Theoretical / Computational Nuclear Physics

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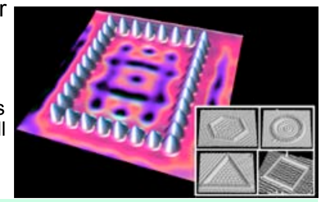
Nuclei are REALLY small

- Atoms are really small
  - Typical atomic size: ~10^{-10} m
  - Put 10,000,000 atoms in a row: thickness of your fingernail
  - Best (scanning tunneling) microscopes are just good enough to resolve individual atoms
- Nuclei are another factor 100,000 smaller
  - Typical nuclear size: ~10^{-15} m
  - Nucleus inside an atom is like a golf ball in a football stadium (but contains almost all of the mass!)



How do we learn about nuclei?

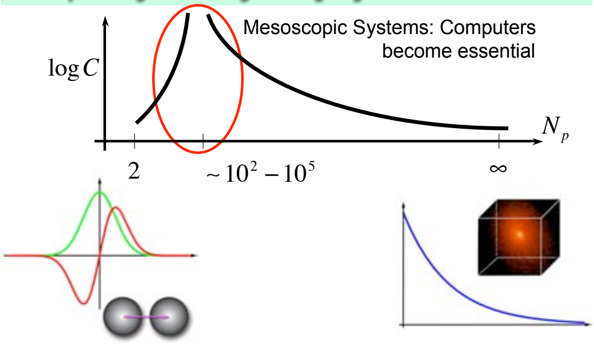
- We hit the nuclei (with other nuclei or elementary particles or gamma rays) and watch what happens.
- Nuclear processes require high energy (> 1 MeV)
  - More than 100,000 times the energy of chemical processes
- Nuclear processes last a very short time (<10^{-21} s)
  - A billionth of a billionth of a millisecond!
  - Once the nuclear reaction products are detected, the reaction has long been over
  - Direct observation of nuclei and nuclear processes is impossible
- We need theory to understand and model the experimental results and thus learn about nuclei!

Nuclear Models

- Liquid drop model
  - Explains basic nuclear masses
- Fermi gas model
  - Independent particle motion mainly governed by Pauli principle
- Shell model
  - Similar to atomic shell model
- Nuclear physics requires quantum mechanics, thermodynamics, fluid dynamics, transport theory, theory of phase transitions, complexity and chaos theory, …, and COMPUTERS

Introduction | History | Utilization | Physics | Grid | Mass | Future

Complexity in Many-Body Systems



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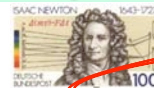
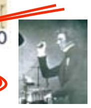
(very abbreviated) History of Physics

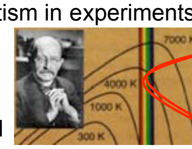
1700s: Newton invents calculus to describe mechanics



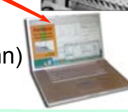
1800s: Faraday et al. study electricity&magnetism in experiments



1900s: Theoretical physics (Planck, Einstein) explores the quantum world



2000s: Computational physics emerges as third branch of physics (von Neumann)



time

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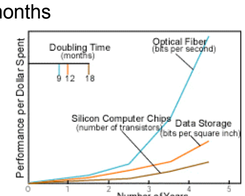
History of Computers (Moore's Law)

- Computer speed doubles every 18 months (Moore's Law)
- Data storage doubles every 12 months
- Network speed doubles every 9 months
- Improvement 1988 to 2005 (length of my MSU tenure)
  - Computers: x 2,500
  - Storage: x 130,000
  - Networks: x 6,600,000
- Physics limits not to be reached for another decade or more



Moore's Law vs. storage improvements vs. optical improvements. Graph from Scientific American (Jan-2001) by Cleo Vilett, source Vined, Khoslan, Kleiner, Caufield and Perkins.

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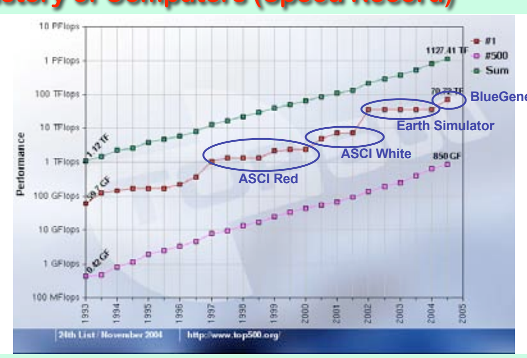
History of Computers (Speed Record)

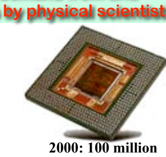


History of Computers

Driven by demand from and inventions by physical scientists!

