Exchanger - coupling multiple solvers for mantle convection

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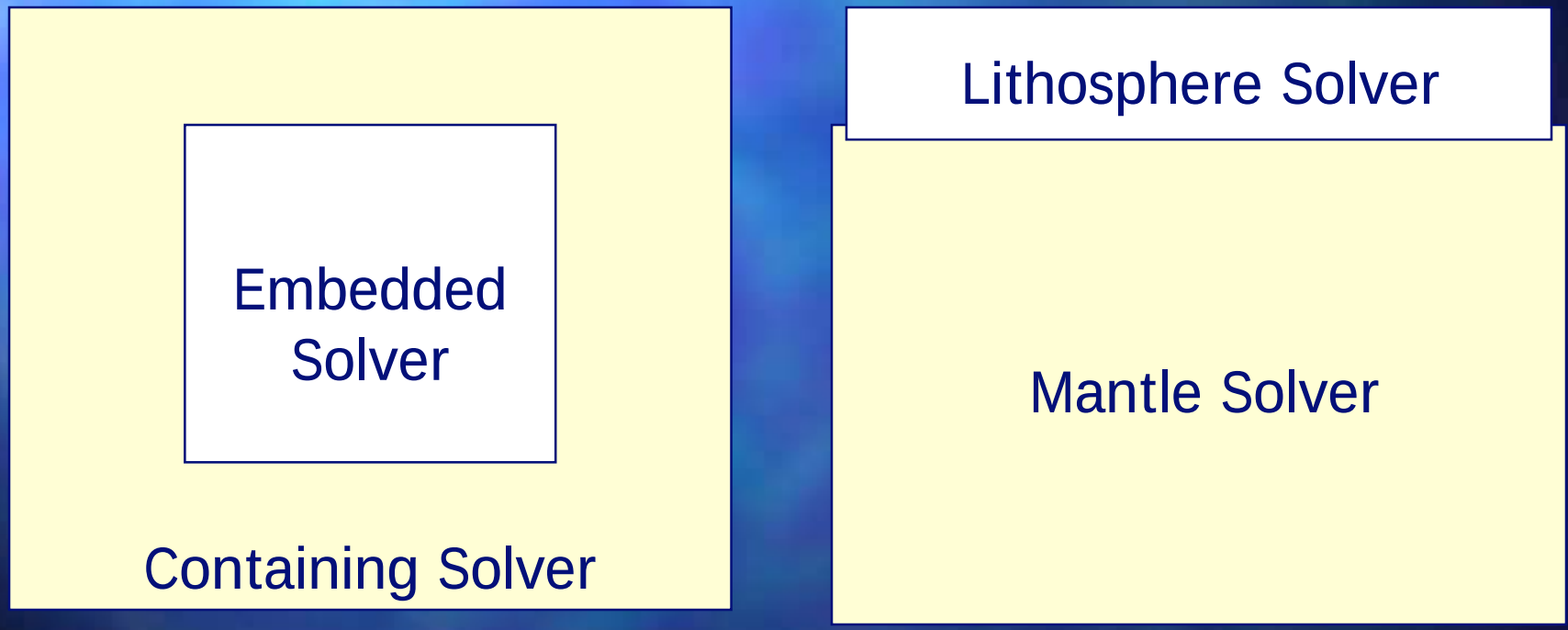
What is “solver coupling”?

- Two solvers, with disjointed memory addresses but overlapping physical domains, computing a joint problem

Coupling

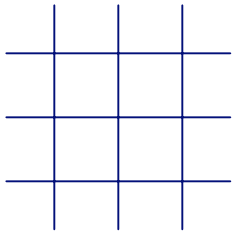

Embedded Solver
Containing Solver
Lithosphere Solver
Mantle Solver

Resolution vs. computation time

- Optimal Stokes solver scales with $O(N) \sim O(1/h^3)$
- Number of time steps $\sim O(1/\Delta t)$ $\sim O(1/h)$ for advection-dominant problems
- Total computation time = Number of time steps x Computation time per step $\sim O(1/h) \times O(1/h^3) \sim O(1/h^4)$
  - Double the resolution, h --> h/2
    16x computation time

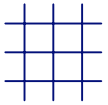
Resolution vs. computation time

- Partially alleviated by local mesh refinement
  - decrease effective h without increasing N too much
- Restriction on Δt still apply



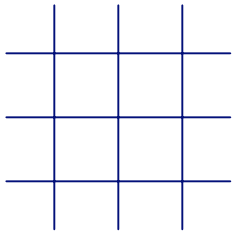
coarser resolution

finer resolution
small Δt



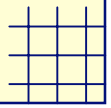
Local Time Stepping

- With solver coupling
  - local mesh refinement
  - Δt's of solvers are independent
- Synchronization issue



coarser resolution
larger Δt

finer resolution
smaller Δt



Time Synchronization

Boundary conditions

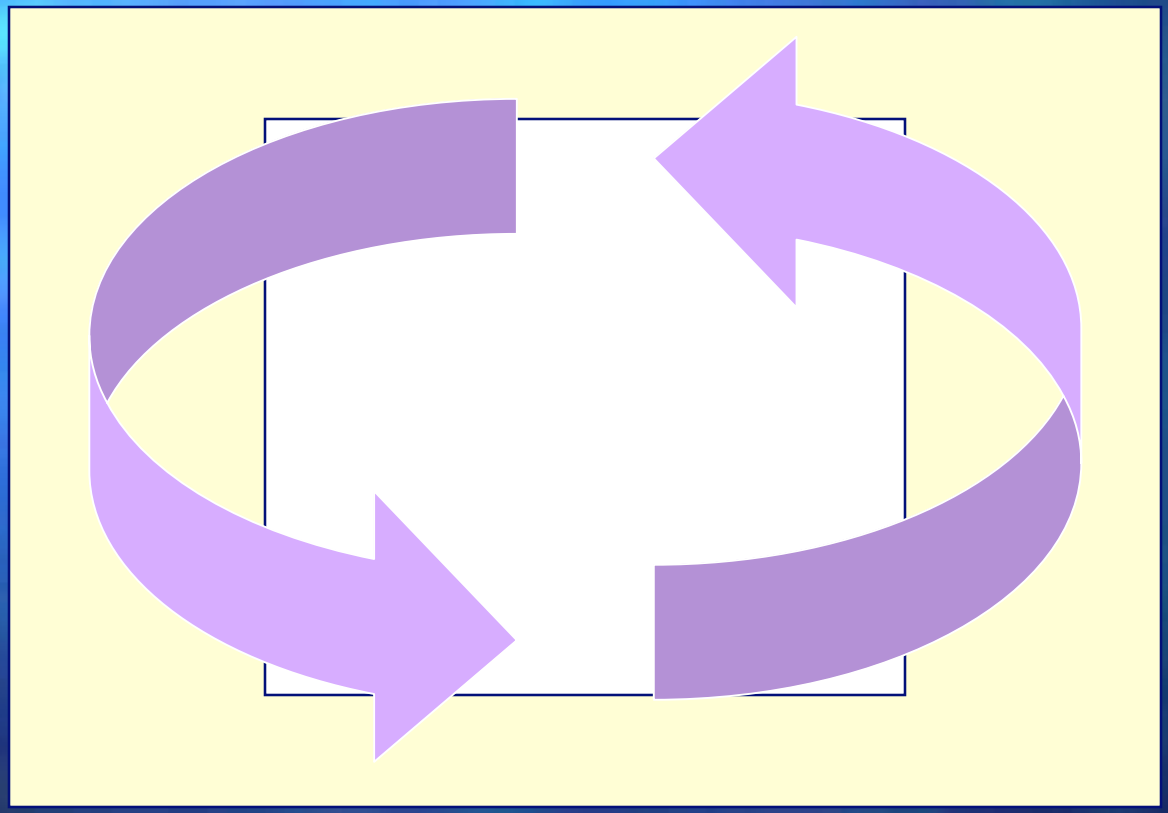
- Boundary conditions are important for Stokes problems
- Boundary is usually put far away from the region of interest
  - local mesh refinement

