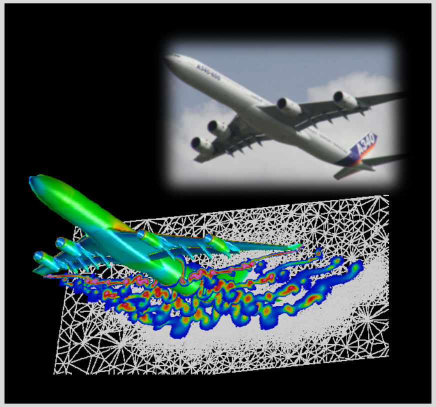


High Performance Computing

ADVANCED SCIENTIFIC COMPUTING

Prof. Dr. – Ing. Morris Riedel

Adjunct Associated Professor

School of Engineering and Natural Sciences, University of Iceland, Reykjavik, Iceland

Research Group Leader, Juelich Supercomputing Centre, Forschungszentrum Juelich, Germany

@Morris Riedel @MorrisRiedel @MorrisRiedel

LECTURE 0

Prologue

August 26, 2019

Room V02-156

UNIVERSITY OF ICELAND
SCHOOL OF ENGINEERING AND NATURAL SCIENCES
FACULTY OF INDUSTRIAL ENGINEERING, MECHANICAL ENGINEERING AND COMPUTER SCIENCE

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

DEEP Projects

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

HAICU HELMHOLTZ ARTIFICIAL INTELLIGENCE COOPERATION UNIT

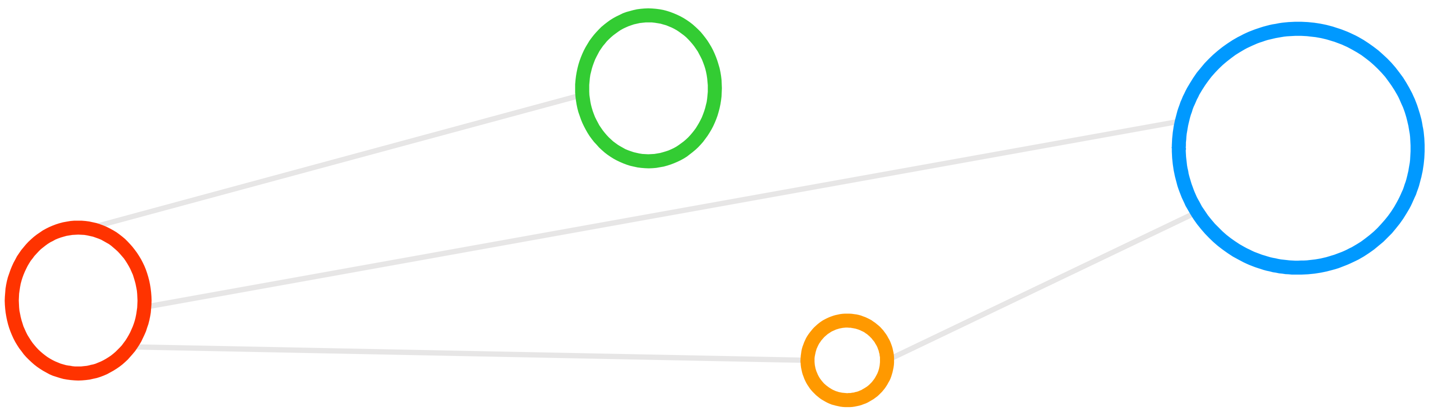
Outline of the Course

1. High Performance Computing
2. Parallel Programming with MPI
3. Parallelization Fundamentals
4. Advanced MPI Techniques
5. Parallel Algorithms & Data Structures
6. Parallel Programming with OpenMP
7. Graphical Processing Units (GPUs)
8. Parallel & Scalable Machine & Deep Learning
9. Debugging & Profiling & Performance Toolsets
10. Hybrid Programming & Patterns
11. Scientific Visualization & Scalable Infrastructures
12. Terrestrial Systems & Climate
13. Systems Biology & Bioinformatics
14. Molecular Systems & Libraries
15. Computational Fluid Dynamics & Finite Elements
16. Epilogue

+ additional practical lectures & Webinars for our hands-on assignments in context

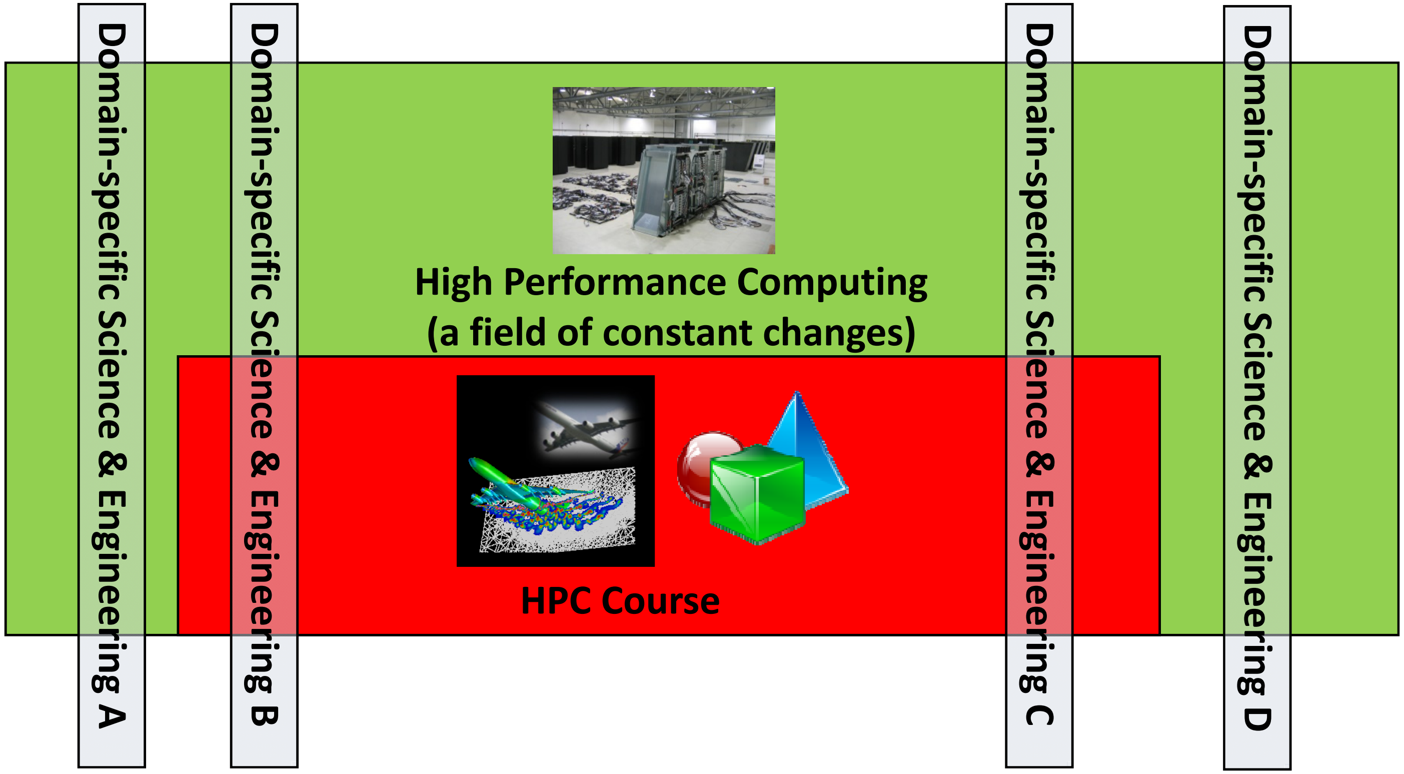
- Practical Topics
- Theoretical / Conceptual Topics

Course Motivation & Information



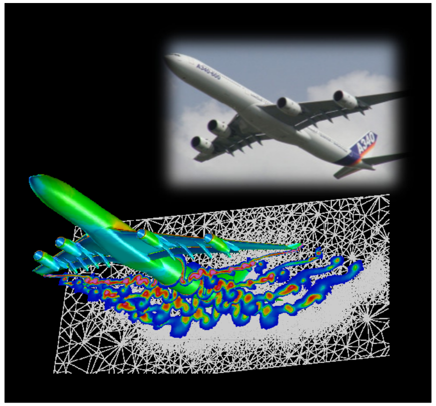
Positioning in the Field of High Performance Computing (HPC)

- Consists of techniques for programming & using large-scale HPC Systems
  - Approach: Get a broad understanding what HPC is and what can be done
  - Goal: Train general HPC techniques and systems and selected details of domain-specific applications



Course Motivation

- Parallel processing and distributed computing
  - Matured over the past three decades
  - Both emerged as a well developed field in computer science
  - Still a lot of innovation, e.g. from hardware / software
- 'Scientific computing' with Maple, Matlab, etc.
  - Performed on small ('serial') computing machines like Desktop PCs or Laptops
  - Increasing number of cores enables 'better scientific computing' today
  - Good for small & less complex applications, quickly reach memory limits
- 'Advanced scientific computing'
  - Used with computational simulations and large-scale machine & deep learning
  - Performed on large parallel computers; often scientific domain-specific approaches
  - Use orders of magnitude multi-core chips & large memory & specific many-core chips
  - Enables 'simulations of reality' often based on known physical laws and numerical methods



Selected Learning Outcomes

- Students understand…
  - Latest developments in parallel processing & high performance computing (HPC)
  - How to create and use high-performance clusters
  - What are scalable networks & data-intensive workloads
  - The importance of domain decomposition
  - Complex aspects of parallel programming
  - HPC environment tools that support programming or analyze behaviour
  - Different abstractions of parallel computing on various levels
  - Foundations and approaches of scientific domain-specific applications

- Students are able to …
  - Programm and use HPC programming paradigms
  - Take advantage of innovative scientific computing simulations & technology
  - Work with technologies and tools to handle parallelism complexity

Lecturer Morris Riedel (since ~2004 in HPC)