1946: ENIAC

1947: Transistor (Bardeen, Brattain, Shockley)



2000: 100 million transistors in each PC chip

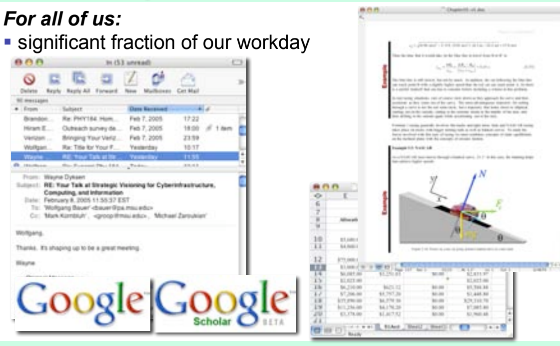
1989: WWW, Berners-Lee, CERN

2004: BlueGene

Use of Computers: Email & Office Software

For all of us:

- significant fraction of our workday



Use of Computers: Programming

Languages:

- FORTRAN
- C(++)
- Java

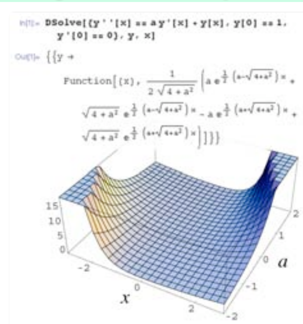
Use of Computers: Symbolic Manipulation

Programs:

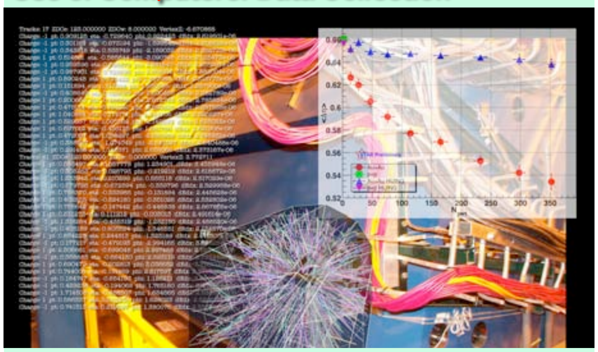
- Mathematica
- Maple
- MathLab

Real Mathematics Research:

e.g. Kepler Conjecture



Use of Computers: Data Collection

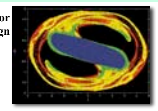


Use of Computers: Visualization ⇒ Insight

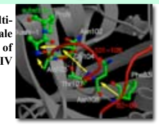
Collection: D. Dean, ORNL

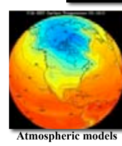
Type IA supernova explosion (BIG SPLASH)

Accelerator design

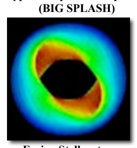


Multi-scale model of HIV

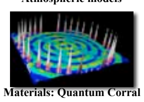




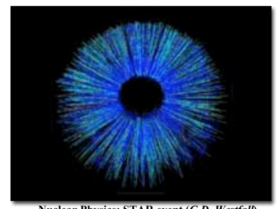
Atmospheric models



Fusion Stellarator



Materials: Quantum Corral



Nuclear Physics: STAR event (*G.D. Westfall*)

Use of Computers: Enabling Science

Three high-tech buzzwords:

Progress in

BIO

relies on advances in

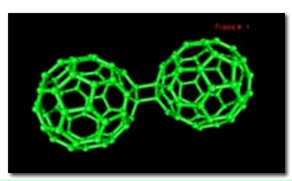
NANO

And both are dependent on

INFO

Computational Nano-Science

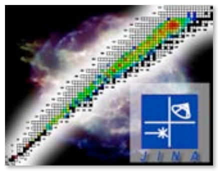
- Prediction of materials' structures and properties
- *Ab initio* calculations of quantum forces between atoms
- Density functional theory



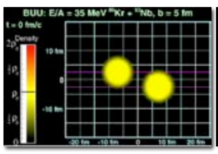
- Example 1: Carbon pea-pod memory
  - U.S. Patent 6,473,351
- Example 2: Time dependence of buckyball fusion
- Calculations done with Earth Simulator