Self-consistent boundary conditions

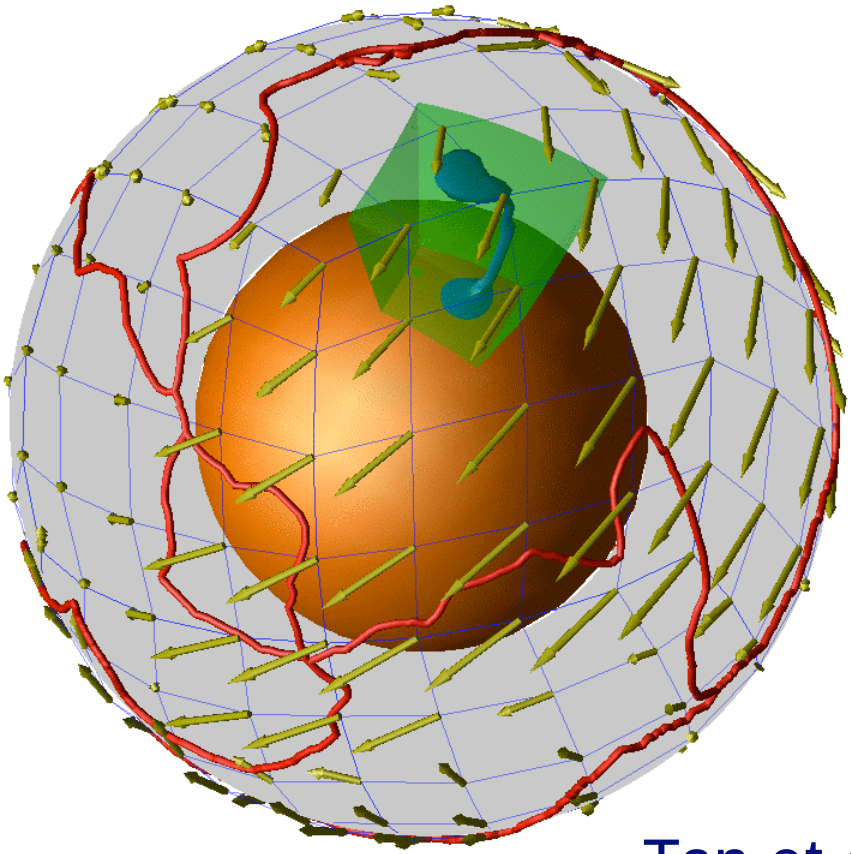
- Types of BCs for Stokes problems:
  - pinned (V=0), fixed velocity (V=const), free (σ=0), traction (σ=const)
  - usually BCs are not varying in time
- Changes in the region of interest can potentially change the BCs