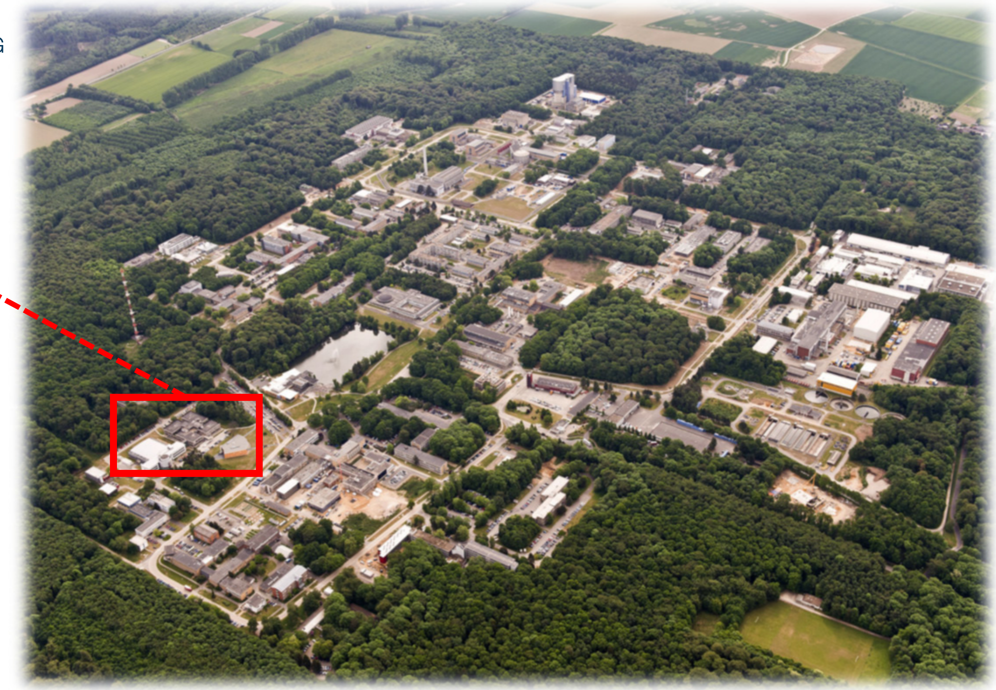
- Holds PhD in Computer Science (from Karlsruhe Institute of Tech.)
  - MSc in data visualization and steering of HPC & Grid applications
- Over the time several Positions at Juelich Supercomputing Centre
  - OS, Grid divisions; later deputy division leader federated systems and data
  - Currently: Research Group Leader – High Productivity Data Processing
- Selected other recent activities
  - Working with CERN & LHC & Grid/Cloud (Strategic Director of EU Middleware)
  - Architect of Extreme Science and Engineering Discovery Environment XSEDE (US HPC Infrastructure)
  - Co-Design of European Data Infrastructure (EUDAT), Research Data Alliance Big Data (Analytics) Chair, DEEP-EST HPC designs, steering group of Helmholtz Artificial Intelligence Cooperation Unit (HAICU)
- University courses
  - University of IcelandCourses: HPC A / B, Statistical Data Mining, Cloud Computing & Big Data
  - Slides from previous years available under teaching of instructors personal Web page

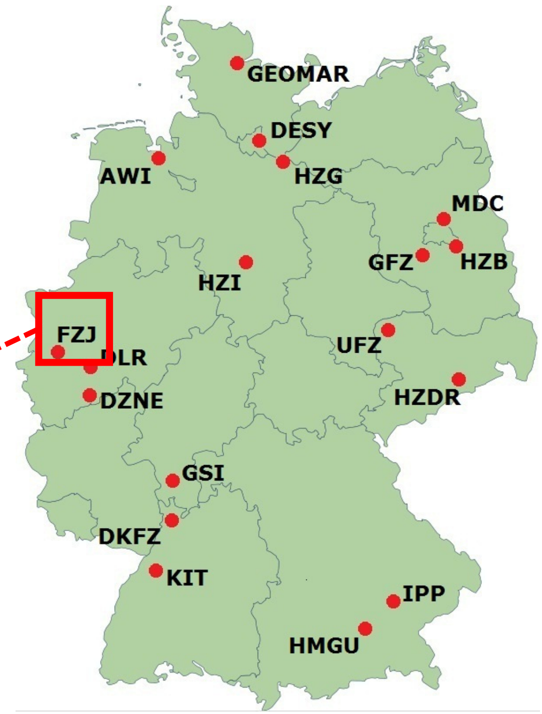
[3] Morris Riedel Web page

Juelich Supercomputinc Centre of Forschungszentrum Juelich – Germany

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

[5] Forschungszentrum Juelich Web page



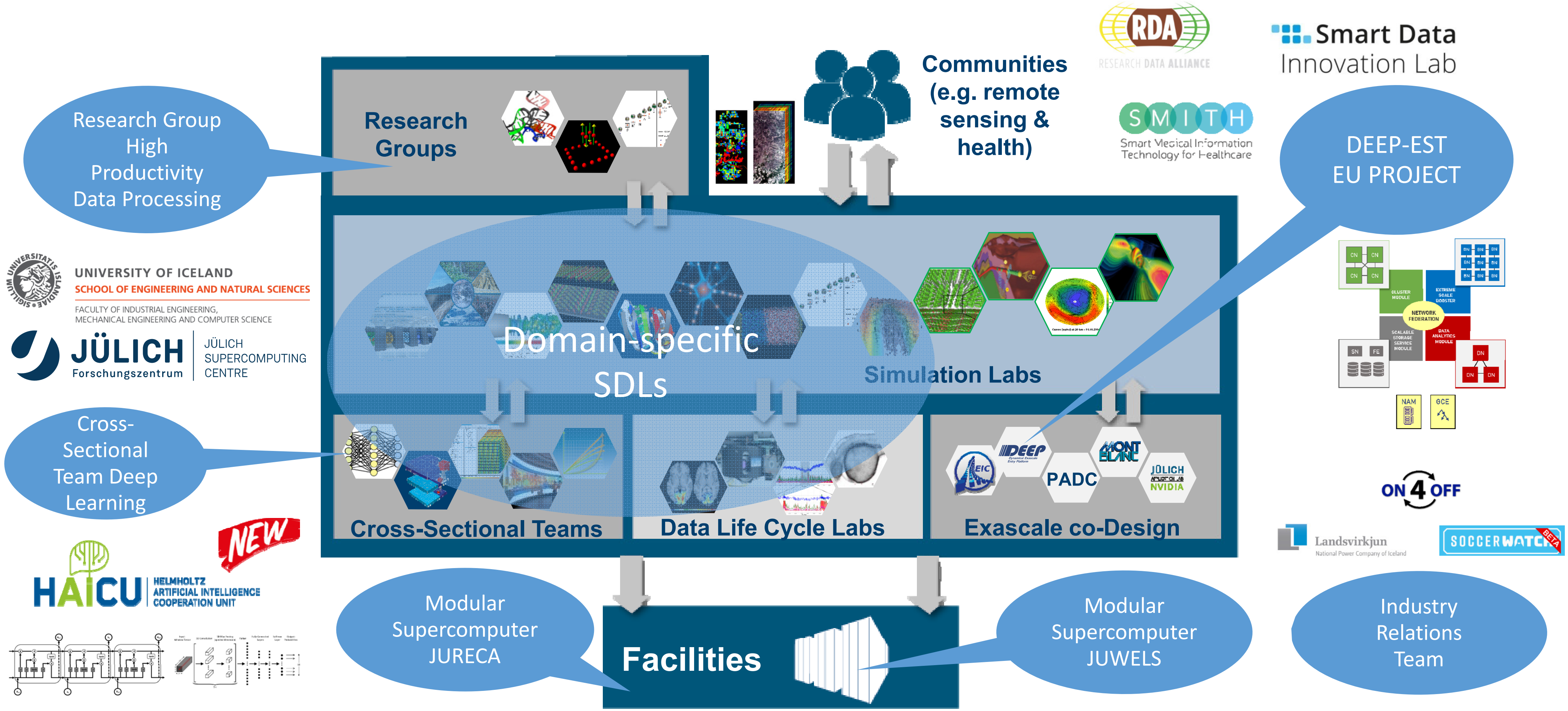


HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

[4] Holmholtz Association Web Page

- Selected Facts
  - One of EU largest inter-disciplinary research centres (~5000 employees)
  - Special expertise in physics, materials science, nanotechnology, neuroscience and medicine & information technology (HPC & Data)

Jülich Supercomputing Centre High Productivity Data Processing Research Group



University of Iceland – School of Natural Sciences & Engineering (SENS)

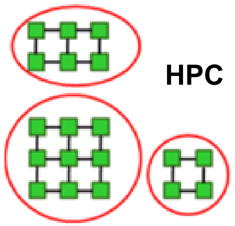
- Selected Facts
  - *Ranked among the top 300 universities in the world (by Times Higher Education)*
  - *Ranked #6 in the field of remote sensing (by Shanghai list)*
  - ~2900 students at the SENS school
  - Long collaboration with Forschungszentrum Juelich
  - *~350 MS students & ~150 PhD students*
  - *Many foreign & Erasmus students*
  - *English courses*

[6] University of Iceland SENS Web Page

UNIVERSITY OF ICELAND
SCHOOL OF ENGINEERING AND NATURAL SCIENCES
FACULTY OF INDUSTRIAL ENGINEERING, MECHANICAL ENGINEERING AND COMPUTER SCIENCE

Understanding High Performance Computing (HPC)

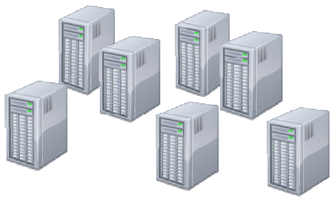
- **High Performance Computing (HPC) is based on computing resources that enable the efficient use of parallel computing techniques through specific support with dedicated hardware such as high performance cpu/core interconnections.**

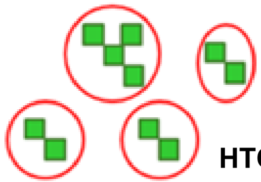


HPC

network interconnection important

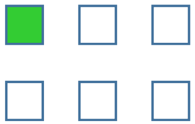
- **High Throughput Computing (HTC) is based on commonly available computing resources such as commodity PCs and small clusters that enable the execution of 'farming jobs' without providing a high performance interconnection between the cpu/cores.**





HTC

network interconnection less important!



