Introduction to the Einstein Toolkit

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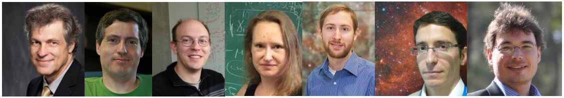
Einstein Toolkit

- Collection of scientific software components and tools to simulate and analyze general relativistic astrophysical systems
- Freely available as open source at http://www.einsteintoolkit.org
- Supported by NSF 1550551/1550461/1550436/1550514, NSF 1212401/1212426/1212433/1212460, NSF 0903973/0903782/0904015 (CIGR), 0701566/0855892 (XiRel), 0721915 (Alpaca), 0905046/0941653(PetaCactus/PRAC)
- State-of-the-art set of tools for numerical relativity, open source
- Currently 356 members from 249 sites and 43 countries
- $>$ 396 publications, $>$ 53 theses building on these components (as of June 2022)
- Regular, tested releases
- User support through various channels



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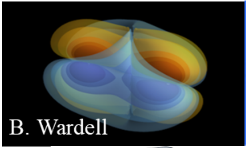
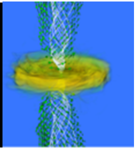
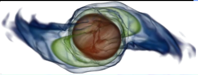
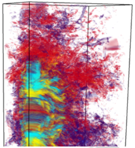
Science

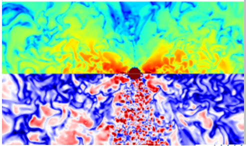
- Binary Black Hole Mergers
- Neutron Star Mergers
- Supernovae
- Accretion Disks
- Boson Stars
- Hairy Black Holes
- Cosmic Censorship

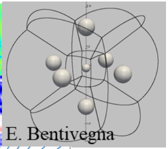


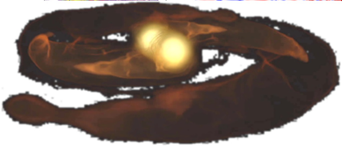


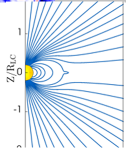












Community Effort!

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Why?

Computational Challenges

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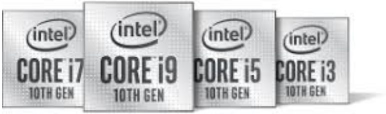
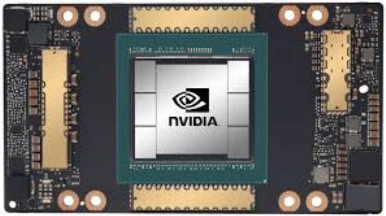
Computational Challenges

More and more diverse hardware





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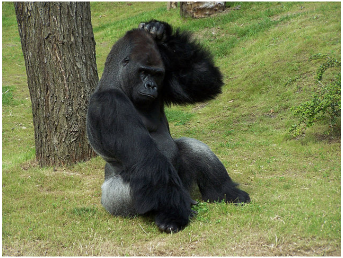
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache



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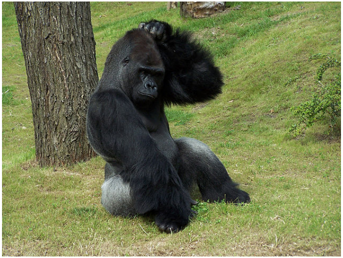
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache
  - Vector



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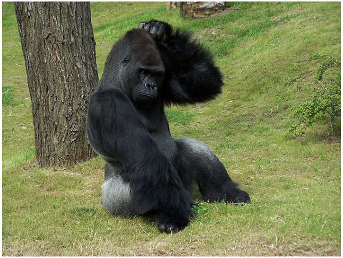
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache
  - Vector
  - Accelerators



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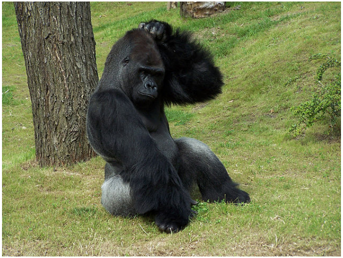
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache
  - Vector
  - Accelerators
  - Scale to many cores