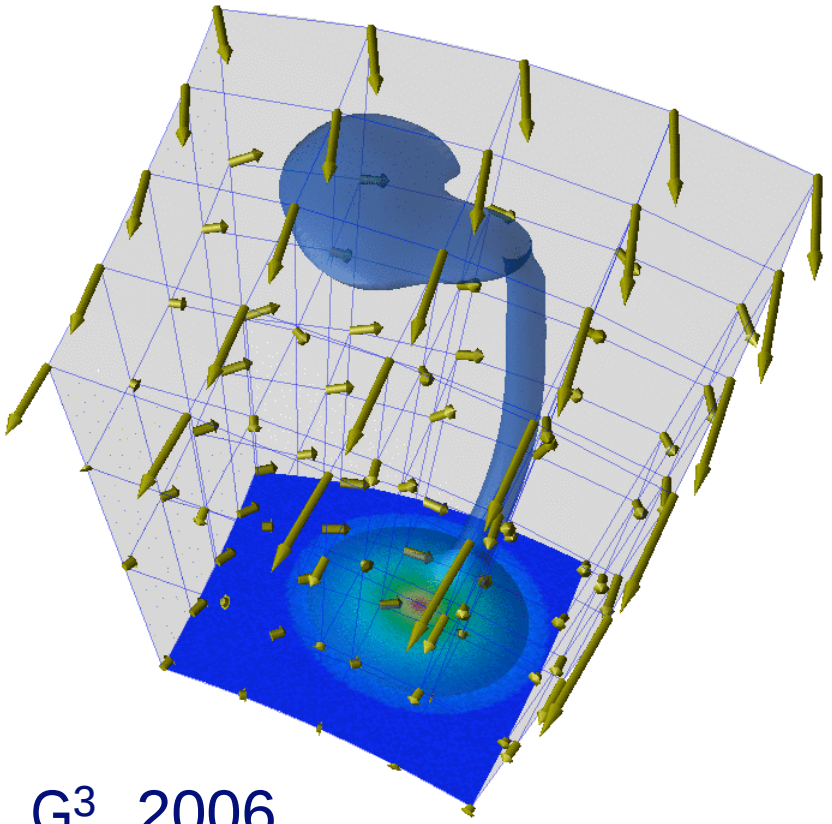

0
1

Self-consistent boundary conditions



CitcomS-CitcomS Coupling

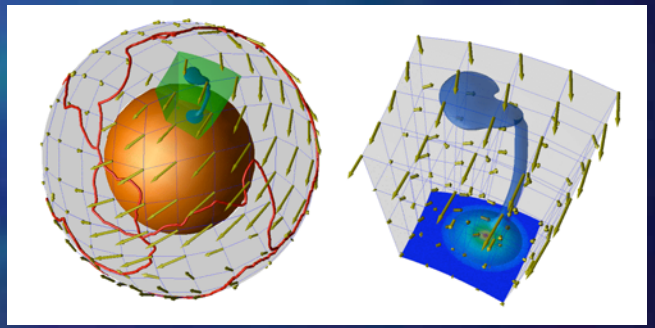




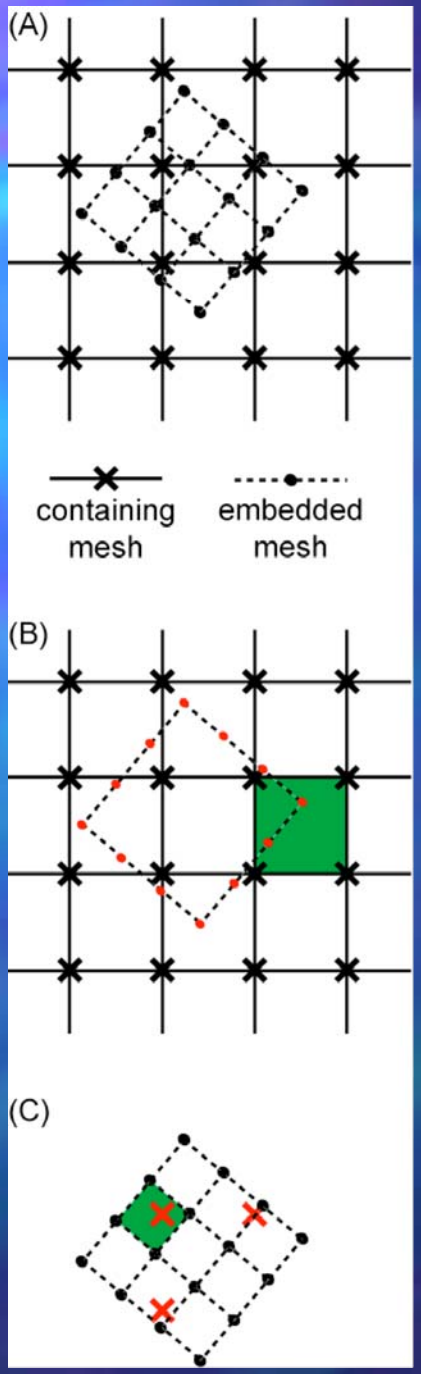
Tan et al., G^3, 2006

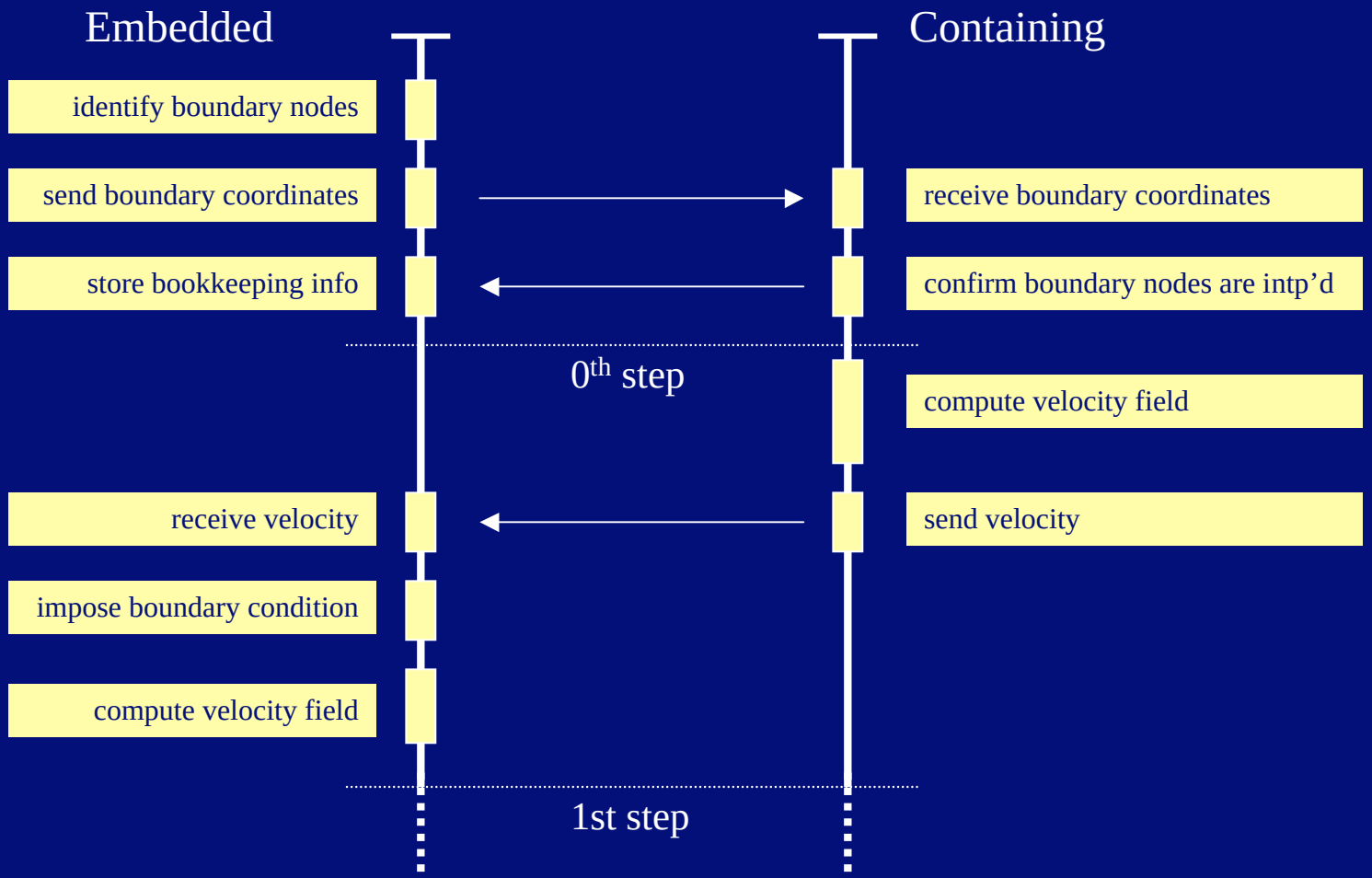
CitcomS-CitcomS Coupling

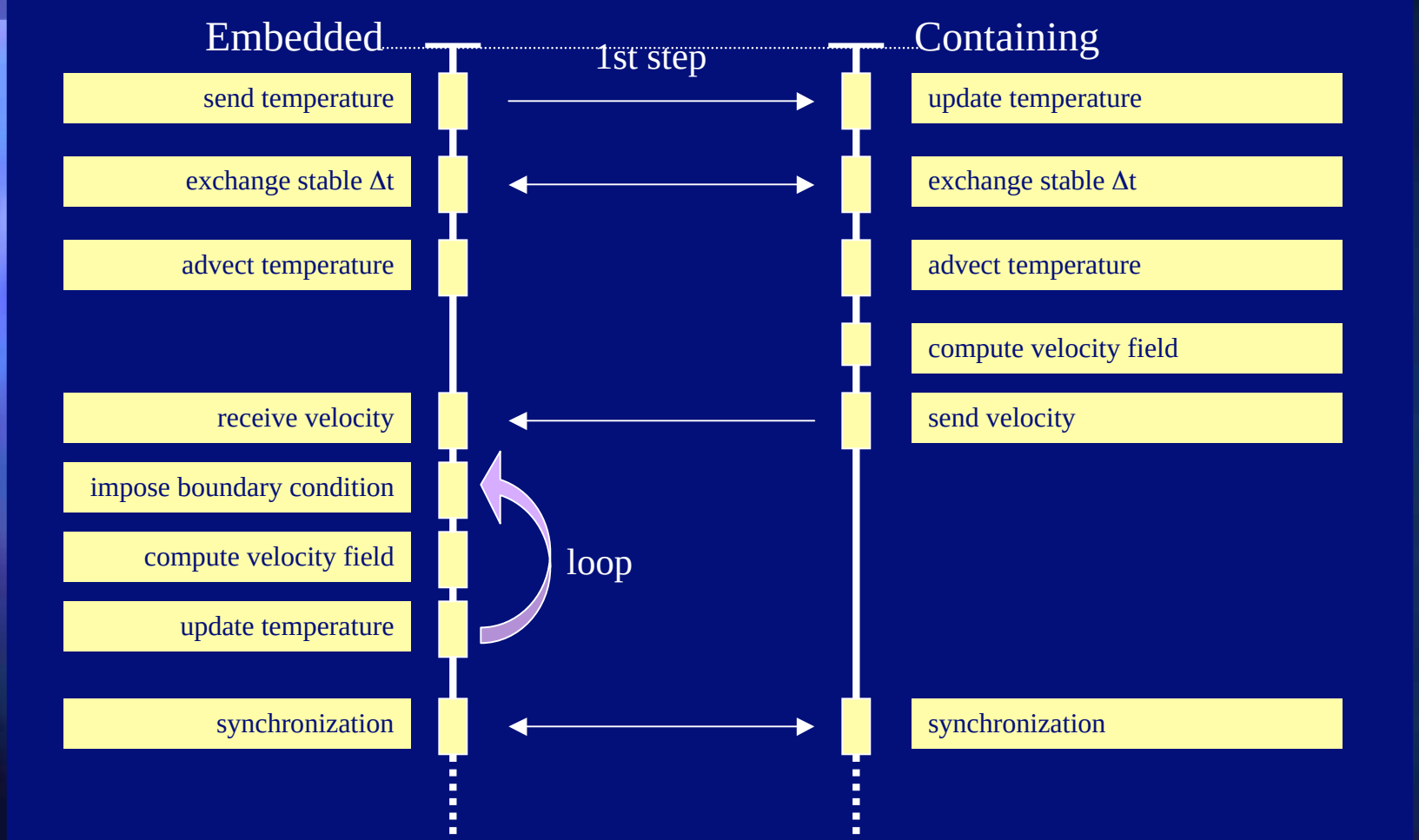
- Containing -> Embedded
  - boundary conditions: fixed temperature + normal velocity + shear stress
  - using 3 components of velocity for BCs will cause mesh locking
- Embedded -> Containing
  - temperature field