➢ The complementary Cloud Computing & Big Data – Parallel Machine & Deep Learning Course focusses on High Throughput Computing

HPC & Data-intensive Sciences – A Field of Constant Evolution

1.000.000 FLOP/s

~1984

© Photograph by Rama, Wikimedia Commons

- **Floating Point Operations per one second (FLOPS or FLOP/s)**
- **1 GigaFlop/s = 10^9 FLOPS**
- **1 TeraFlop/s = 10^{12} FLOPS**
- **1 PetaFlop/s = 10^{15} FLOPS**
- **1 ExaFlop/s = 10^{18} FLOPS**

1.000.000.000.000.000 FLOP/s

~295.000 cores~2009 (JUGENE)

>5.900.000.000.000.000 FLOP/s
~ 500.000 cores
~2013 → end of service in 2018

German GAUSS Centre for Supercomputing

Gauss Centre for Supercomputing

[7] GCS Web page

- Supercomputer JUWELS @ JSC
  - Juelich Wizard for European Leadership Science (JUWELS)
  - Cluster architecture based on commodity multi-core CPUs
  - 2,550 compute nodes: two Intel Xeon 24-core Skylake CPUs & 48 accelerated compute nodes (4 NVIDIA Volta GPUs)
- Supercomputer SuperMUC @ LRZ
  - 155,000 cores
- Supercomputer Hazel Hen @HLRS
  - 185,088 compute cores
- GCS represents Germany in the Partnership for Advanced Computing in Europe (PRACE) HPC infrastructure

[8] PRACE Web page

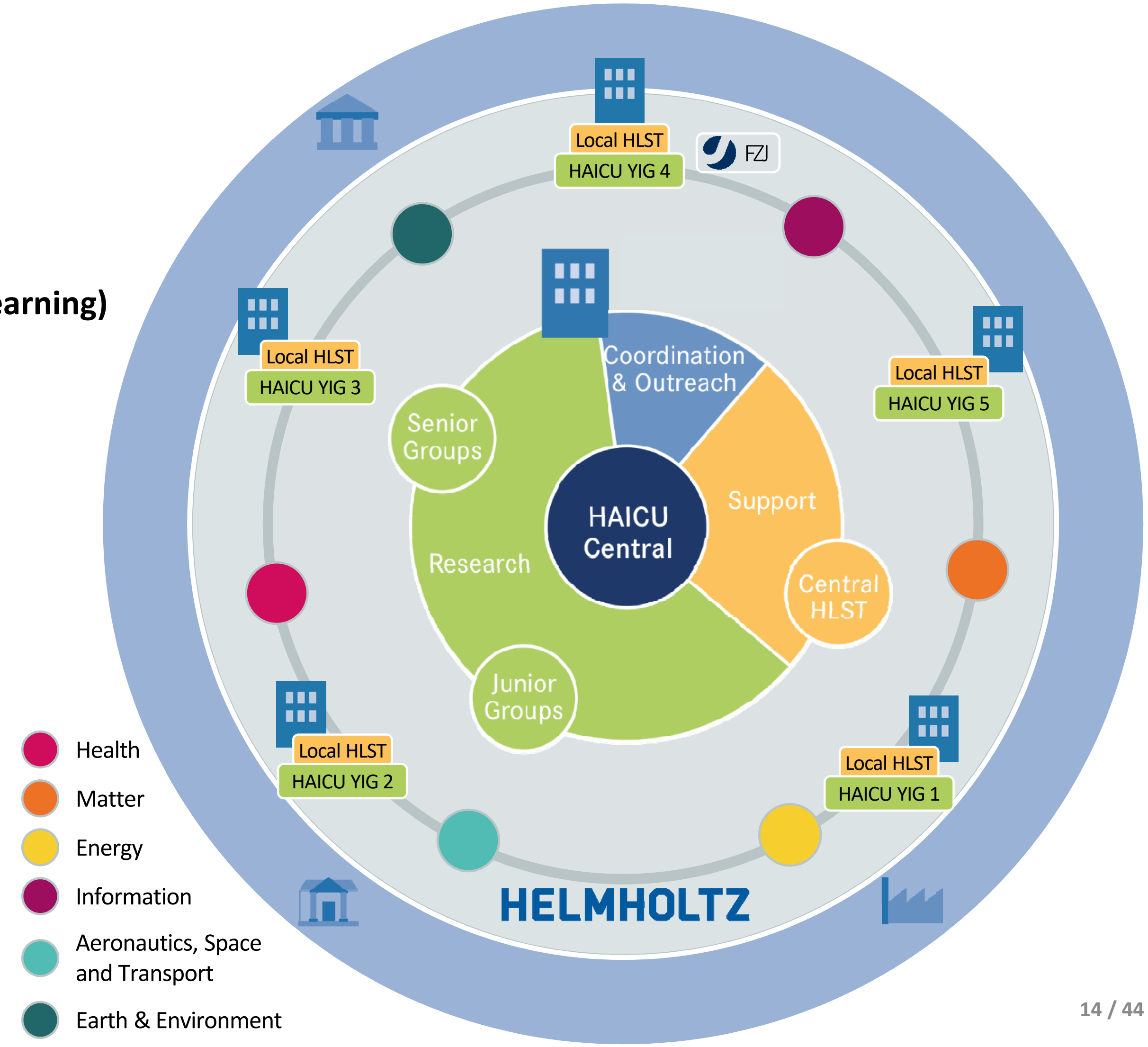
Artificial Intelligence & HPC

- **Forschungszentrum Jülich (HAICU Local ‘Information‘)**
  - **Young Investigator Group at INM-1 (~3 FTEs)**
  - **High Level Support Team (HLST) at JSC (~ 5 FTEs)**
    (specific expertise in parallel & scalable machine learning)
- Helmholtz Zentrum München (HMGU)
  (HAICU Central ‘Health‘)
- Karlsruhe Institute of Technology (KIT)
  (HAICU Local ‘Energy’)
- Helmholtz-Zentrum Geesthacht (HZG)
  (HAICU Local ‘Earth & Environment‘)
- Helmholtz-Zentrum Dresden Rossendorf (HZDR)
  (HAICU Local ‘Matter‘)
- German Aerospace Center (DLR)
  (HAICU Local ‘Aeronautic/Space & Transport‘)

