Singularity replacement for black hole evolutions

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Overview

- Motivation for binary black hole research
- Methods for handling singularities, especially "Moving Punctures"
- Application to binary black hole simulations

CCT

- Interdisciplinary research centre at LSU, about four years old
- Physicists, mathematicians, computer scientists, biologists, ...
- Strong group in numerical relativity

T. Sterling

Simulating Black Holes

- Simulating black holes is easy, because there is only vacuum
- Simulating black holes is difficult, because the spacetimes have singularities

Binary Black Holes

- Many stars live in binary systems
- Many black holes are expected to be in binary systems
- They will slowly spiral together ...
- ... and merge to a single black hole ...
- ... releasing a tremendous amount of gravitational radiation. Enter LIGO, LISA.

Numerical Methods for Singularities

- Foliation which avoids singularity
- Factor out singularity and handle it analytically
- Excision, i.e., cut out singularity from domain
- Since recently: *Moving punctures*, which are still somewhat mysterious

History

- Arbona et al. (1997): Stuffed black holes
- Alcubierre et al. (1999): Puncture evolutions
- Brandt et al. (2000): Excision evolutions
- Bona et al. (2004): Free black hole initial data
- Campanelli et al., Baker et al. (2005): Moving punctures

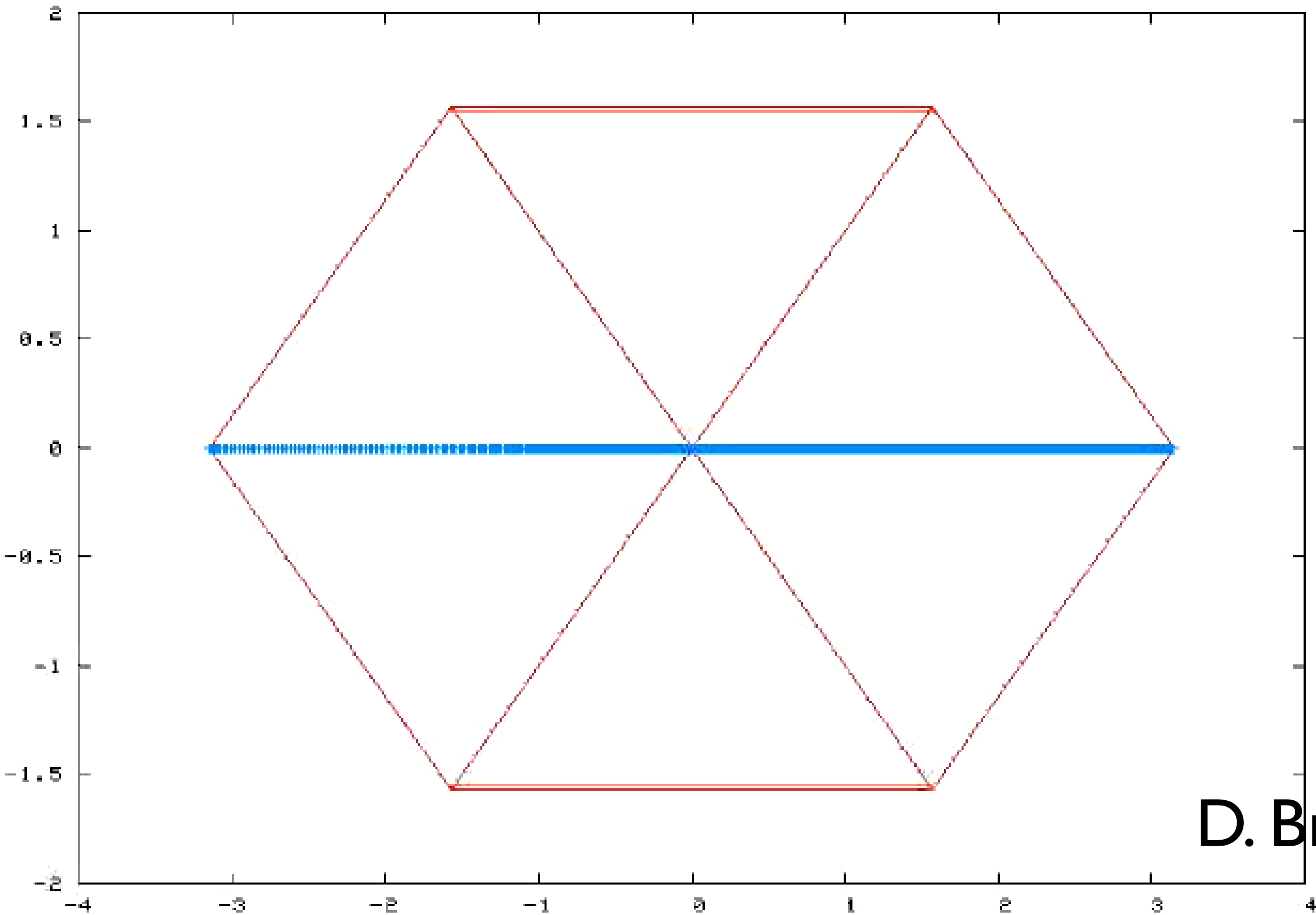
Moving Puncture Recipe

- Begin with puncture initial data (e.g. Brill-Lindquist)
- Use BSSN formulation, 1+log slicing, Gamma-driver shift
- Stagger grid about coordinate singularities
- Sprinkle with a bit of magic
- Evolve and enjoy [movie]