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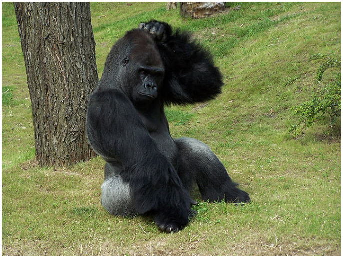
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache
  - Vector
  - Accelerators
  - Scale to many cores
  - Scale to many nodes



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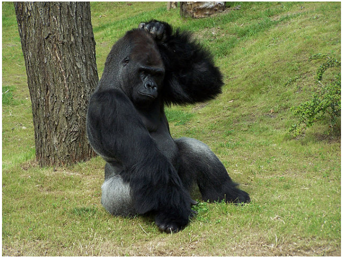
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache
  - Vector
  - Accelerators
  - Scale to many cores
  - Scale to many nodes
  - Algorithms



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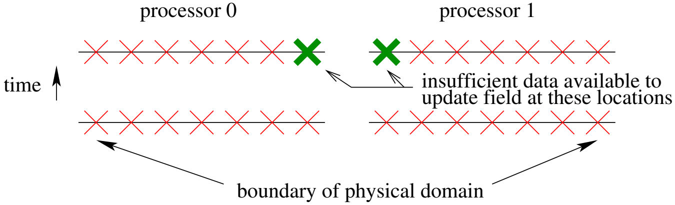
Computational Challenges

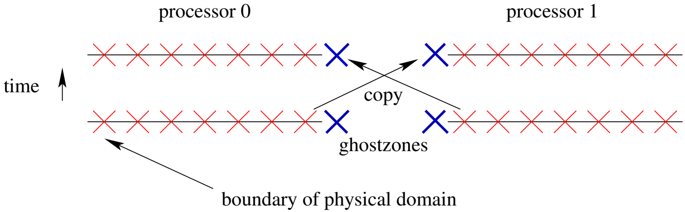
- Efficient use of all hardware is complex and tedious.
- Requires experts from different disciplines
- Requires good data layouts and APIs
- To ensure correctness, need good modularization on a number of levels and understanding of advanced programming concepts.
- Design and implementation needs to be carefully thought out in order to ensure extensibility and portability.

Domain Decomposition

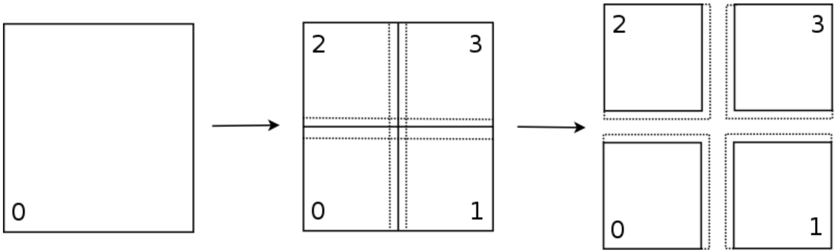
Without Ghostzones:



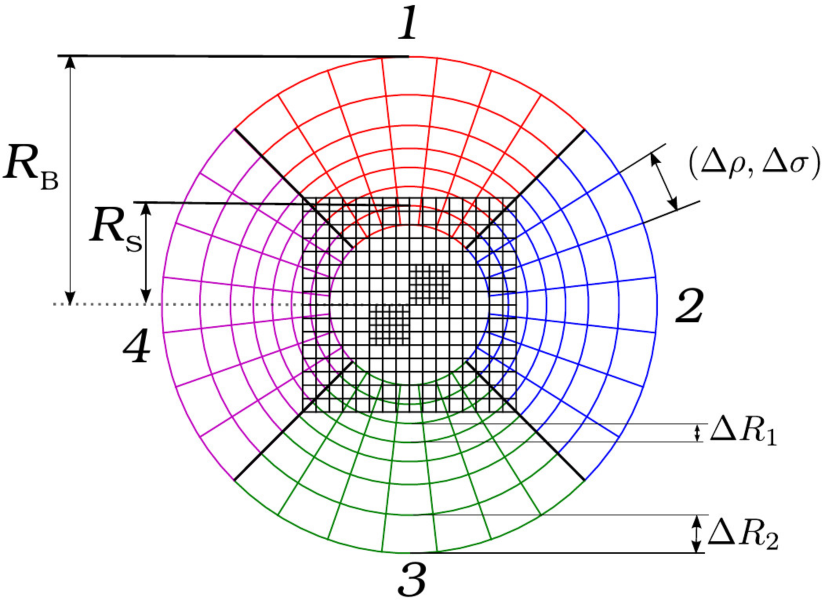
With Ghostzones:



Domain decomposition



Multiblock and refinement



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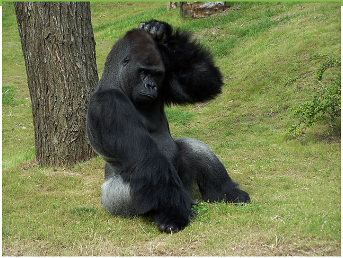
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Vector (Kranc, NRPy+)



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Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
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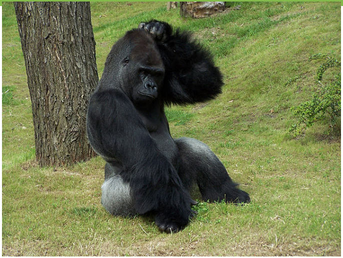
  - Vector (Kranc, NRPy+)
  - Scale to many cores (OpenMP)



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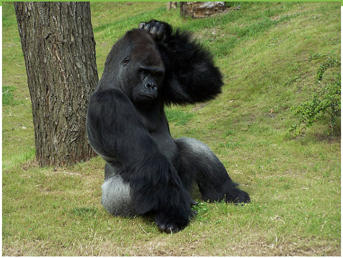

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  - Scale to many nodes (MPI, Carpet, CarpetX)

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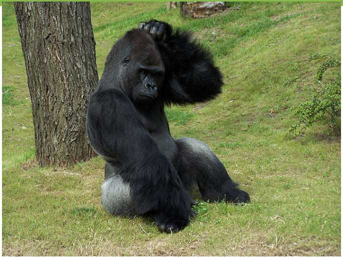

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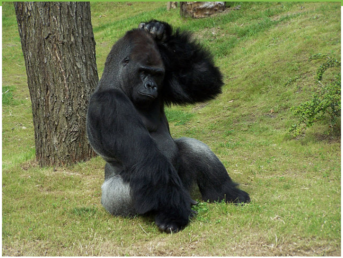

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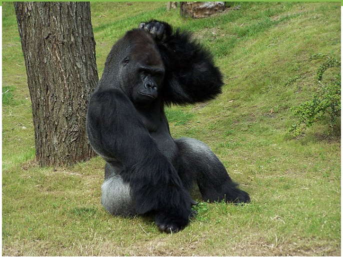

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  - Machine learning?

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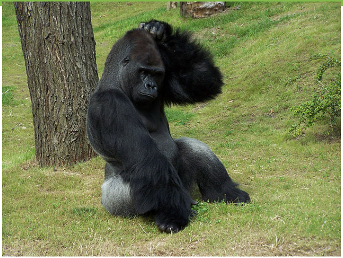

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  - FPGA?

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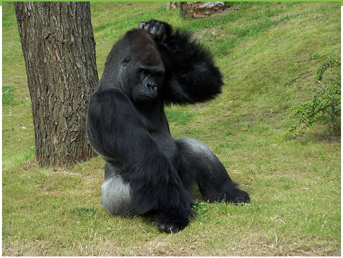

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  - Machine learning?
  - FPGA?
  - ASIC?

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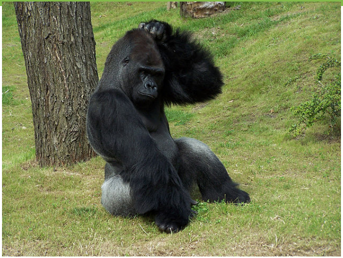
Computational Challenges



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  - Machine learning?
  - FPGA?
  - ASIC?
  - Neuromorphic processor?

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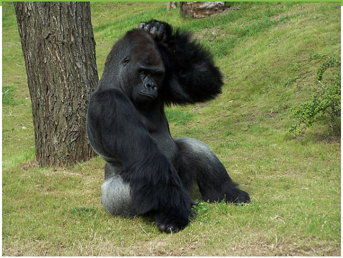
Computational Challenges



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    - GPU (CarpetX)
    - Machine learning?
    - FPGA?
    - ASIC?
    - Neuromorphic processor?
    - Q-bits?