HAICU HELMHOLTZ ARTIFICIAL INTELLIGENCE COOPERATION UNIT

~11.4 million € / year

[9] HAICU Web Page

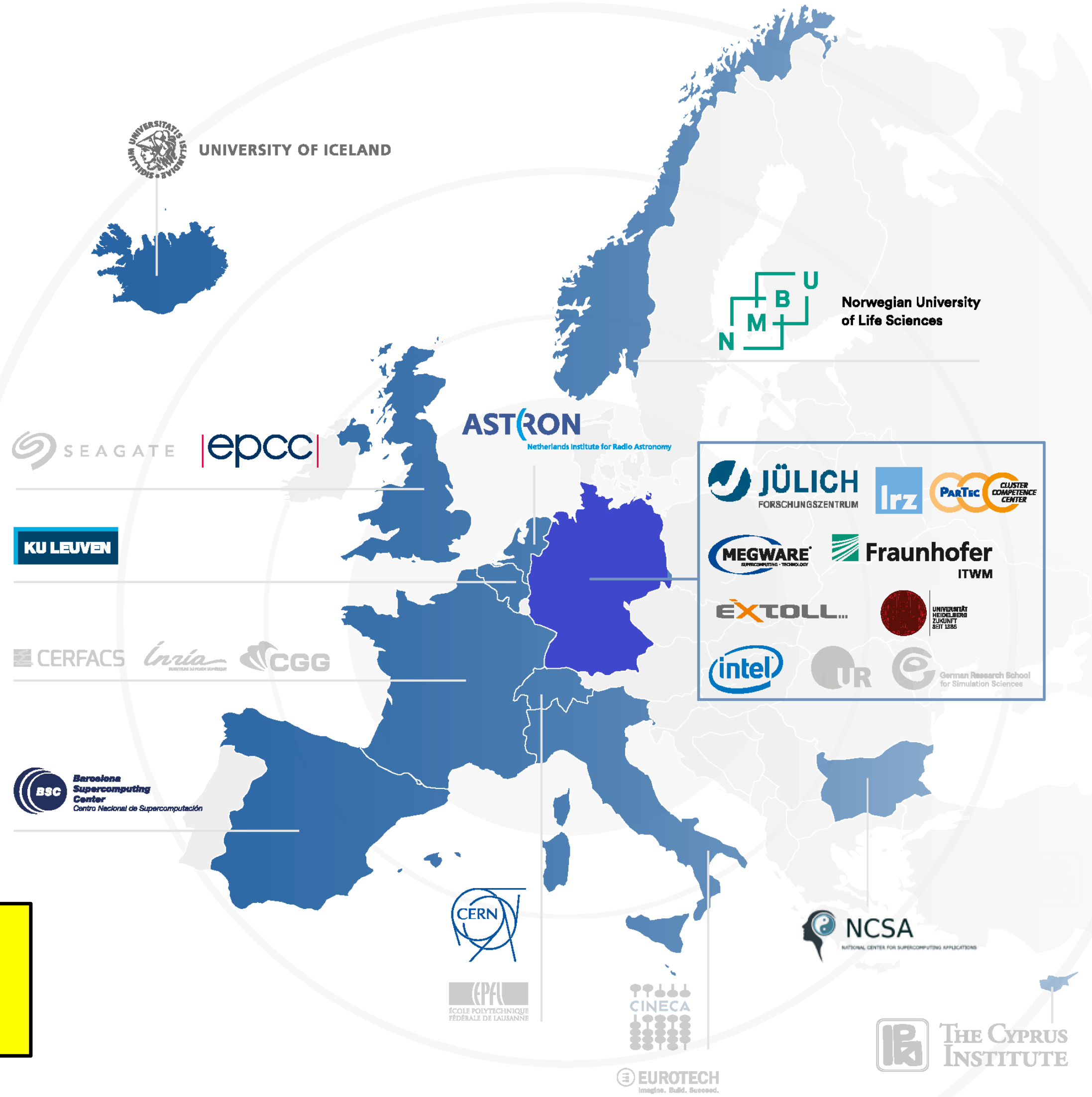


DEEP series of PROJECTS & HPC

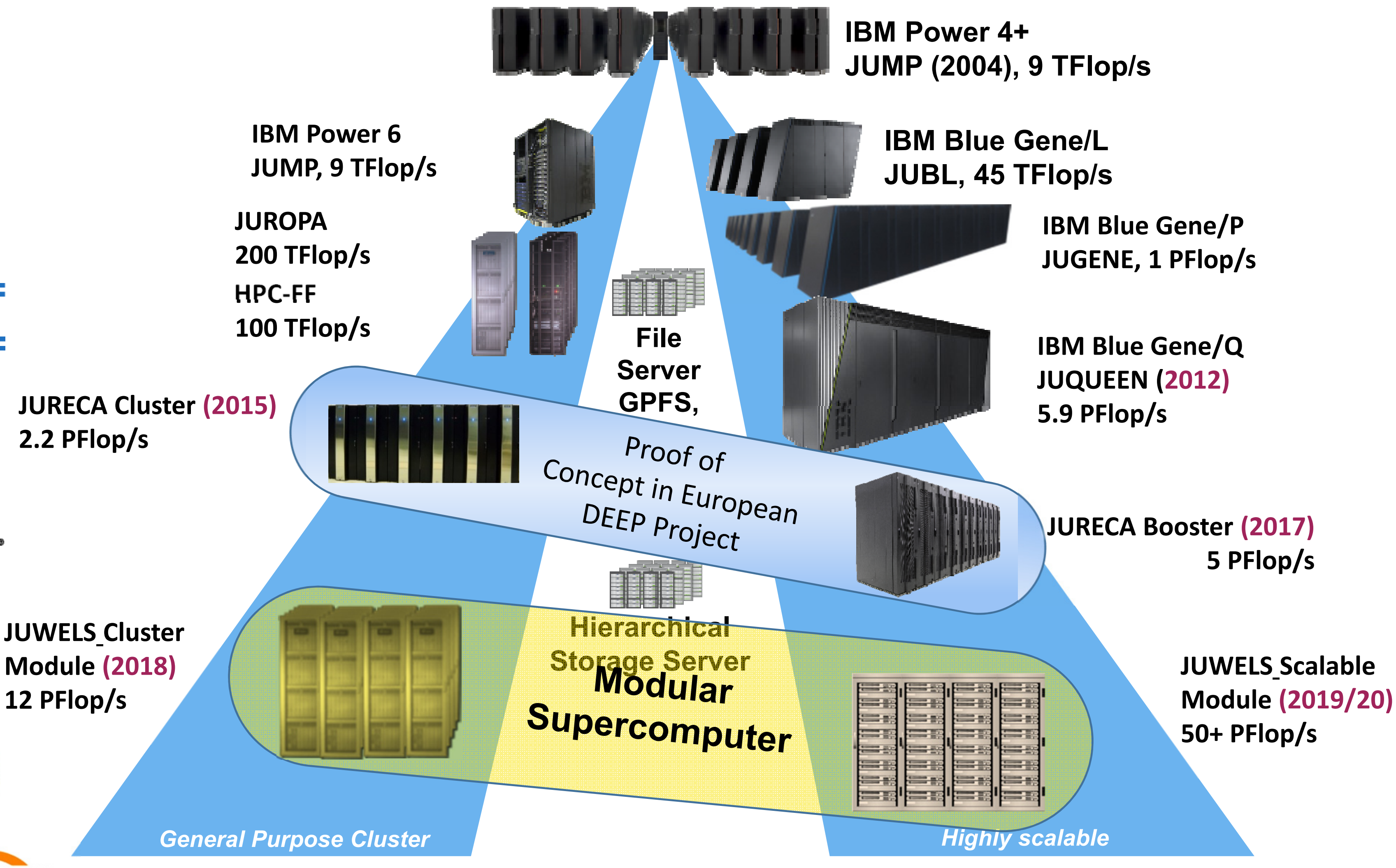
- 3 EU Exascale projects
  DEEP, DEEP-ER, DEEP-EST
- 27 partners
  Coordinated by JSC
- EU-funding: 30 M€
  JSC-part > 5,3 M€
- Nov 2011 – Dec 2020

- **Strong collaboration with our industry partners Intel, Extoll & Megware**

- **Juelich Supercomputing Centre implements the DEEP projects designs in its production infrastructure**



[10] DEEP Projects Web Page



IBM Power 4+
JUMP (2004), 9 TFlop/s
IBM Power 6
JUMP, 9 TFlop/s
IBM Blue Gene/L
JUBL, 45 TFlop/s
IBM Blue Gene/P
JUGENE, 1 PFlop/s
JUROPA
200 TFlop/s
HPC-FF
100 TFlop/s
File
Server
GPFS,
IBM Blue Gene/Q
JUQUEEN (2012)
5.9 PFlop/s
JURECA Cluster (2015)
2.2 PFlop/s
Proof of
Concept in European
DEEP Project
JURECA Booster (2017)
5 PFlop/s
Hierarchical
Storage Server
JUWELS Cluster
Module (2018)
12 PFlop/s
Modular
Supercomputer
JUWELS Scalable
Module (2019/20)
50+ PFlop/s
General Purpose Cluster
Highly scalable

UGLA Tool & Office Hours (!)

- Reference course information
  - High Performance Computing
  - REI105M, Fall 2019
- Use it for course communication
  - Every course member requires account
  - Contact other students & discuss topics
  - Contact lecturer
- Find course materials
  - Slides of Lectures and Practical Lectures
  - Handouts and Recordings
  - Further reading topics (e.g. papers, etc.)
- Questions, major difficulties, etc.? → Don’t wait long!
  - Use my office hours, send meeting request email to morris@hi.is

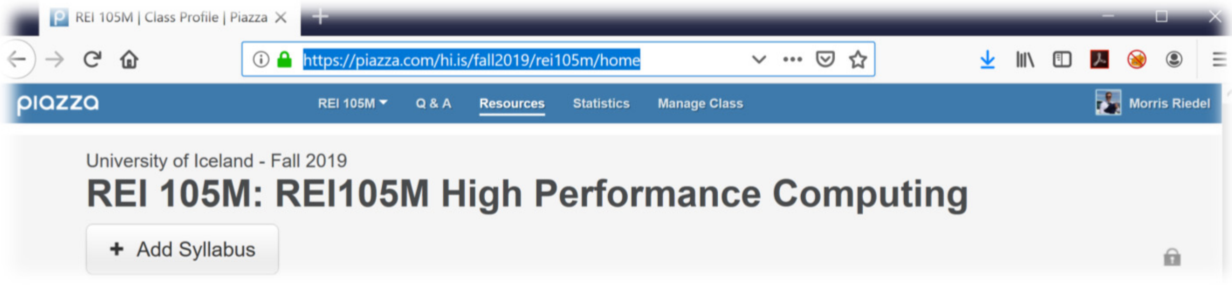
[13] High Performance Computing UGLA Course Page Online

Overall Course Organization

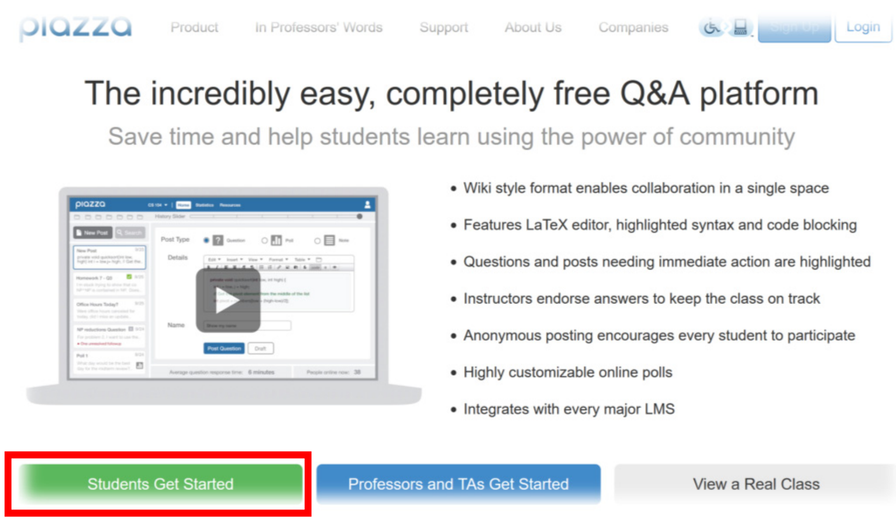
- 3 Assignments (40% of grade)
  - Guided by practical lectures in context with hands-on elements for all
  - Cloud configuration & cloud programming projects
  - Influence in the overall grade
  - TBD(all): Create Groups of 2-3 and send the group to morris@hi.is
- Quizzes (10% of grade)
  - Small quiz from time to time (pre-announced) to check understanding
  - Minor influence in the overall grade – good preparation for exam
- Exam (50% of grade)
  - End of the lecture series (~December) – major part of the overall grade
  - ‘Not knowing everything is key – but understand the important elements‘
- Invited Lectures
  - A couple of presentations (e.g. companies, interesting projects, etc.)

Course @ Q&A Platform Piazza

- Q&A Platform
  - Mixture between a wiki and a forum for students
  - Can be used by academic institutions for free
  - Idea: come together to share ideas and knowledge
  - E.g. ask questions about course assignments/ content
- Course information
  - Name: REI105M High Performance Computing
  - Semester: Fall 2019
  - URI: https://piazza.com/hi.is/fall2019/rei105m/home
  - TBD (all students): Please check whether you have been registered for the course
  - TBD (all students): Get familiar with Piazza