Moving Puncture Interpretation

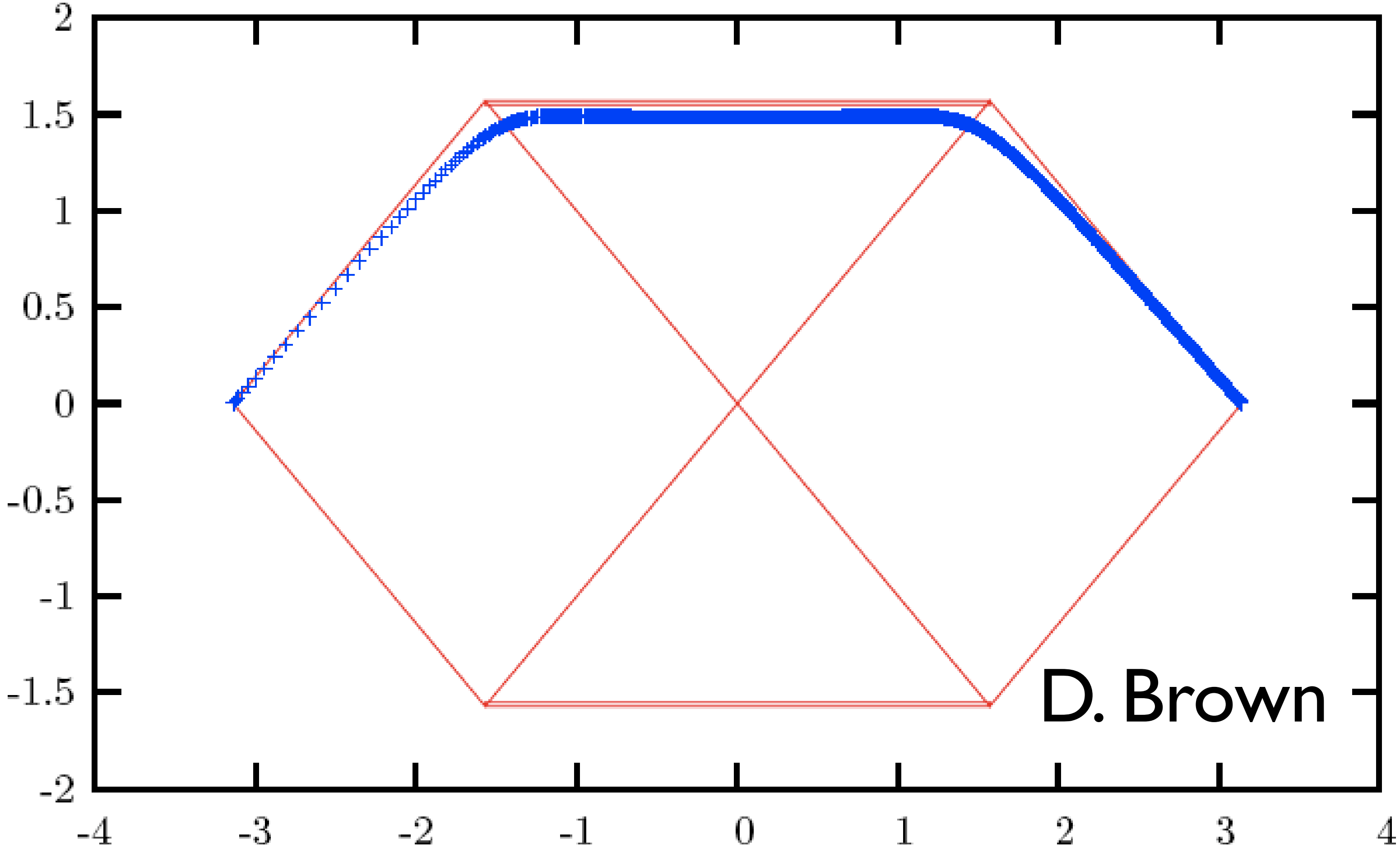
- David Brown (EGM 10, http://baba.astro.cornell.edu/~ecgm10/):
  - Slicing remains attached to other spacelike infinity
  - Other infinity is not resolved
  - Moving punctures is essentially an excision method