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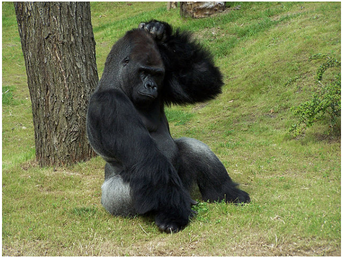
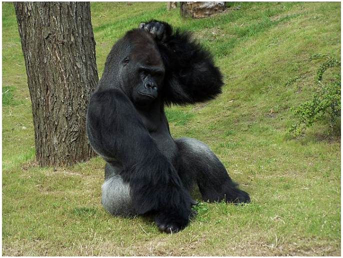
More Mundane Challenges



Computational Challenges

More Mundane Challenges

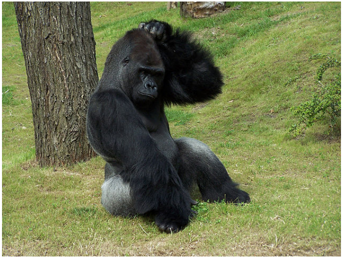
- Efficient I/O



Computational Challenges

More Mundane Challenges

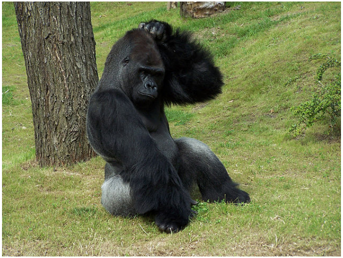
- Efficient I/O
- HDF5



Computational Challenges

More Mundane Challenges

- Efficient I/O
- HDF5
- Checkpoint/Restart



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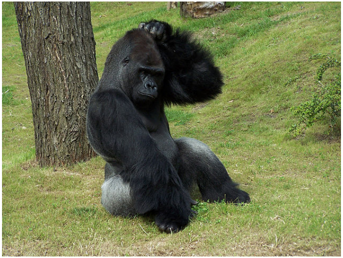
Computational Challenges

More Mundane Challenges

- Efficient I/O
- HDF5
- Checkpoint/Restart
- Parameter Parsing



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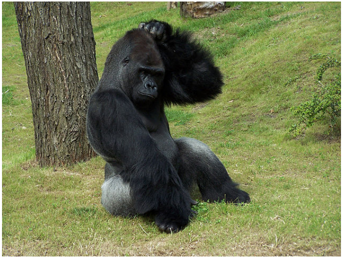
Computational Challenges

More Mundane Challenges

- Efficient I/O
- HDF5
- Checkpoint/Restart
- Parameter Parsing
- Visualization



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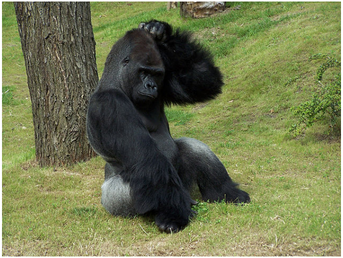
Computational Challenges

More Mundane Challenges

- Efficient I/O
- HDF5
- Checkpoint/Restart
- Parameter Parsing
- Visualization
- Analysis



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Computational Challenges

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- Efficient I/O
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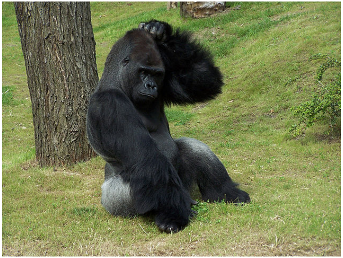
- Visualization
- Analysis
- Steering



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Collaborative Challenges

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Collaborative Challenges

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problem

group

group

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problem

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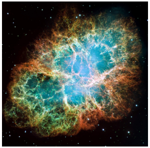

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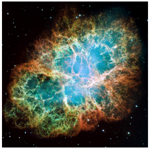
computation



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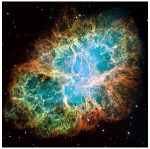
community