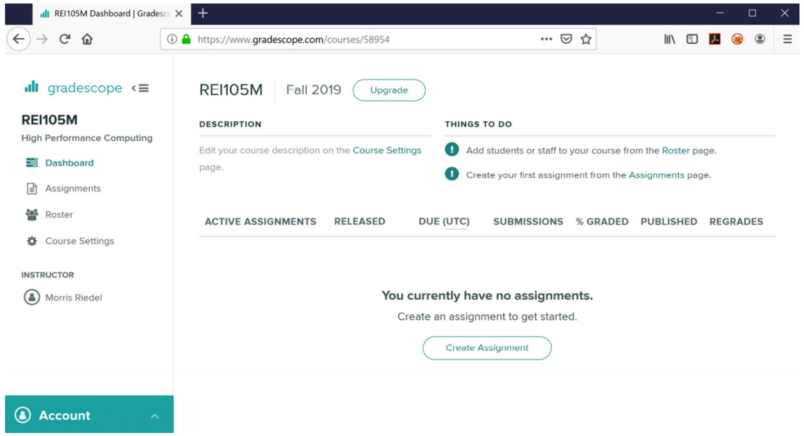


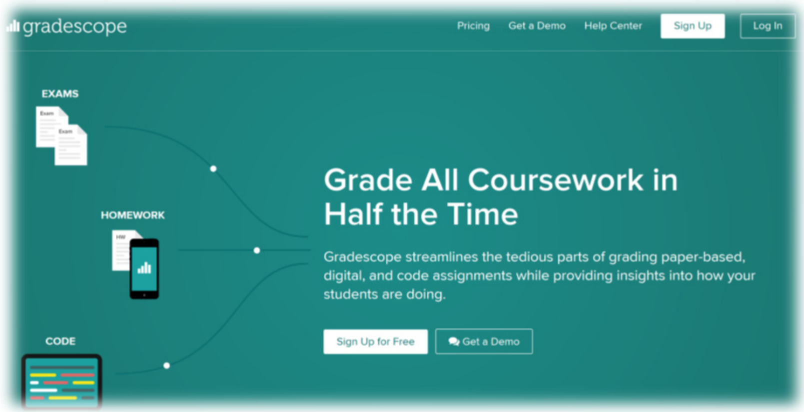
[1] Piazza Web page



Course @ Gradescope

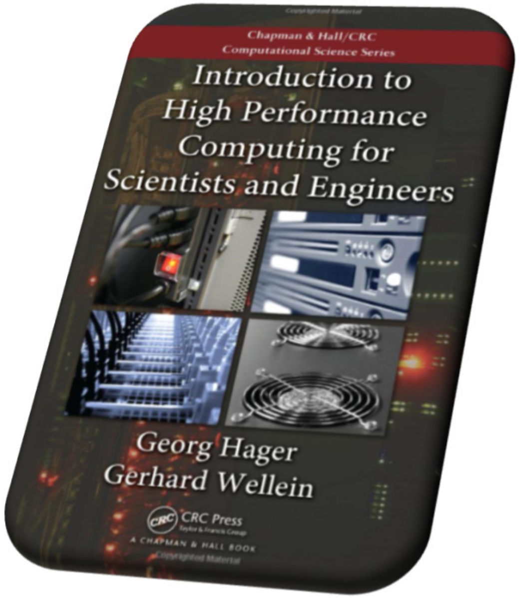
- Student Grading Platform
  - Grading for quizzes, assignments & exam will be performed
  - Can be used by academic institutions for free
  - Idea: get faster feedback for course content and a more fair grading process
  - E.g. professor does not see the name of students per task
- Course information
  - Name: REI105M High Performance Computing
  - Semester: Fall 2019
  - URI: https://www.gradescope.com/courses/58954
  - TBD (all students): Please check whether you have been registered for the course
  - TBD (all students): Get familiar with Gradescope





[2] Gradescope Web page

Associated Literature



Introduction to High Performance Computing for Scientists and Engineers,
Georg Hager & Gerhard Wellein,
Chapman & Hall/CRC Computational Science,
ISBN 143981192X, English, ~330 pages, 2010

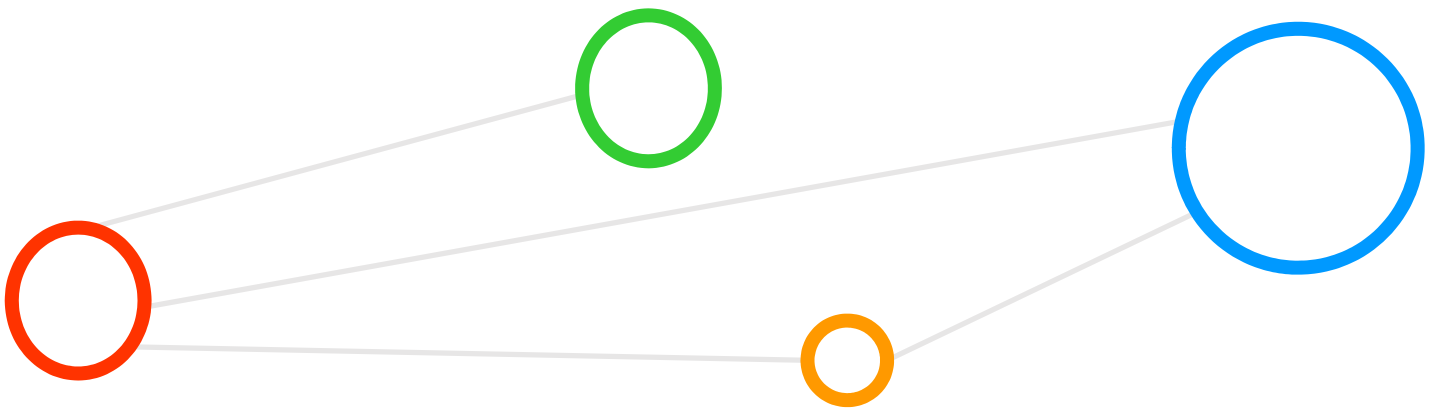
[14] Introduction to High Performance Computing, 2010

- Further bibliography and readings will be provided in context
  - E.g. Papers, Web pages, etc.

[Video] High Performance Computing by Dreamworks

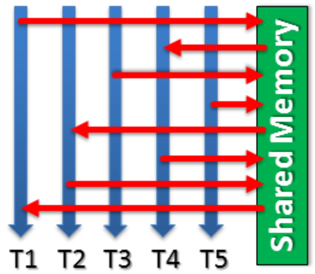
[11] YouTube, Dreamworks

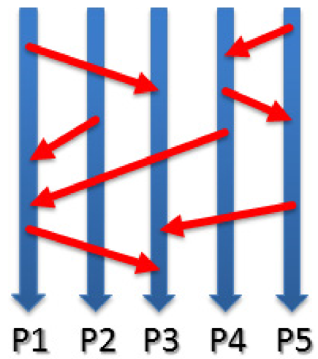
Course Organization & Content

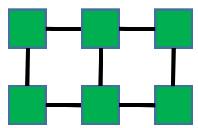


Lecture 1 – High Performance Computing

- What means ‘high performance‘?
  - Four basic building blocks of HPC
  - TOP500 and Performance Benchmarks
  - Relationship to ‘Parallelization‘
- HPC Architectures
  - Shared Memory & Distributed Memory Architectures
  - Hybrid and Emerging Architectures
  - Parallel Applications and Infrastructures
- HPC Ecosystem
  - Software Environments & Scheduling
  - System Architectures & Data Access
  - Multicore Processor Design
  - Network Topologies
  - Interesting international HPC Projects

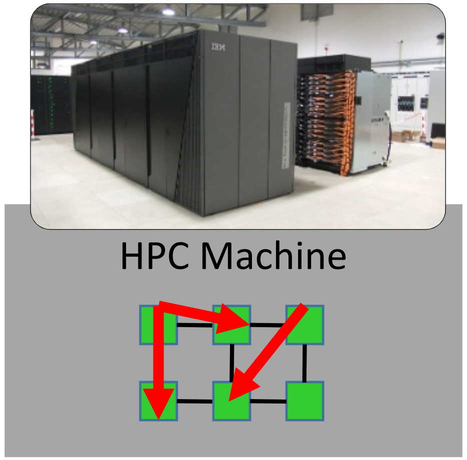


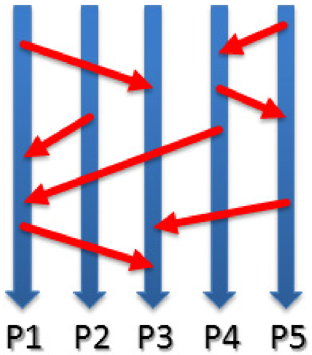


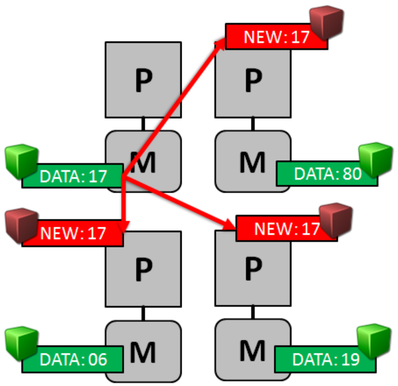


Lecture 2 – Parallel Programming with MPI

- Message Passing Interface (MPI) Concepts
  - Distributed memory systems
  - Message passing functions
  - Understanding the functionality of MPI collectives
  - Standardization & portability
  - Using MPI rank and communicators
  - MPI collective communications
- MPI Parallel Programming Basics
  - Environment with libraries & modules
  - Thinking parallel
  - Basic building blocks of a program
  - Compilations of codes
  - Parallel executions and MPI runtime
  - ‘Bad‘ code examples vs. good code examples

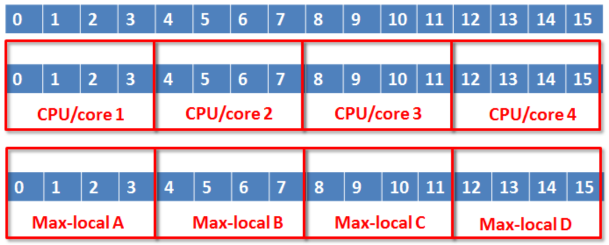


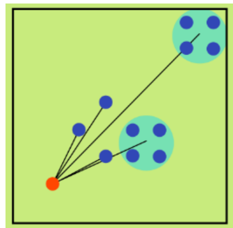


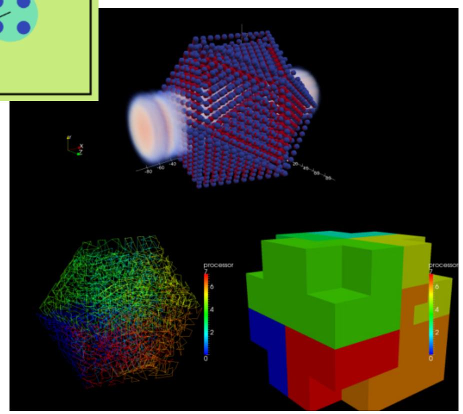


Lecture 3 – Parallelization Fundamentals

- Parallel Applications
  - Simple first parallel application examples
  - Gradually more complex applications
- Common Strategies for Parallelization
  - Moore’s law
  - Parallelization reasons and approaches
  - Various domain decompositions
  - Data parallelism methods
  - Functional parallelism methods
- Parallelization Terms & Theory
  - Speedup & Load Imbalance
  - Role of Serial Elements
  - Scalability Metrics & Performance
  - Amdahl’s Law & Performance Analysis







- Amount of work/overall problem size:

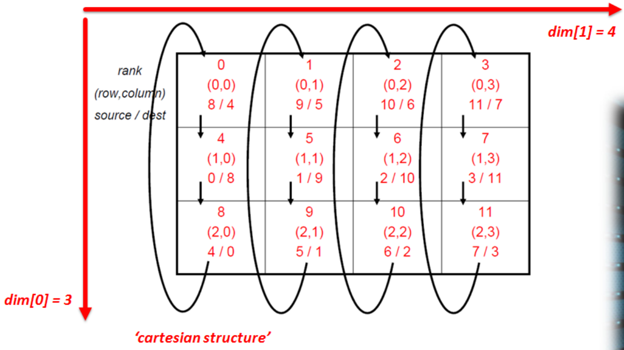
$$s + p = 1$$

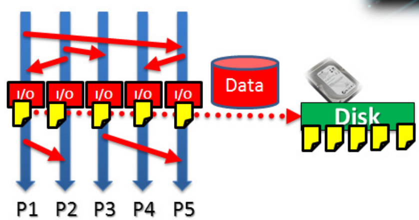
- s = serial (nonparallelizable part)
- p = parallelizable part