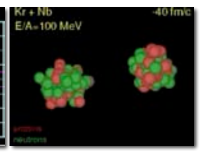
David Tomanek, MSU-PA

Computational Nuclear Physics



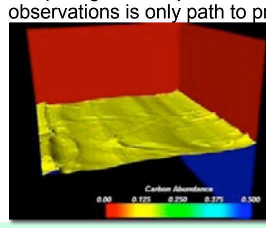
- Big questions:
  - How are the heaviest elements made in the universe?
  - What is the equation of state of nuclear matter?
- Experimental Facilities
  - NSCL, (future) RIA
- Computational Tools
  - Transport Theory
  - Reaction Networks

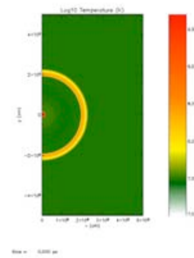




Computational Astrophysics

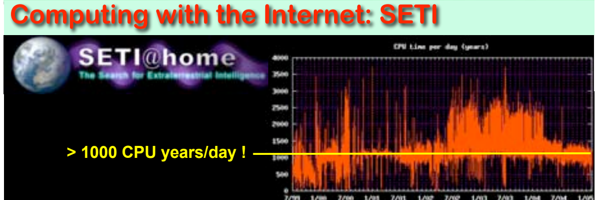
- Astrophysics has to answer questions without any chance of doing experiments
- Running computer simulations and comparing their output to static observations is only path to progress





E. Brown, with Flash Center, Chicago

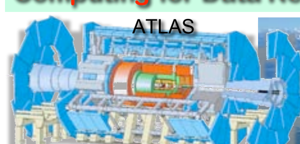
Computing with the Internet: SETI



	Total	Last 24 Hours
Users	5343984	1049
Results received	1758329525	1320508
Total CPU time	2213000.413 years	963.120 years
Floating Point Operations	6.441670e+21	5.149981e+18 (59.61 TeraFLOPs/sec)
Average CPU time per work unit	11 hr 01 min 30.6 sec	6 hr 23 min 20.9 sec

~60 TeraFLOP/s

Computing for Data Reduction

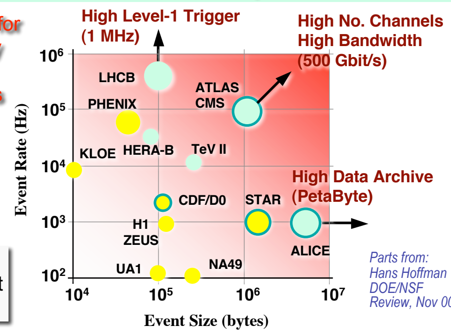


- Data rate: 40 MHz, 40 TB/s
- Level 1 - Special hardware
- 75 kHz, 75 GB/s
- Level 2 - embedded processors
- 5 kHz, 5 GB/s
- Level 3 - dedicated PCs
- 100 Hz, 100 MB/s

Data storage and offline analysis
ATLAS: **~10 PetaByte/year**
(~100,000 PC hard drives of 100 GB)

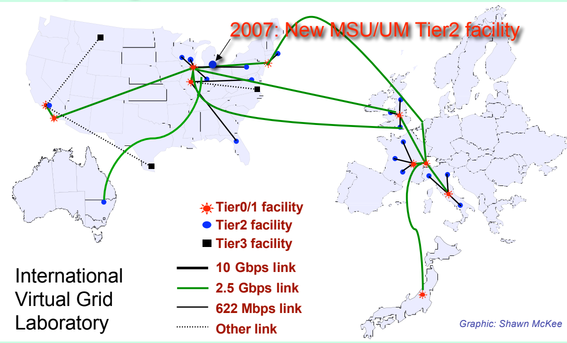
Data Streams for Different Experiments

Data Rates for High Energy Physics Experiments



Parts from: Hans Hoffman DOE/NSF Review, Nov 00

Computing with the Internet: Grid

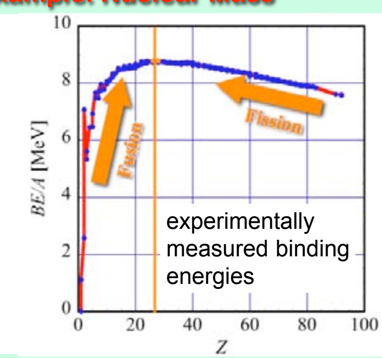


International Virtual Grid Laboratory

One example: Nuclear Mass

- Energy and mass are related
- Nuclei weigh less than the sum of the masses of the protons and neutrons in them.
- Nuclear binding!