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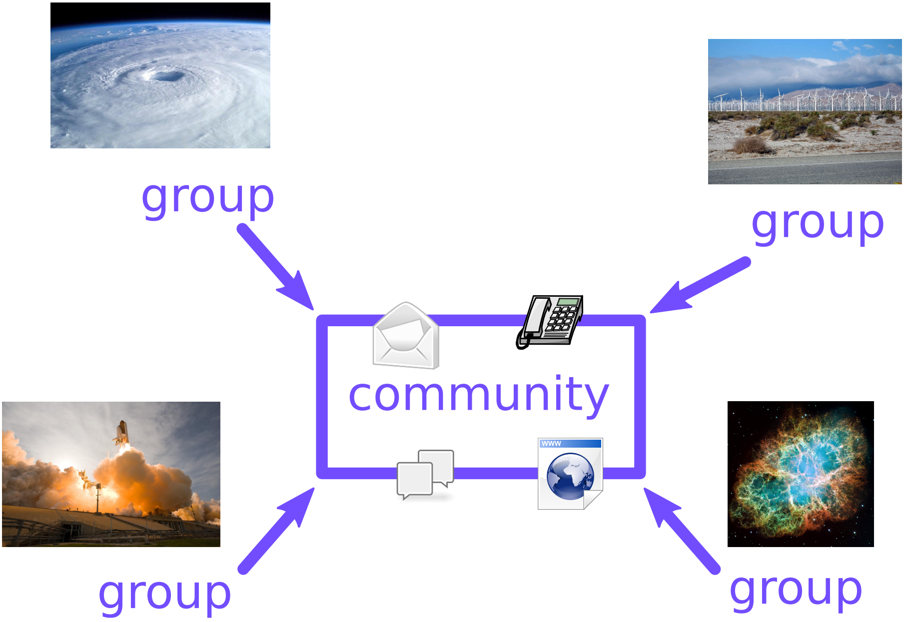

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WWW


www

SUBVERSION

git

mercurial

MEDIAWIKI

SUBVERSION

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MEDIAWIKI

Workshop

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group

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problems

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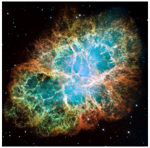

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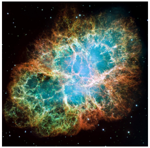

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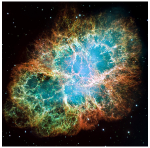

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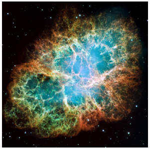
competition



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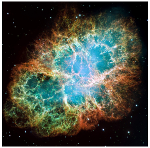

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standards

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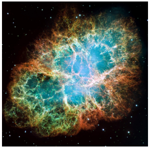

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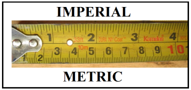

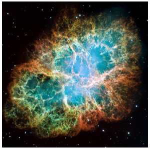

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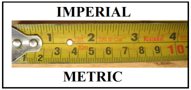

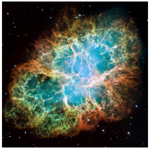

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group

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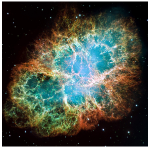
tools



group

group

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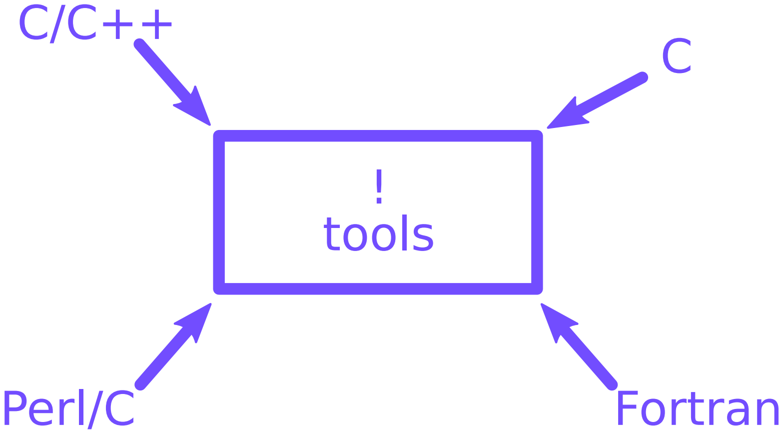
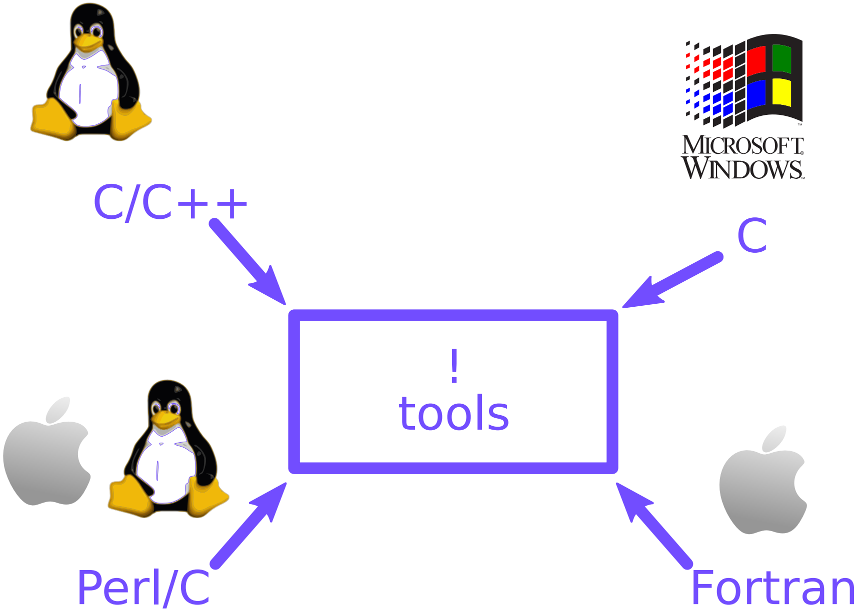