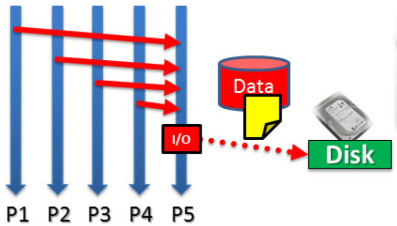
$$T_f^P = s + p/N$$

Lecture 4 – Advanced MPI Techniques

- MPI Communication Techniques
  - MPI Communicators
  - Cartesian Communicator
  - Hardware & Communication Issues
  - Network Interconnects
  - Task-Core Mappings
  - Application examples
- MPI Parallel I/O Techniques
  - I/O Terminologies & Challenges
  - Parallel Filesystems
  - MPI I/O Techniques
  - Higher-Level I/O Libraries
  - Portable File Formats
  - Application examples

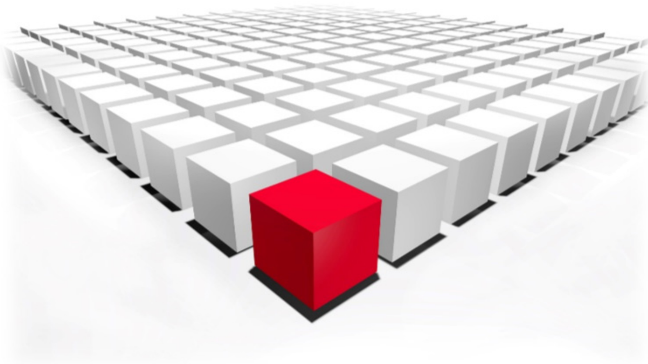


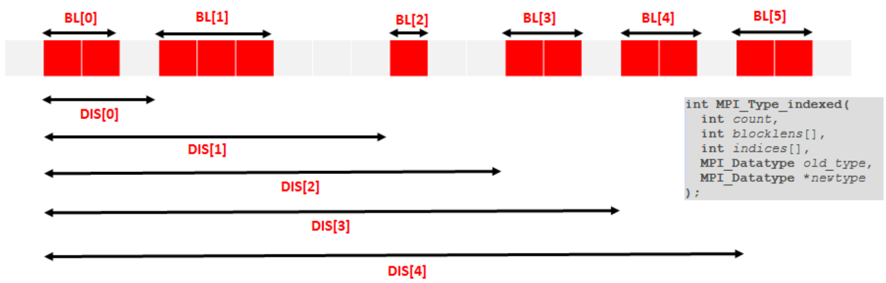




Lecture 5 – Parallel Algorithms & Data Structures

- Selected Parallel Algorithms
  - Vector Addition in MPI & OpenMP
  - Matrix – Vector Multiplication in MPI
  - Fast Fourier Transform with MPI
  - Advanced Algorithm Examples
  - Use of MPI collectives in applications
- Selected Data Structures
  - Basic MPI Datatypes
  - Arrays &
    Multi-dimensional datasets
  - Derived MPI Datatypes
  - Relationships to
    Parallel IO & Filesystems

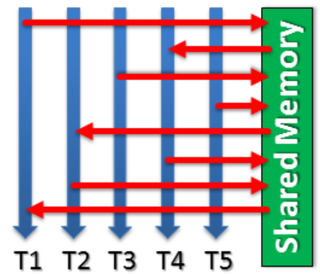


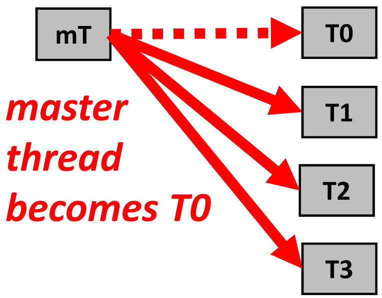


Lecture 6 – Parallel Programming with OpenMP

- Shared-Memory Programming Concepts
  - Parallel and Serial Regions
  - Fork & Joins
  - Master and Worker Threads
  - Portability
  - Application Examples
  - Differences to distributed memory
- OpenMP Parallel Programming Basics
  - Basic building blocks
  - Local/shared variables & Loops
  - Synchronization & Critical Regions
  - Selected Comparisons with MPI
  - Simple Applications

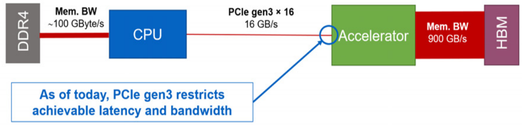
```
int main()
{
  #pragma omp parallel
  printf(„Hello World“);
}
```

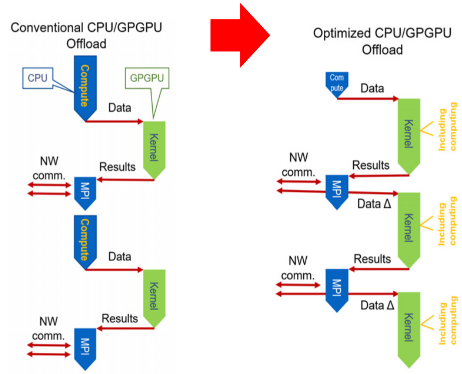


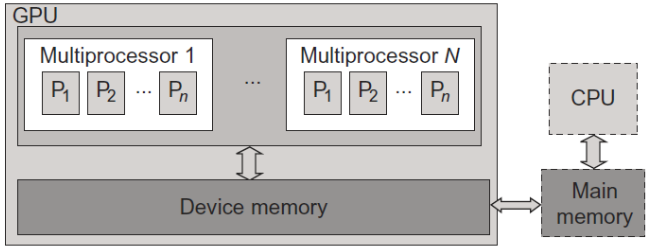


Lecture 7 – Graphical Processing Units (GPUs)

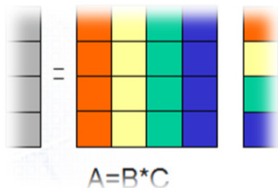
- General Purpose Graphical Processing Units (GPGPUs)
  - Often known as just ‘GPU‘
  - Many-core vs. Multi-core
  - Terminology & Architecture
  - Architecture differences from Kepler, Pascal, Volta
  - Programming Models
  - Usage Models & Applications
  - NVidia & CUDA Examples
  - Programming with OpenACC
  - Programming with HIP
  - GPU Toolsets
  - GPU Direct
- Selected GPU Applications
  - Simple Examples
  - Simulation Sciences
  - Machine & Deep Learning





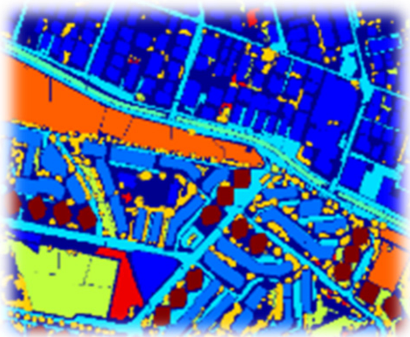


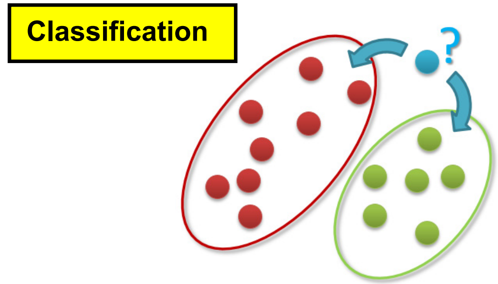
[15] Distributed & Cloud Computing Book

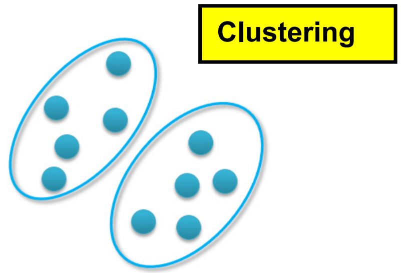


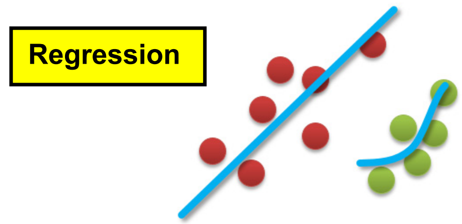
Lecture 8 – Parallel & Scalable Machine & Deep Learning

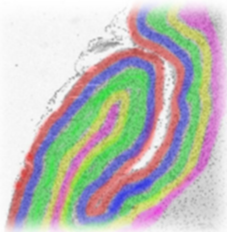
- Machine Learning & Deep Learning
  - Terminology & Motivation
  - Contrast to High Throughput Computing
  - HPC for Classification, Clustering & Regression
  - Selected Remote Sensing Use Case
  - Parallel Support Vector Machines
  - HBDBSCAN for Clustering
  - Deep Learning with Keras & TensorFlow
  - Inverse Problems
  - Relationship to Parallel I/O
  - Application Examples