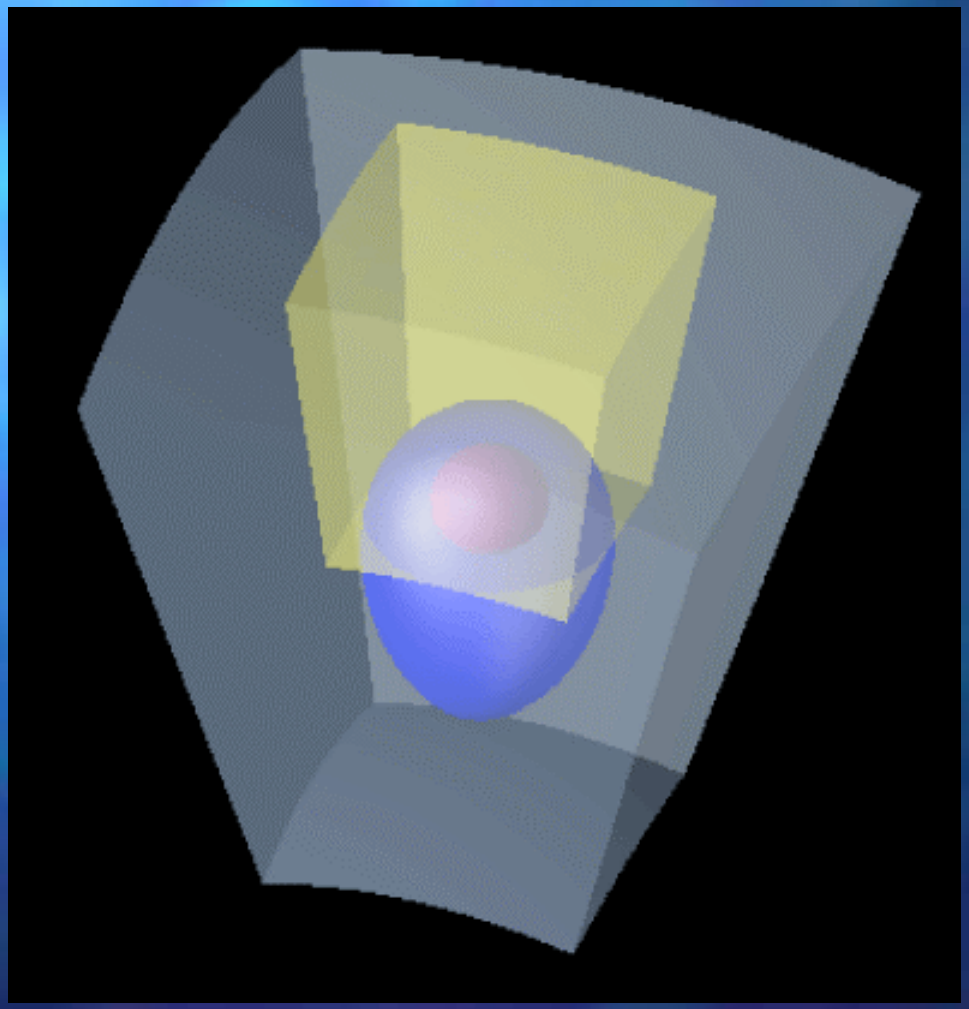
Interpolation

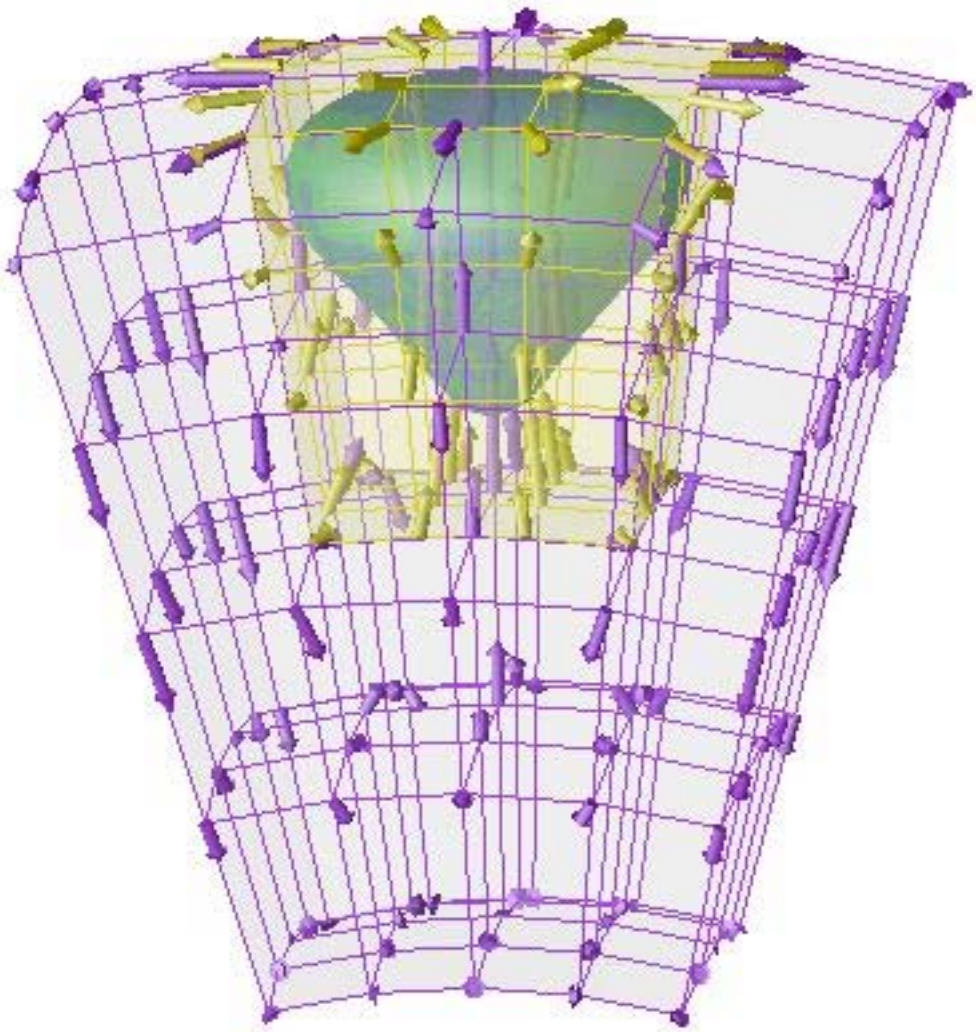


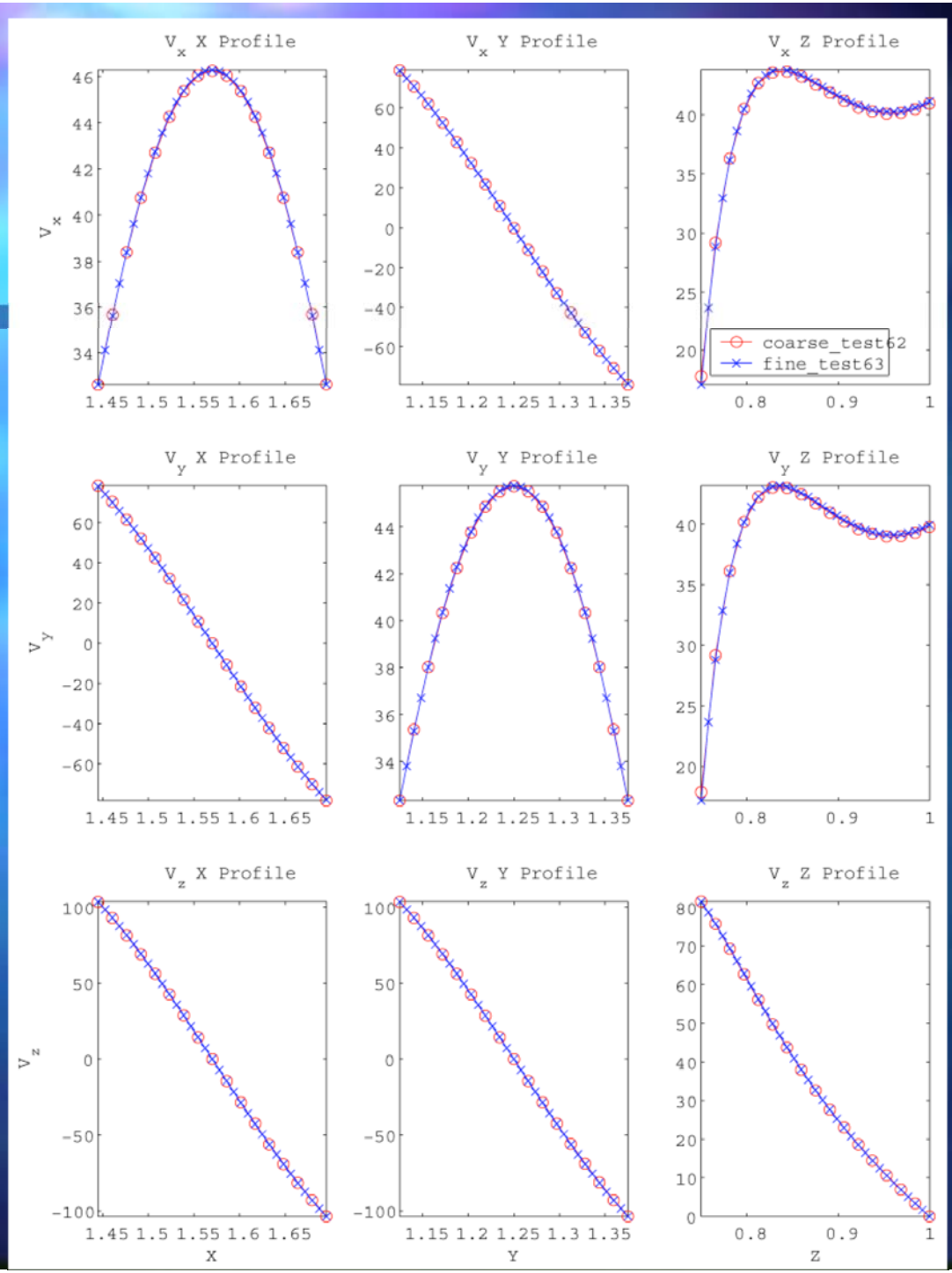

Embedded
Containing
identify boundary nodes
send boundary coordinates
store bookkeeping info
receive boundary coordinates
confirm boundary nodes are intp'd
0th step
compute velocity field
receive velocity
send velocity
impose boundary condition
compute velocity field
1st step


Embedded
Containing
1st step
send temperature
update temperature
exchange stable Δt