C/C++
C
!
tools
Perl/C
Fortran



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group

group

!
credit

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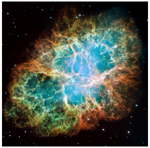

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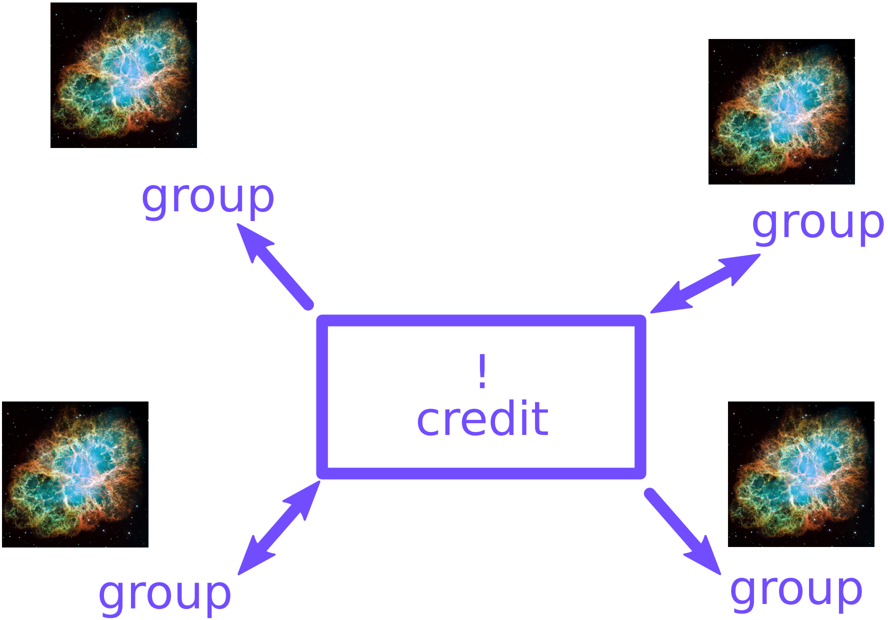

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Collaborative Challenges

How can we work together?

- Researchers in the USA
  - Arizona
  - Florida
  - Georgia
  - Louisiana
  - Illinois
  - Indiana
  - New York
  - Tenessee
  - Texas
  - Pennsylvania
  - California

- In other countries
  - Canada
  - Germany
  - Italy
  - Ireland
  - Mexico
  - Portugal
  - Spain
  - Turkey
  - United Kingdom
  - and many more

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Einstein Toolkit

Goals:

- Community Driven
- Core computational tool for numerical astrophyscis
- General purpose tool!