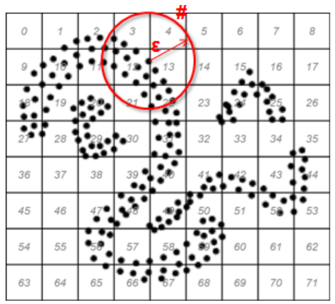


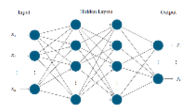


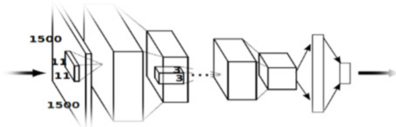






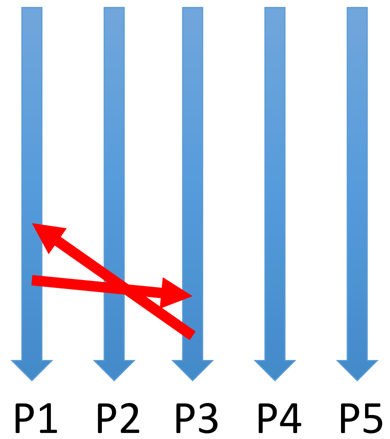


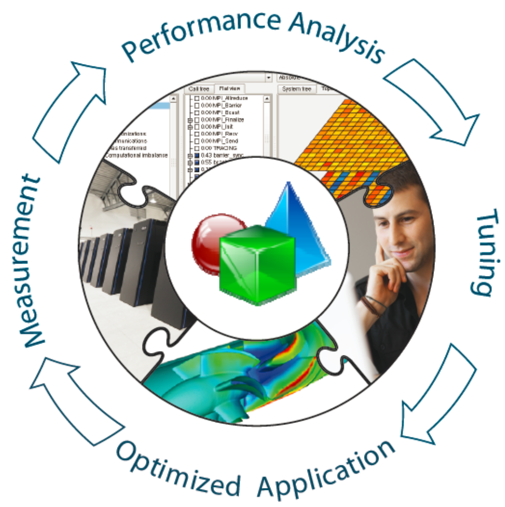


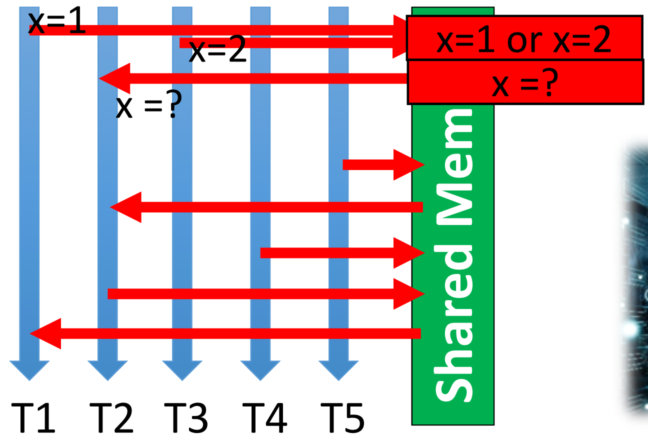


Lecture 9 – Debugging & Profiling & Performance Toolsets

- Debugging & Profiling Techniques
  - Origin and Terminologies
  - Bug Prevention Approaches
  - Review Printf Debugging
  - Advanced Debugging Techniques
  - Selected Debugging Tools
  - Understanding Wall-clock time
  - Simple MPI Timing Approaches
  - MPI Profiling Interface & Tools
- Selected Profiling Tools
  - Performance Optimization
  - Tracing Technique & Open Trace Format
  - MPI & OpenMP Problem Patterns
  - Tensorflow & Deep Learning Tool Support

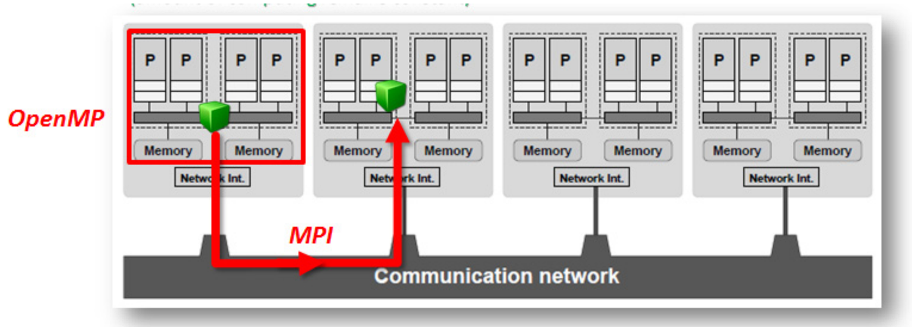


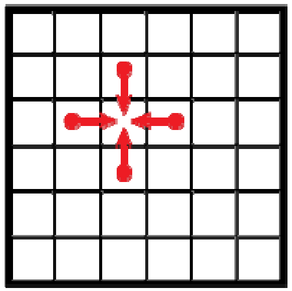


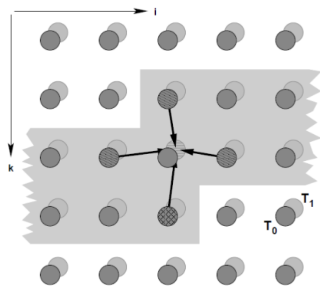


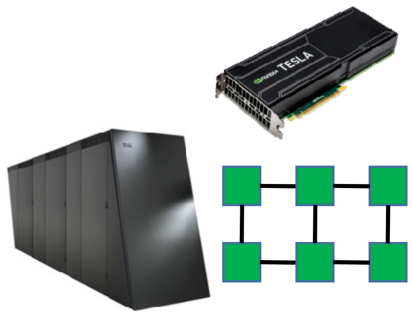
Lecture 10 – Hybrid Programming and Patterns

- Hybrid Programming
  - Motivation and Memory Benefits
  - Programming Hybrid Systems
  - Vector Mode and Task Mode
  - Lessons Learned & Performance
  - Another type of Hybrid Programming
  - Application Examples in OpenMP, MPI & GPUs
- Programming Patterns
  - Neareast Neighbour Communication
  - Cartesian Communicator Shifts
  - Stencil-based Iterative Methods
  - Jacobi 2D Application Example
  - Working with Halo Regions
  - Application Examples



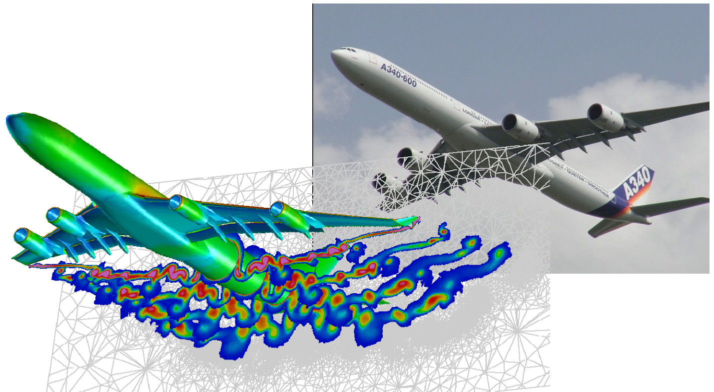




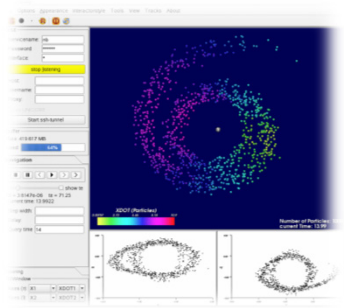


Lecture 11 – Scientific Visualization & Scalable Infrastructures

- Scientific Visualization
  - Motivation & Objectives
  - Understanding HPC Simulation Data
  - Selected Visualization & Computational Steering Techniques
  - Selected Tools and Technologies
  - Multi-scale Visualization Example
  - Application Examples
- Scalable Infrastructures
  - Large Scale HPC Infrastructures
  - e-Science and Grid Computing
  - Cloud Computing Infrastructures
  - Collaborative Data Infrastructures
  - Scientific Workflows
  - Applications



('a picture is worth 1000 ~~words~~ numbers')

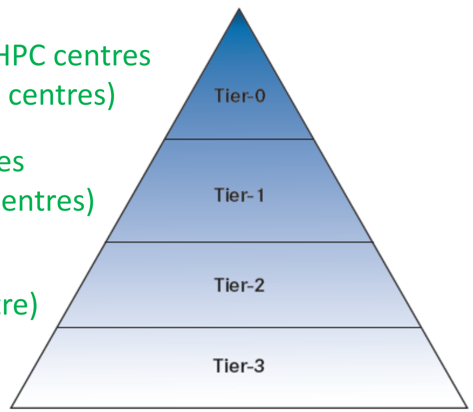


Large-scale HPC centres
(e.g. EU HPC centres)

National HPC centres
(e.g. German HPC centres)

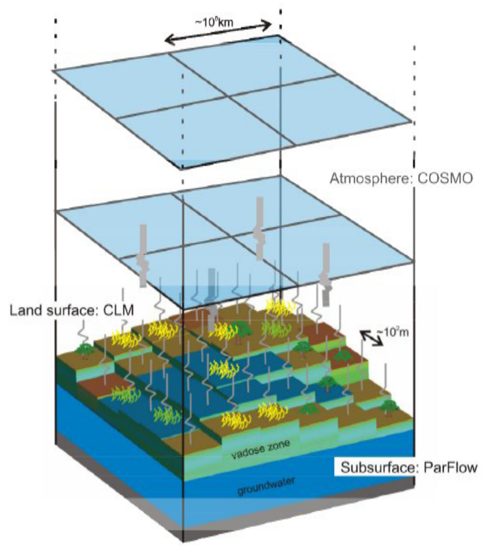
Topical and Regional HPC
Centres (e.g. climate centre)

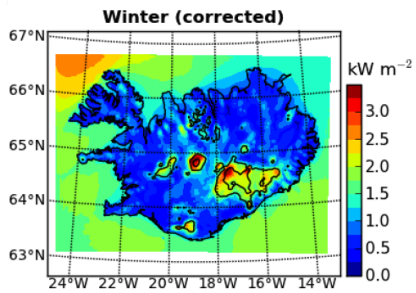
Servers and small clusters
(e.g. universities, institutes)



Lecture 12 – Terrestrial Systems & Climate

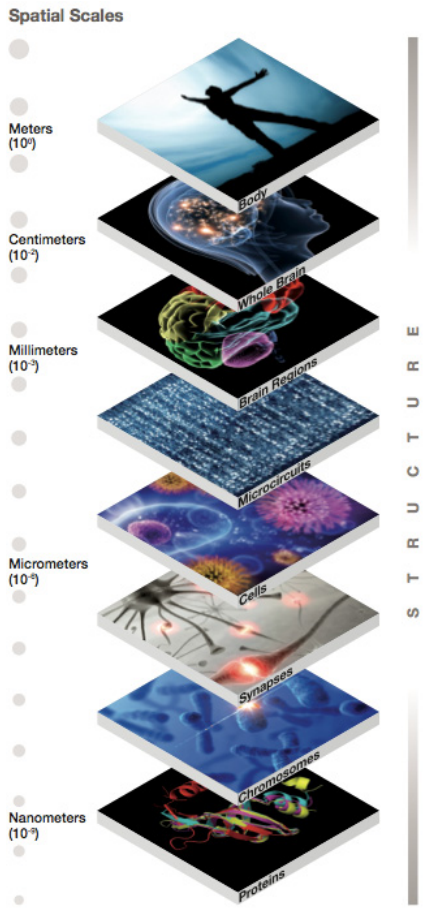
- Terrestrial Systems
  - Numerical Terrestrial Simulations & Models
  - ParFlow Hydrology Parallel Application
  - CLM Land-Surface Model Parallel Application
  - COSMO Weather Model Parallel Application
  - Coupled Models & Other Models & Libraries
  - Application Examples
- Climate
  - Numerical Weather Prediction & Forecast
  - Role of Partial Differential Equations (PDEs)
  - WRF Model Parallel Application
  - SAR Weather Project & Business Case
  - Other Models & Libraries
  - Application Examples