exchange stable Δt
advect temperature
advect temperature
compute velocity field
receive velocity
send velocity
impose boundary condition
compute velocity field
loop
update temperature
synchronization
synchronization

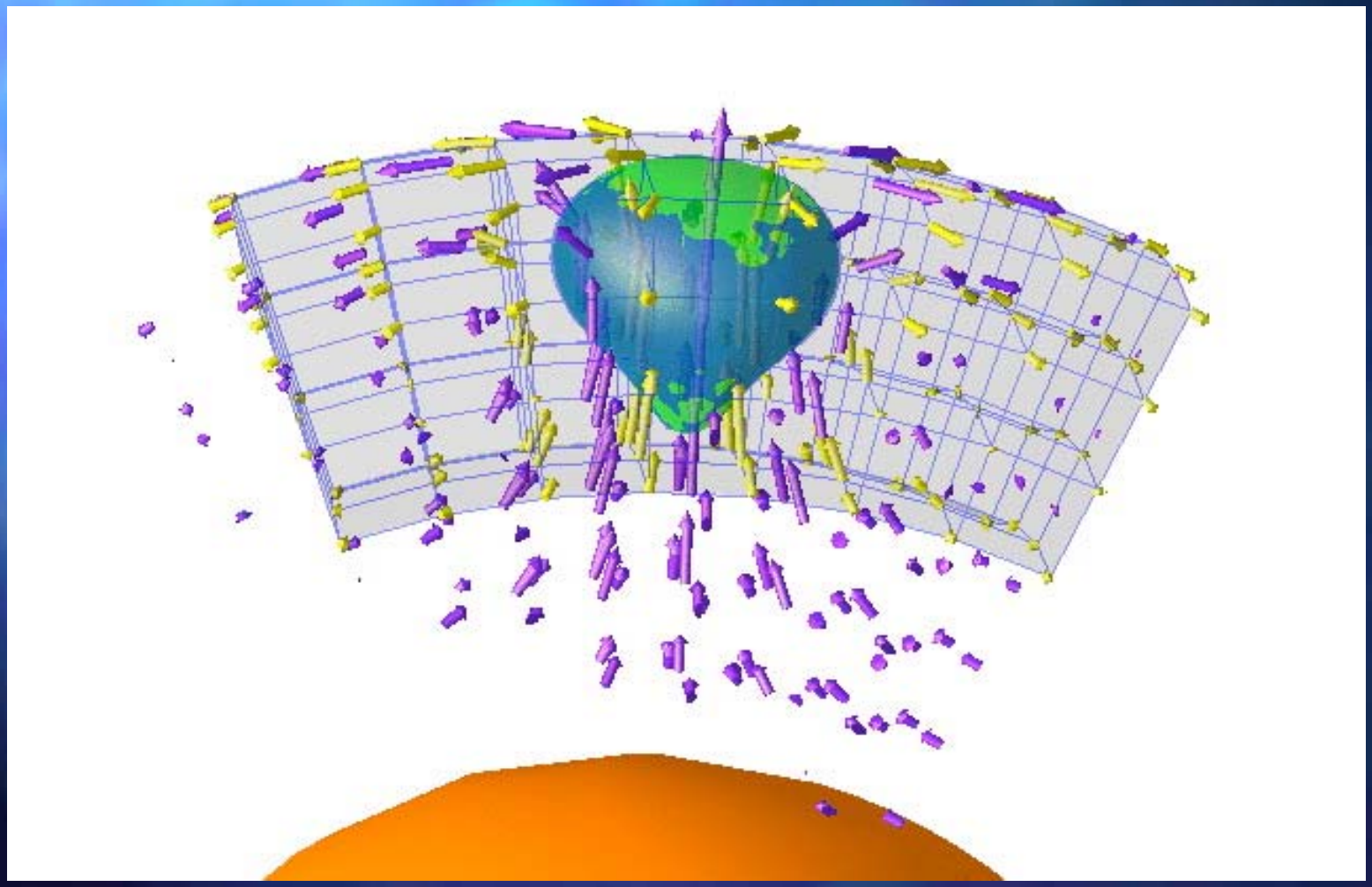
Validation (Regional-Regional)





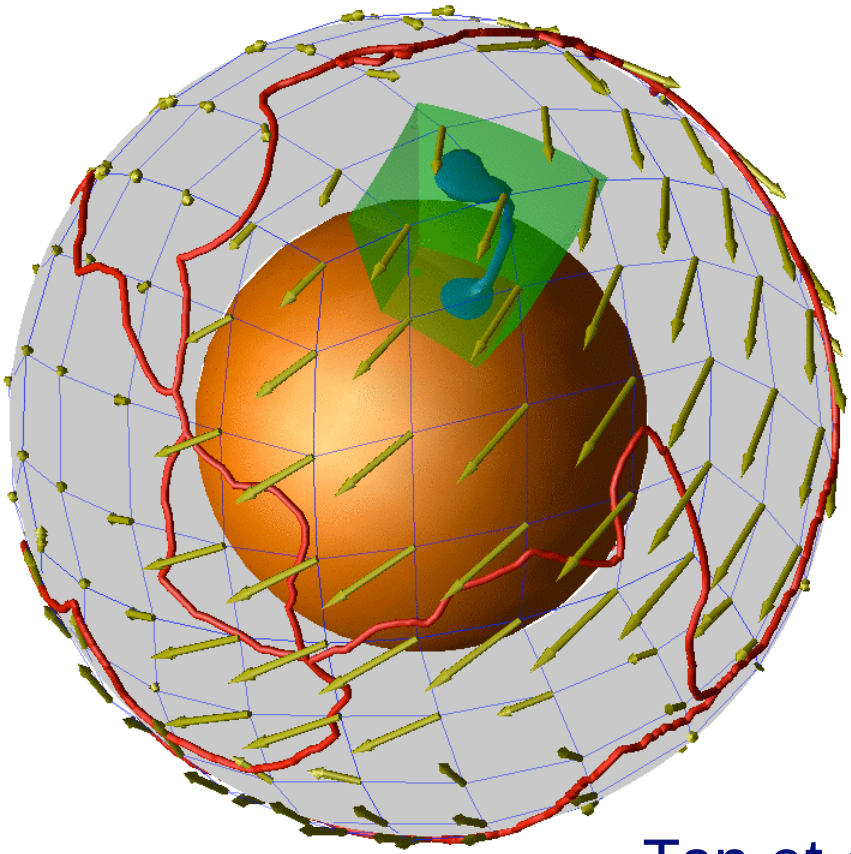

V_x X Profile
V_x Y Profile
V_x Z Profile
V_x
coarse_test62
fine_test63
V_y X Profile
V_y Y Profile
V_y Z Profile
V_y
V_z X Profile
V_z Y Profile
V_z Z Profile
V_z
X
Y
Z