Penrose Diagram



D. Brown

Moving Puncture in Penrose Diagram



Generalisation of Moving Punctures

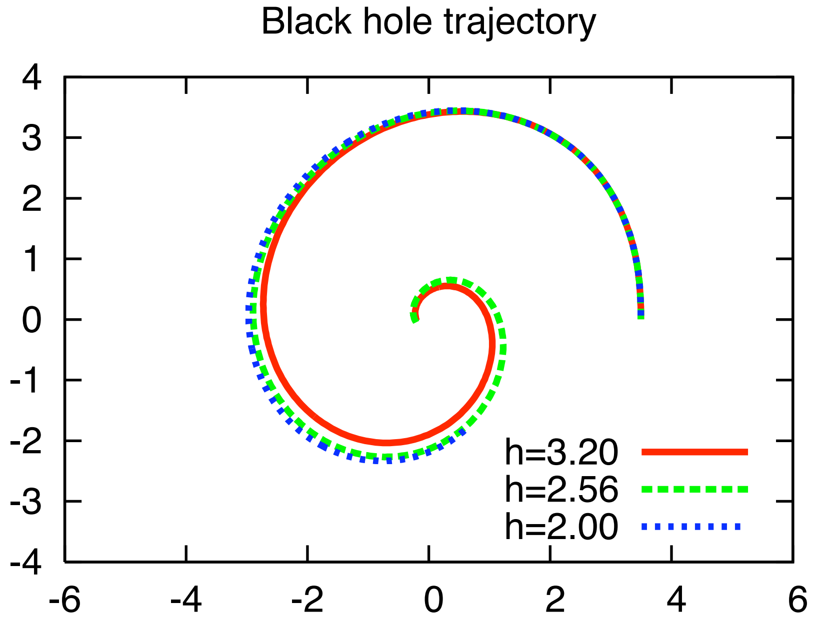
- Replace singularity in initial data by something non-singular (smoothing), or invent excised initial data
- Accept constraint violation inside horizon
- Ensure constraints do not propagate out
- Ensure discretisation is stable and consistent
- Ensure final state is stationary

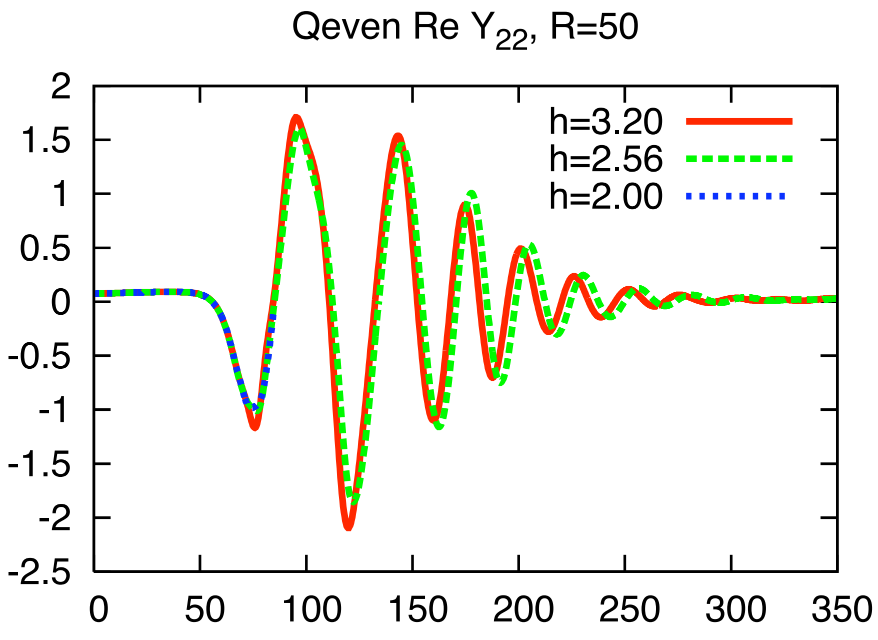
Characteristic Speeds

- There are several versions of BSSN; we choose a specific "typical" system
- O. Sarbach found:
  - BSSN itself is strongly hyperbolic almost everywhere
  - Constraint propagation system is symmetric hyperbolic: constraints propagate along the light cone, *even if the constraints are violated*

Quasi-Equilibrium Binary Black Holes

- Cook-Pfeiffer data sep_07.00_59a
  http://www.black-holes.org/researchers3.html





Our Magic

- Some artificial dissipation necessary (not much)
- Avoid large initial dynamics: e.g., start with a small lapse inside the horizon
- Often, initial data need not be smooth
- Check convergence inside and outside of horizon separately
- Note: A spike near the origin appears / remains

Later This Week

- Show convergence and accuracy for BBH evolution (in progress)
- Work with Francisco and Olivier on boundary conditions