Components:

- Cactus
- Simulation Factory
- Kranc
- NRPy+
- Science Modules

Guiding Principles

- Open
- Community Driven
- Good interfaces
- Separation of physics from computational infrastructure
- Production ready
- High quality code

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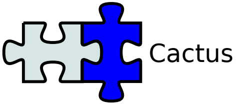
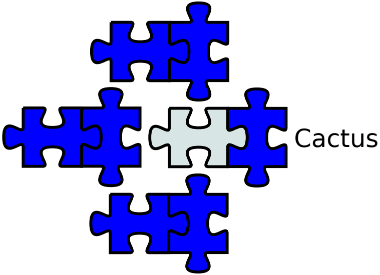
Einstein Toolkit as growing project

- Initially: some infrastructure, some application code



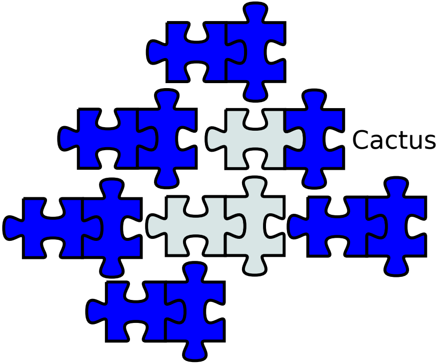
Einstein Toolkit as growing project

- Growing application suite



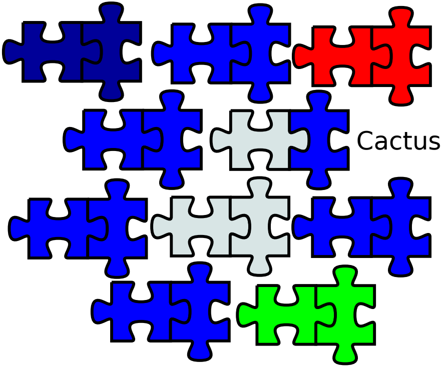
Einstein Toolkit as growing project

- Growing infrastructure "return"



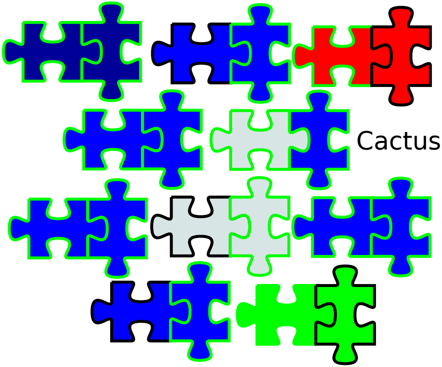
Einstein Toolkit as growing project

- Users from more fields of science



Einstein Toolkit as growing project

- Most modules open-source, but not necessarily all



Base Modules

The Einstein Equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

spacetime
curvature

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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spacetime curvature

constants

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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spacetime
curvature

constants

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

matter

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spacetime curvature

constants

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

matter

hydrodynamics

el.-magnetism

scalar fields

particle radiation

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

ADMBase

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

ADMBase

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

TmunuBase

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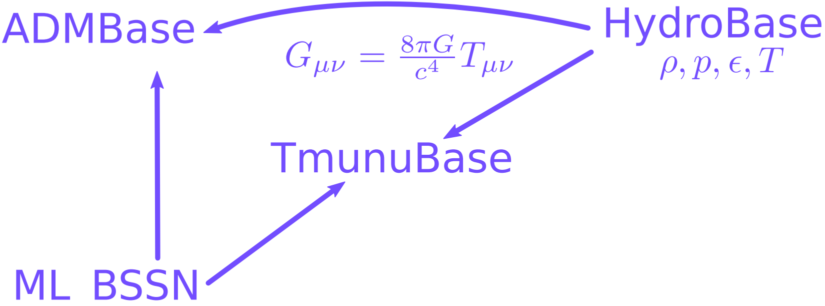
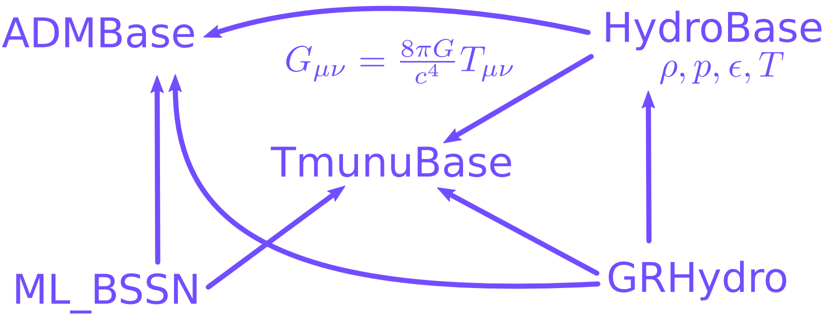
ADMBase