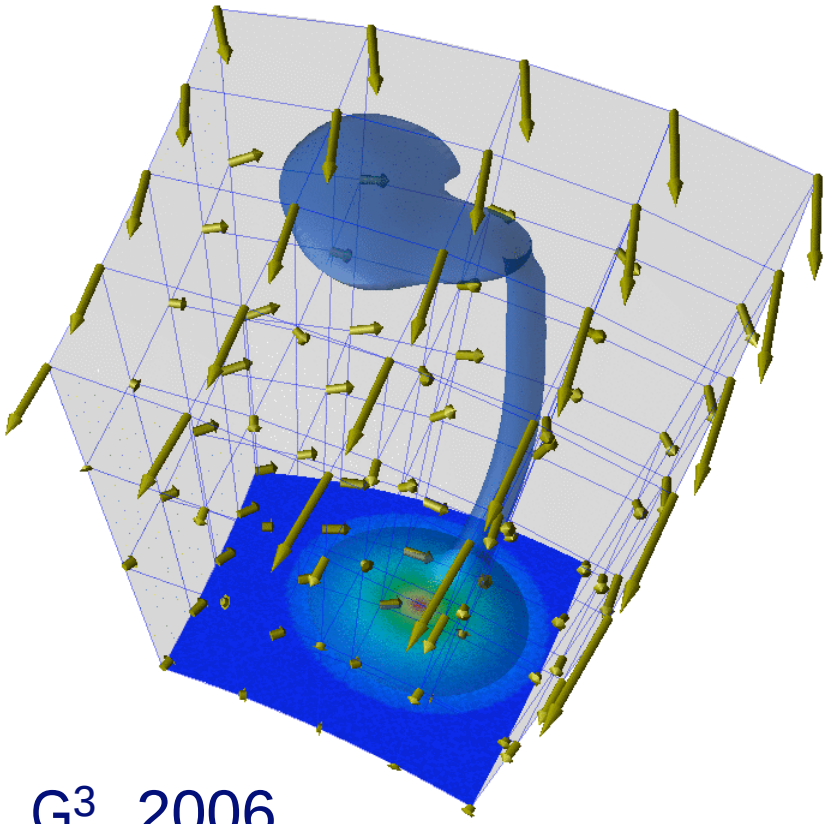
Validation (Global-Regional)



