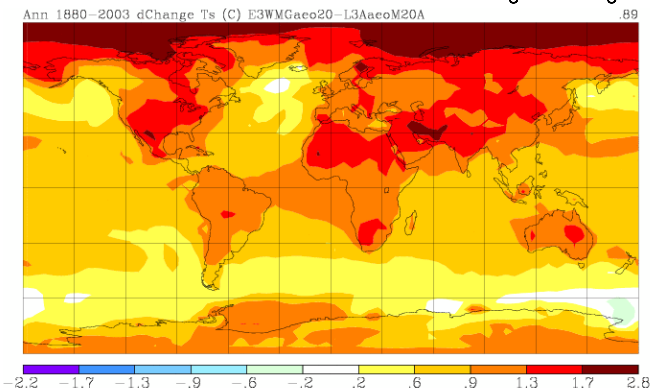
- **I'll start on time, duration ~1:30 (without break)**
  - be on time, it's good style
- **It is important to attend**
  - many things I'll teach are not in books
  - I'll use part slides part blackboard
- **Ask questions**
- **I will provide some anonymous feedback mechanism (maybe every 3-4 weeks)**

Questions?

Motivation: Concrete Applications

Scientific Computing (Large Clusters)

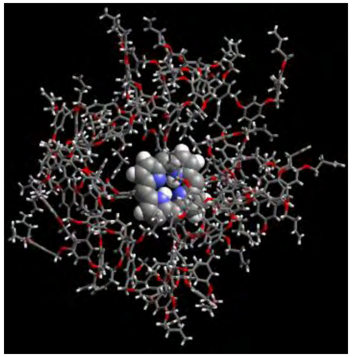
data.giss.nasa.gov



Climate modelling

Finance simulations

www.foresight.org



Molecular dynamics

Other application areas:

- Fluid dynamics
- Chemistry
- Biology
- Medicine
- Geophysics

Methods:

- Mostly linear algebra
- PDE solving
- Linear system solving
- Finite element methods

Consumer Computing (Desktop, ...)

Photo/video processing

Audio coding

Security

Original

JPEG

JPEG2000

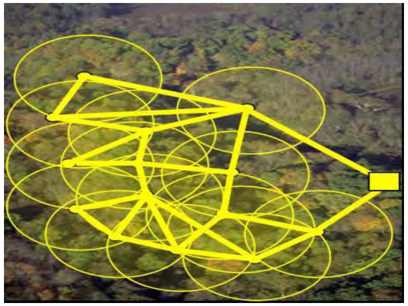
Image compression

Methods:

- Linear algebra
- Transforms
- Filters
- Many others

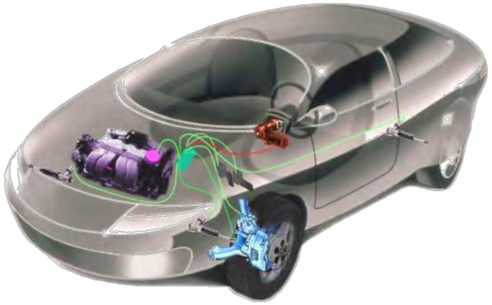
Embedded Computing (Low-power processors)

www.dei.unipd.it



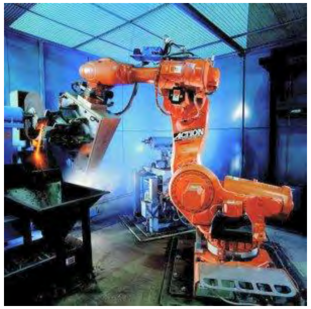
Sensor networks

www.ece.drexel.edu



Cars

www.microway.com.au



Robotics

Computation needed:
- Signal processing
- Control
- Communication

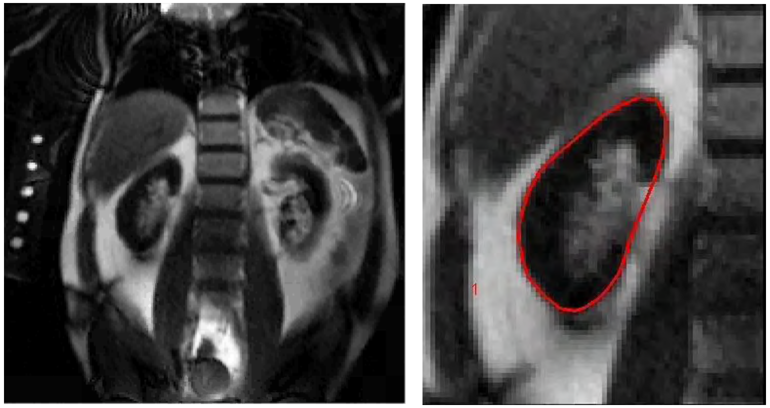
Methods:
- Linear algebra
- Transforms, Filters
- Coding

Research (Examples at ECE/CMU)

Bhagavatula/Savvides

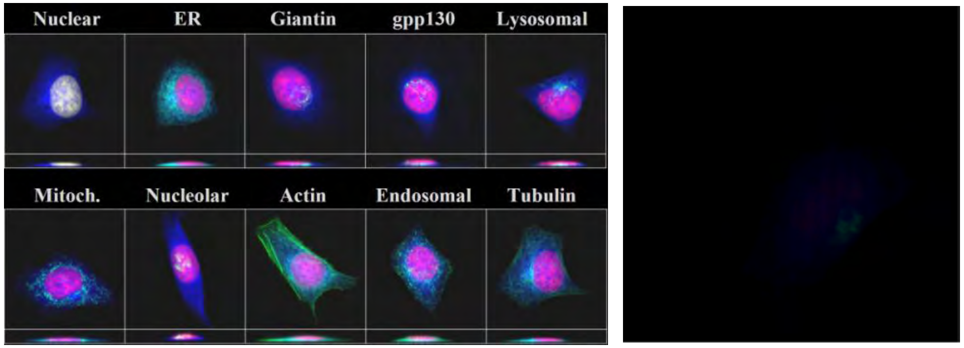
Biometrics

Moura



Medical Imaging

Kovacevic



Bioimaging

Kanade

Computer vision

Summary

- A very large number of diverse applications in engineering, science, consumer market rely on numerical computation
- The computations are diverse but rely on basic mathematical functionality (see 13 dwarfs, Berkeley report on parallel computing landscape)
  - Linear algebra (dense/sparse)
  - Transforms/filters
  - Grid methods
  - Encryption
  - Graph traversals, sorting
  - …
- Unlimited need for performance
- In this course you learn how to make numerical applications run fast on modern computing platforms (focus desktop)