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

TmunuBase

ML_BSSN


ADMBase
HydroBase
$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
ρ, p, ϵ, T
TmunuBase
ML_BSSN



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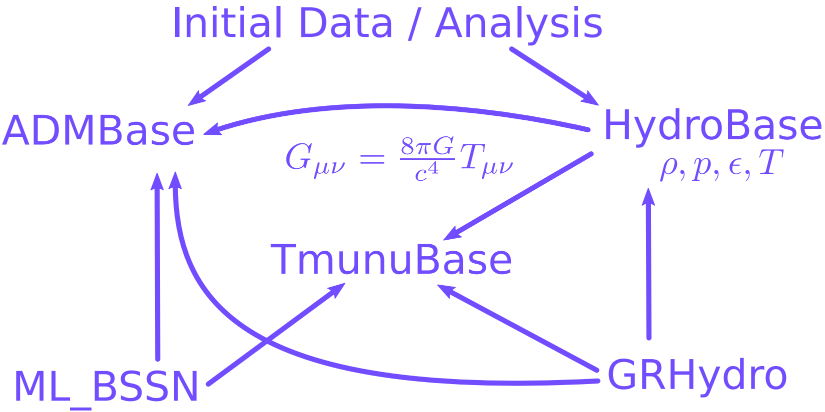
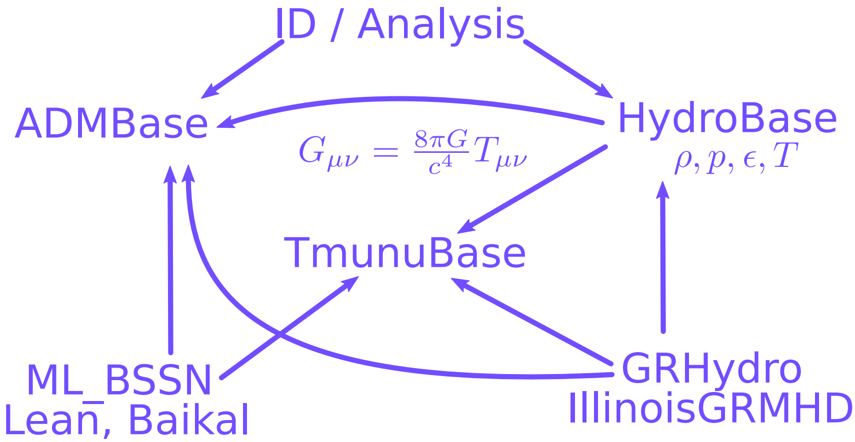

Initial Data / Analysis
ADMBase
HydroBase
$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
ρ, p, ϵ, T
TmunuBase
ML_BSSN
GRHydro



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Guiding Principles

- Open, community-driven software development
- Separation of **physics** software and **computational** infrastructure
- Stable interfaces, allowing extensions
- Simplify usage where possible:
    - Doing science $>>$ Running a simulation
    - Students need to know a lot about physics (meaningful initial conditions, numerical stability, accuracy/resolution, have patience, have curiosity, develop a "gut feeling" for what is right ...)
    - Einstein Toolkit **cannot** give that, **however**: Open codes that are easy to use allow to concentrate on these things!

Credits, Citations

In academics: citations, citations, citations!
For Einstein Toolkit:

- Open and free source
- No **requirement** to cite anything
- However: **requested** to cite
  - The DOI doi:10.5281/zenodo.3350841
  - Maybe the ET or Cactus papers
  - Some papers for the components list a few as well
  - List published on website and manage through publication database
- Soon: auto-generate list of citations during simulation run

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Vision

Cutting Edge / Future

- New Driver Thorn: CarpetX
- New Spherical Coordinates Thorn (RIT)
- New Python Code Generator: Full thorn output from NRPy+
- Kerr background support in SelfForce1D

Recent

- PN based initial data and eccentricity reduction
- New Declarative Synchronization: Presync
- Python based simulation analysis: kuibit

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Summary

Einstein Toolkit

- http://www.einsteintoolkit.org/
- Tools for high-performance computing in numerical relativity
- Open Source
- World-wide, open Community
- Used in high-end research

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Supported By

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