180 km resolution

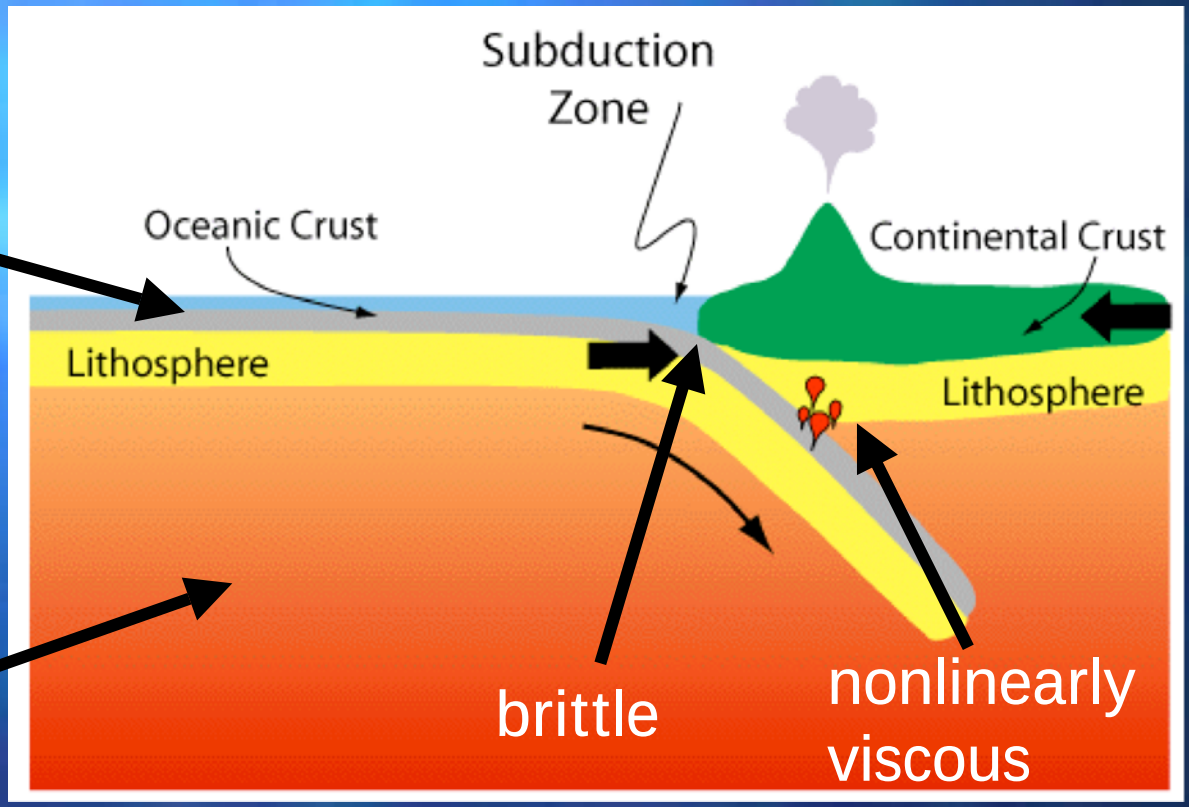
40 km resolution





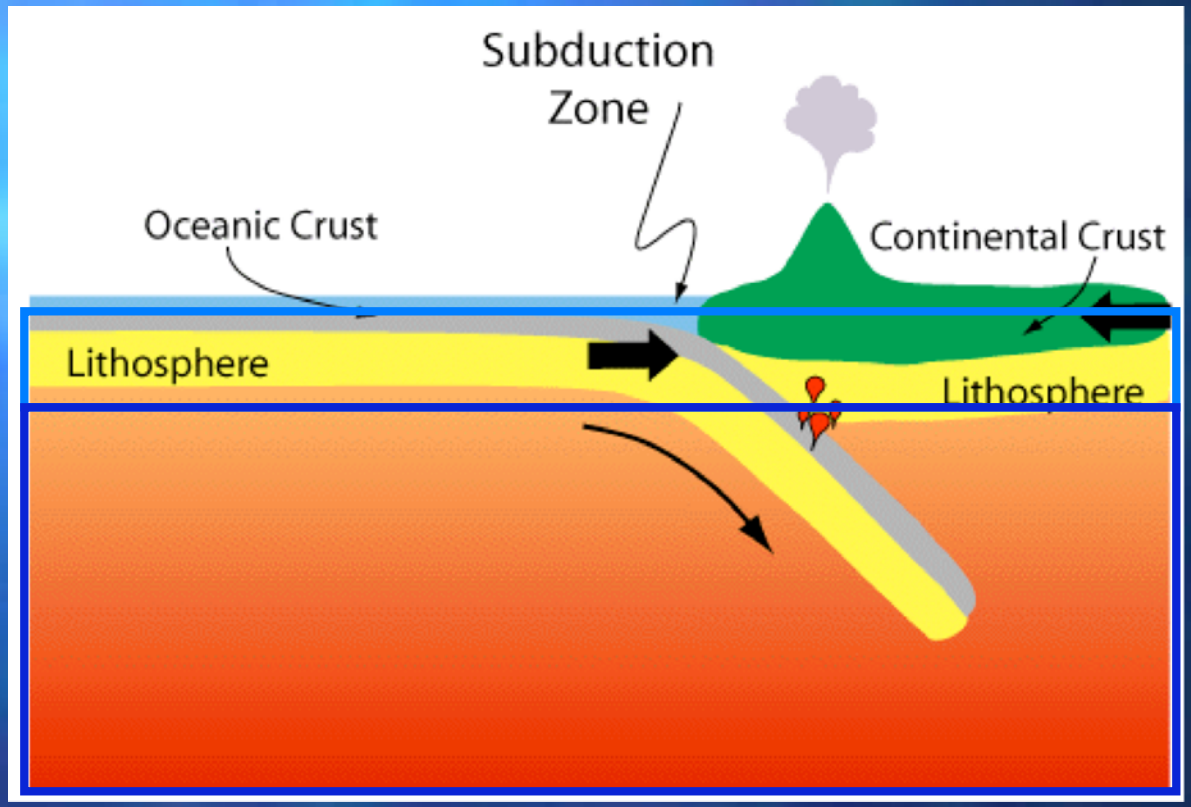
Tan et al., G^3, 2006

Multi-physics



http://atlas.geo.cornell.edu

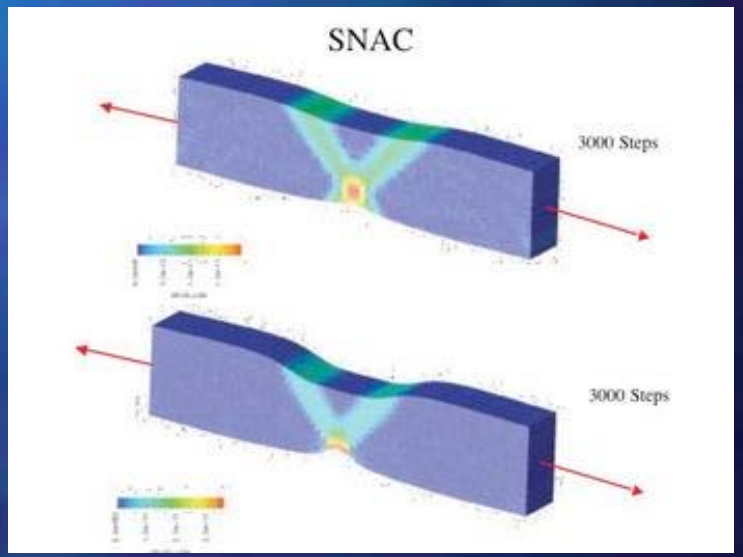
Multi-physics



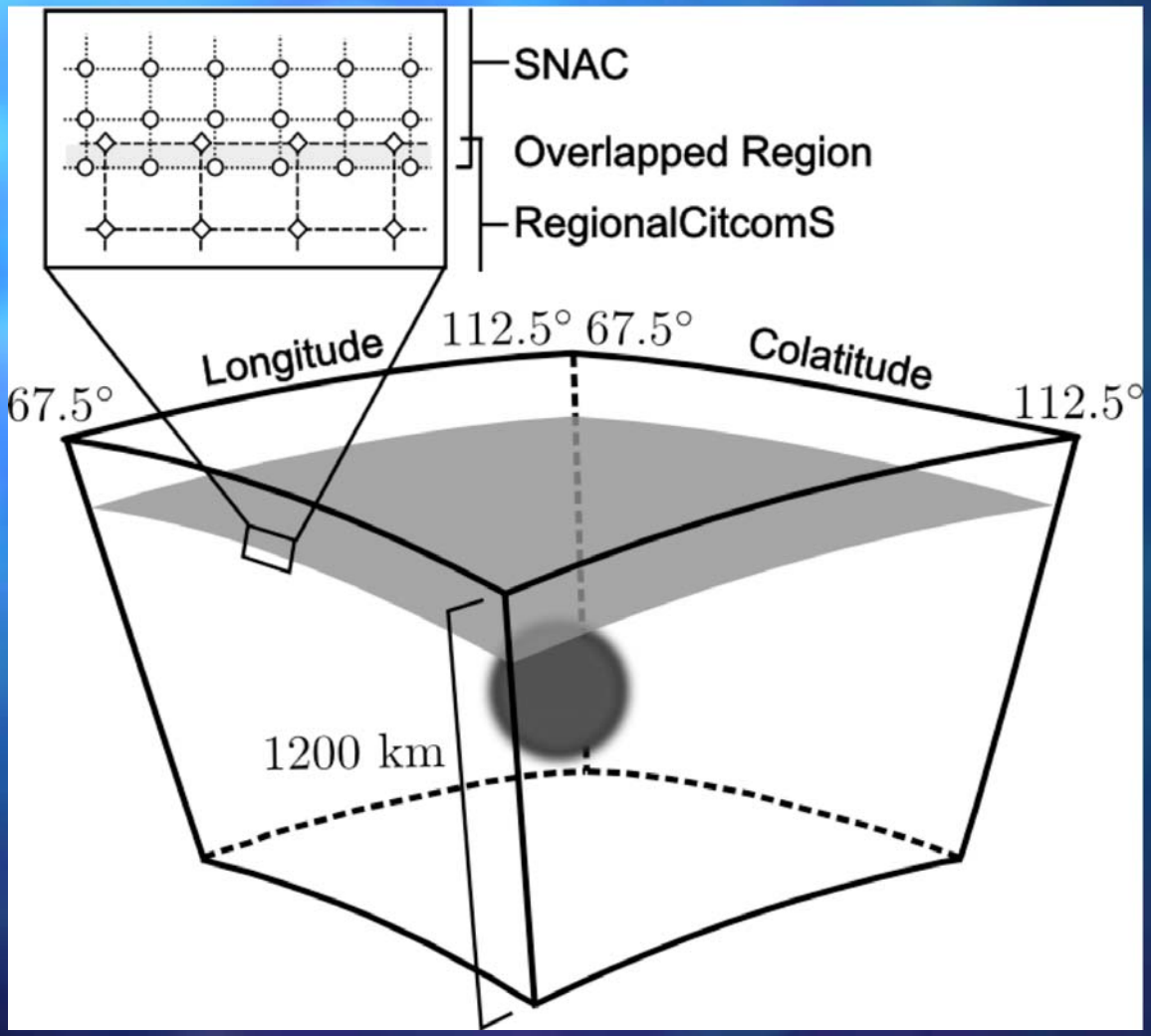
http://atlas.geo.cornell.edu

SNAC

- 3D Lagrangian visco-plasto-elastic FD code (Choi & Gurnis, EPSL, 2008)
- FLAC algorithm for Stokes solver
  - explicit solver, pseudo inertia
  - quasi-static equilibrium state