One example: Nuclear Mass



One example: Nuclear Mass

- Can we understand this?
- Strong force is short-ranged; nucleons only interact with nearest neighbors
- No neighbors at the surface
- Add Coulomb repulsion between protons (+ …)

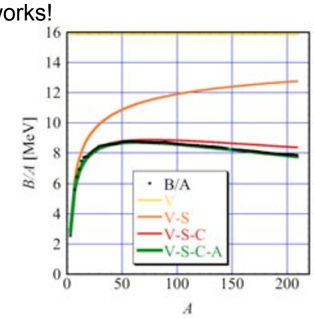
$$B(N,Z) = B_s(N,Z) + B_c(N,Z) + B_a(N,Z) + B_p(N,Z)$$

$$= a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_a \frac{\left(Z - \frac{1}{2}A\right)^2}{A} - a_p \frac{(-1)^Z + (-1)^N}{\sqrt{A}}$$

$$B(N,Z)/A = a_v - a_s A^{-1/3} - a_c \frac{Z^2}{A^{4/3}} - a_a \left(\frac{Z}{A} - \frac{1}{2}\right)^2 - a_p \frac{(-1)^Z + (-1)^N}{A^{3/2}}$$

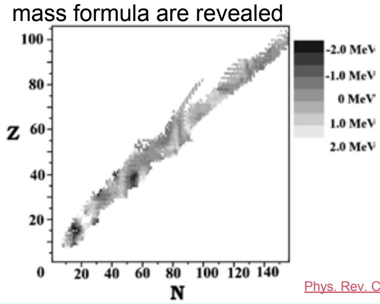
One example: Nuclear Mass

- Yep, it works!



One example: Nuclear Mass

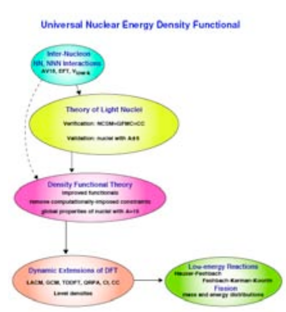
- Modern picture: on closer examination differences to mass formula are revealed



Phys. Rev. C 69, 037304 (2004): Hirsch et al.

One example: Nuclear Mass

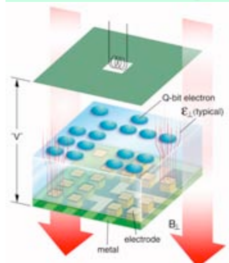
- Huge national effort to find better energy density functional
- Leader: George Bertsch, UW
- MSU has big part in this multi-million $ effort



Predictions

- Predictions are hard …
  - *"Prediction is very difficult, especially about the future"*
    (Niels Bohr)
- But still useful …
  - *Predictions are like Austrian train schedules. Austrian trains are always late. So why do the Austrians bother to print train schedules? How else would they know by how much their trains are late?*
    (Viktor Weisskopf, paraphrased)
- So here we go …
  - Moore's Law will continue for at least another 2 decades
  - Network bandwidth will become infinitesimally cheap and eventually (~2 decades) saturate the human input bandwidth
  - Caution 1: *"Software is a gas" (Nathan Myhrvold)*
  - Caution 2: Growth in content will only be linear, not exponential

Future of Computing: Quantum Computer



Proposed 16-bit quantum computer design: electrons on liquid helium
(M. Dykman et al.)

- Conventional computer:
  - *N* processors can process *N* instructions simultaneously
- Quantum computer:
  - *N* processors can process 2^N instructions simultaneously
- Example:
  - $N = 16$: $2^{16} = 65{,}536$
  - $N = 32$: $2^{32} = 4{,}294{,}967{,}296$
- Future collaboration potential between PA, Math, CSE

Summary

- **Physical science has provided technological innovation to advance computer science and will continue to do so**
- **Computers have enabled a third branch of physical science (besides theory and experiment)**
- **Nuclear theory is now very dependent on large-scale computer use**
- **Nuclear theory provides the only link between experiments and understanding in nuclear physics**