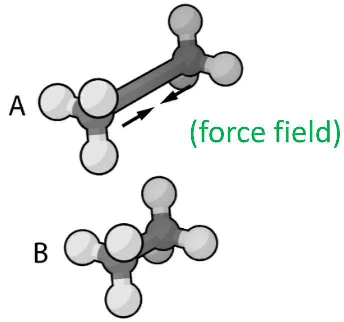
Lecture 13 – Systems Biology & Bioinformatics

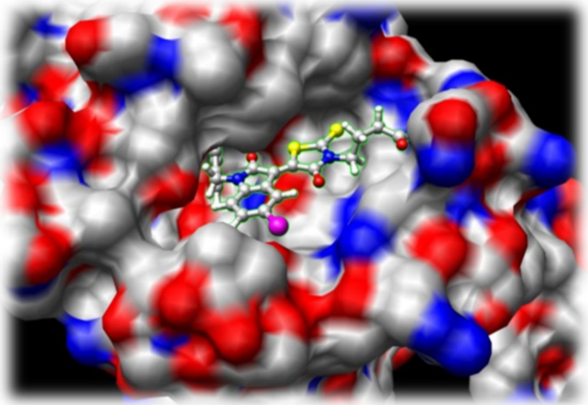
- Systems Biology
  - Motivation & Basic Terminology
  - Selected Scientific Case Protein Folding
  - Role of Monte Carlo Methods
  - SMMP & Neuroscience Parallel Applications
  - Other Models & Libraries
  - Application Examples
- Bioinformatics
  - Motivation & Basic Terminology
  - Selected Scientific Case Gene Sequencing
  - Role of Databases and Web-based Portals
  - BLAST Parallel Application
  - Other Tools & Techniques
  - Application Examples



Lecture 14 – Molecular Systems & Libraries

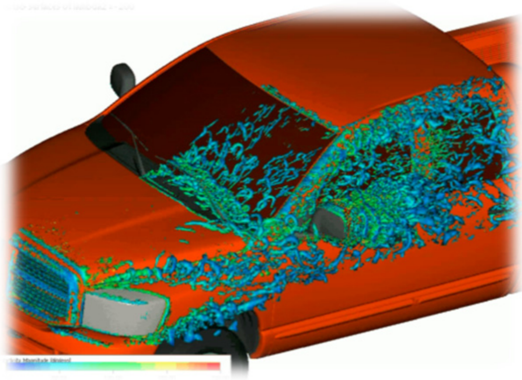
- Molecular Systems
  - Terminology & Motivation
  - Ab Initio Calculations
  - Molecular Docking & Dynamics
  - Application Examples
- Selected Methods & Libraries
  - NAMD
  - CPMD
  - MP2C
  - AMBER
  - Parallel Interoperability Application



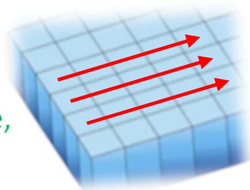


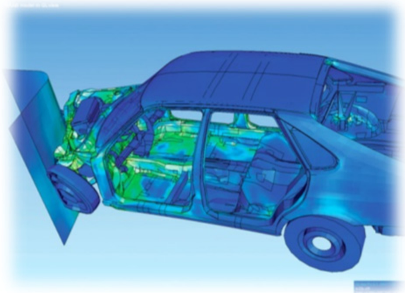
Lecture 15 – Computational Fluid Dynamics & Finite Elements

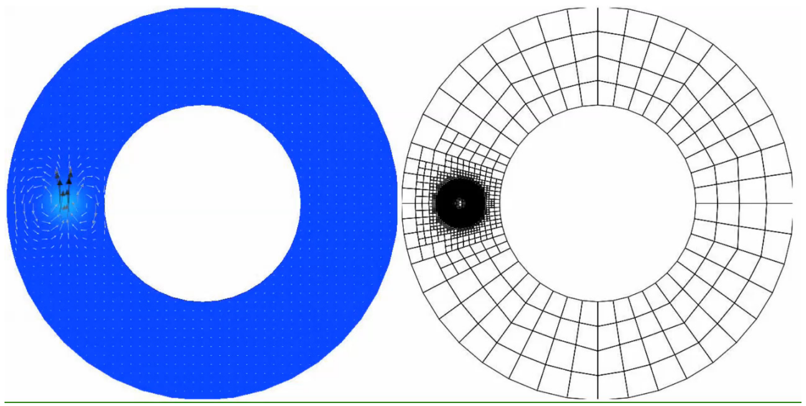
- Computational Fluid Dynamics
  - Terminology & Motivation
  - Naviar-Stokes Method
  - Lattice-Boltzmann Method
  - Large Eddy Turbulence Model
  - Modelling Methodology Revisited
  - Application Examples & Libraries
- Finite Elements
  - Terminology & Motivation
  - Boundary Value Problems
  - Mesh Generation Technique
  - Adaptive Mesh Refinement
  - Application Examples & Libraries



(classical mechanics solutions
are rather trajectories
of positions of a certain particle,
here fluid velocity is in focus)







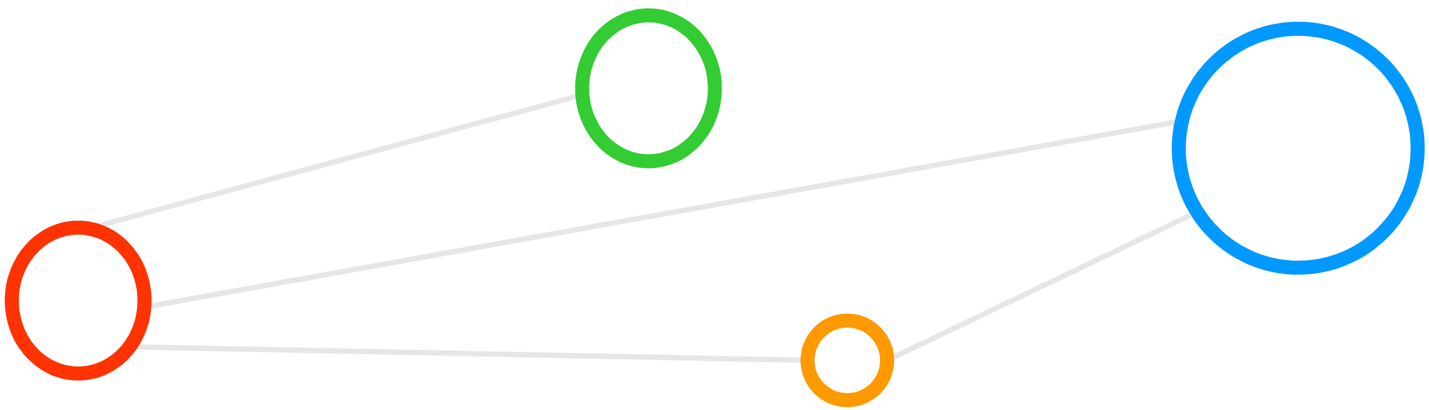
Epilogue

- Informal final lecture
  - Answering remaining questions & guidance to future topics
  - Summary & preparation for final exam and quizzes debrief
- Mindset
  - Discussion of job offers on the market in the light of the course
  - What we have learned & how to turn knowhow into action
- Skillset
  - Knowledge of various HPC system techniques & parallel computing skills
  - PHD positions & Master Thesis topics HPC and/or Machine & Deep Learning
- Toolset
  - Knowledge of parallel programming tools & machine/deep learning libraries
  - Future Topics to study: Quantum computing, neural networks on the chip, neuromorphic computing, modular supercomputing, etc.

[Video] PRACE – What is High Performance Computing

[12] YouTube, PRACE – Dare to Think the Impossible

Lecture Bibliography



Lecture Bibliography (1)

- [1] Piazza Web page, Online:
  https://piazza.com/
- [2] Gradescope Web page, Online:
  https://www.gradescope.com/
- [3] Morris Riedel Web page, Online:
  http://www.morrisriedel.de
- [4] Helmholtz Association Web Page, Online:
  https://www.helmholtz.de/en/
- [5] Forschungszentrum Juelich Web page, Online:
  http://www.fz-juelich.de
- [6] University of Iceland – School of Engineering and Natural Sciences Web page, Online:
  https://english.hi.is/school_of_engineering_and_natural_sciences
- [7] GCS Web page, Online:
  http://www.gauss-centre.eu/gauss-centre/EN/Home/home_node.html
- [8] PRACE Web page, Online:
  http://www.prace-ri.eu
- [9] HAICU Web page, Online:
  http://www.haicu.de/
- [10] DEEP Projects Web page, Online:
  http://www.deep-projects.eu/
- [11] YouTube Video, Dreamworks, High Performance Computing, Online:
  http://www.youtube.com/watch?v=TGSRvV9u32M

Lecture Bibliography (2)

- [12] YouTube Video, PRACE – Date to Think the Impossible, Online:
  http://www.youtube.com/watch?v=fgy-ZkJyom0
- [13] UGLA HPC Course Web page, Online:
  https://ugla.hi.is/kv/index2.php?sid=219&namsknr=70067120176&kennsluvefur_efnisatridi=1
- [14] Introduction to High Performance Computing for Scientists and Engineers, Georg Hager & Gerhard Wellein, Chapman & Hall/CRC Computational Science, ISBN 143981192X, English, ~330 pages, 2010, Online:
  http://www.amazon.de/Introduction-Performance-Computing-Scientists-Computational/dp/143981192X
- [15] K. Hwang, G. C. Fox, J. J. Dongarra, 'Distributed and Cloud Computing', Book, Online:
  http://store.elsevier.com/product.jsp?locale=en_EU&isbn=9780128002049


Data
Science
Big
Research
science
analysis
methods
big
simulations
processing
computing
technologies
TB
European
Scientific
computational
research
Computational
E.g
Centre
climate
Computing
nodes
centers
PB
community
Environment
scientific
important
storage
Infrastructure
ENES
EUDAT
increasing
Supercomputing
images
performance
datasets
Juelich
HPC
access
data-intensive
Service
Climate
modelling
structures
System
DLCLs
databases
brain
Project
resources
services
year
new
management
different
Enable
Modelling