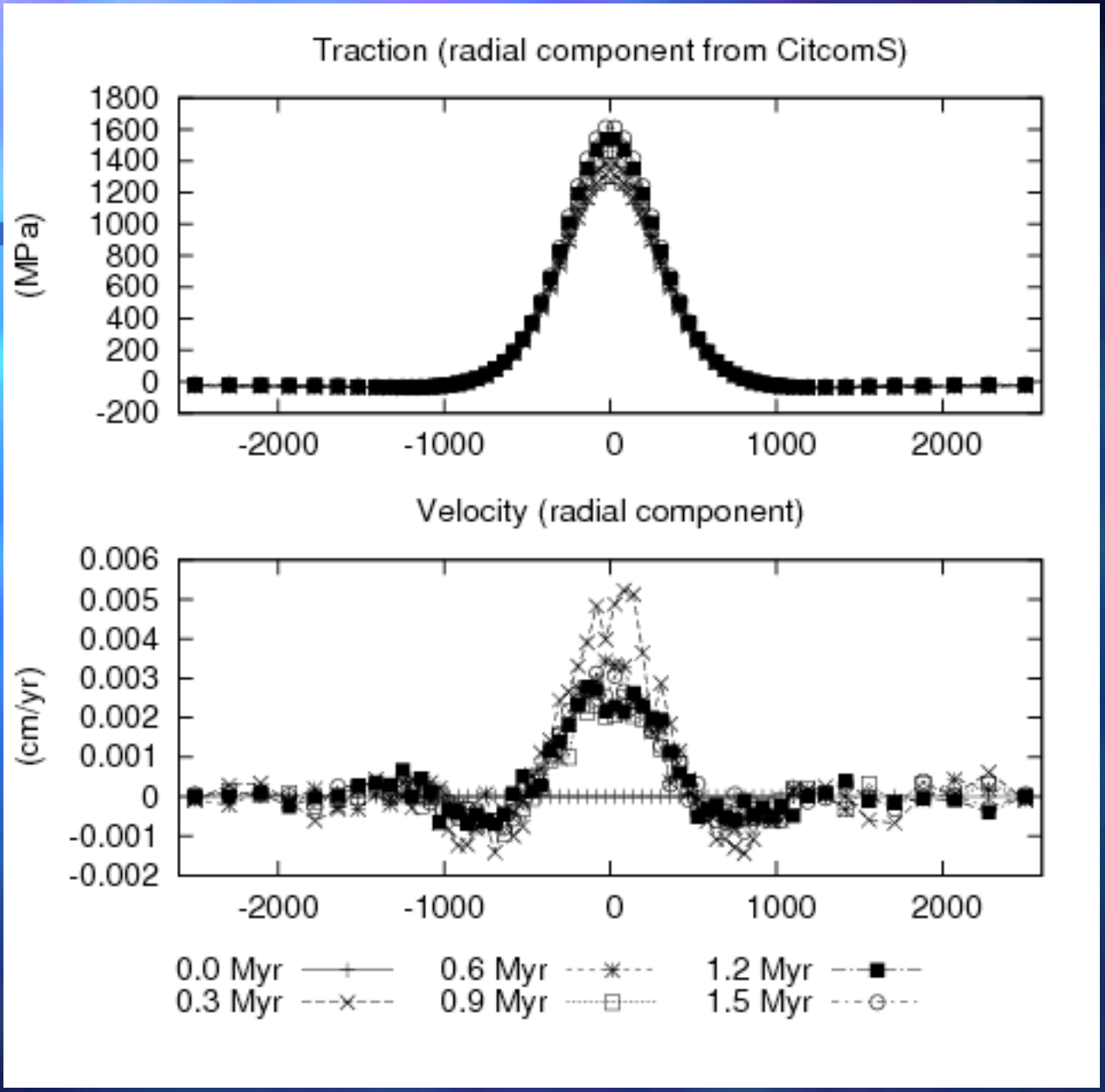


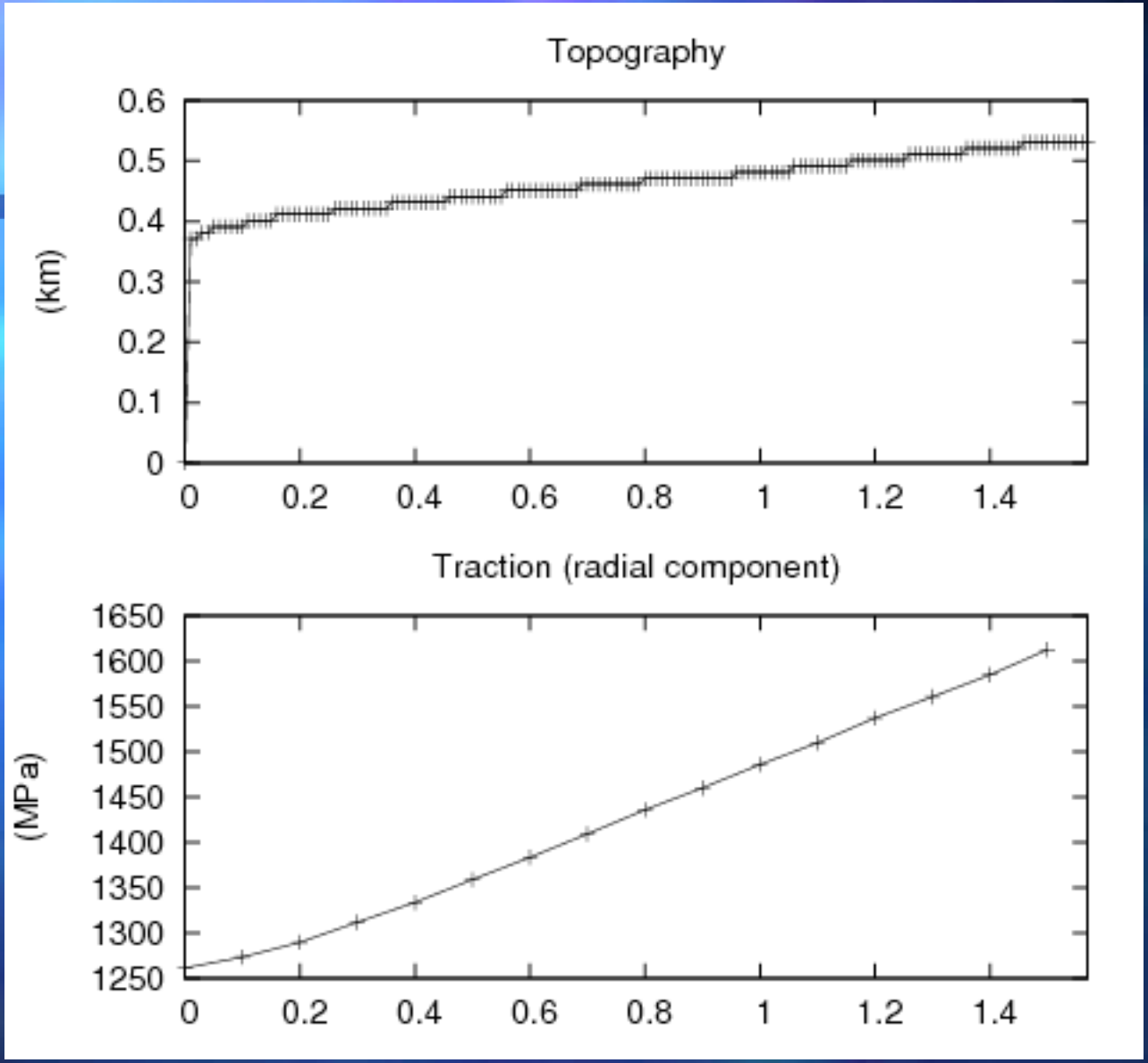
SNAC-CitcomS coupling



SNAC-CitcomS coupling

- CitcomS -> SNAC:
  - boundary conditions for bottom nodes: stress (traction) & temperature
- SNAC -> CitcomS:
  - velocity boundary conditions for top nodes
- All exchanged quantities are in Cartesian coordinates and SI units


Traction (radial component from CitcomS)
(MPa)
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-2000
-1000
0
1000
2000
Velocity (radial component)
(cm/yr)
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-2000
-1000
0
1000
2000
0.0 Myr
0.3 Myr
0.6 Myr
0.9 Myr
1.2 Myr
1.5 Myr


Topography
(km)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Traction (radial component)
(MPa)
1650
1600
1550
1500
1450
1400
1350
1300
1250
0
0.2
0.4
0.6
0.8
1
1.2
1.4

Limitation

- Stokes solver: implicit (CitcomS) vs explicit (SNAC)
  - SNAC solution is not in a steady state
- Each CitcomS time step ~ 10^4 SNAC time steps
- Computing 1.5 Myrs took 10 days
  - 2 months for the hot blob to rise to surface

CitcomS Scaling Performance

Multi-core

- FE codes are memory bandwidth hungry
- Performance will degrade if run on multi-core machines
- Test: regional CitcomS 2x2x2 processors, total run time
  - 8 CPUs, 1 core/CPU, 688 sec., 100%
  - 4 CPUs, 2 cores/CPU, 771 sec., 89%
  - 2 CPUs, 4 cores/CPU, 975 sec., 70%

Parallel scaling (weak scaling)

- Fixed number of elements (32^3) per processors, constant viscosity, 50 time steps
- Not a right test for scaling. Take with a grain of salt.

# of proc.	run time	# of Uzawa iterations	time per iterations
12 (1x1x1)	60.53	112	0.54
24 (1x1x2)	54.33	95	0.57
48 (2x2x1)	43.99	73	0.60
96 (2x2x2)	45.17	74	0.61
192 (4x4x1)	35.94	55	0.65
384 (4x4x2)	37.02	55	0.67
768 (4x4x4)	42.36	58	0.73
1536 (8x8x2)	42.23	60	0.70
3072 (8x8x8)	41.53	54	0.77