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Towards fault tolerance in HPC for numerical weather and climate prediction

Tommaso Benacchio

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DIPARTIMENTO DI MATEMATICA

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Fault-tolerant computing

First Record of Single-Event Upset on Ground,
Cray-1 Computer at Los Alamos in 1976

"... so we know that during those six months of operation, 152 parity errors were recorded [...] caused by atmospheric neutrons"

Normand et al. 2010

Fault-tolerant design

1. How likely is a component/system to fail?

Fault-tolerant design

1. How likely is a component/system to fail?

Systems	2009	2011	2015	2020 ?
System peak	2 Peta	20 Peta	100-200 Peta	1 Exa
System memory	0.3 PB	1.6 PB	5 PB	10 PB
Node performance	125 GF	200GF	200-400 GF	1-10TF
Node memory BW	25 GB/s	40 GB/s	100 GB/s	200-400 GB/s
Node concurrency	12	32	O(100)	O(1000)
Interconnect BW	1.5 GB/s	22 GB/s	25 GB/s	50 GB/s
System size (nodes)	18,700	100,000	500,000	O(million)
Total concurrency	225,000	3,200,000	O(50,000,000)	O(billion)
Storage	15 PB	30 PB	150 PB	300 PB
IO	0.2 TB/s	2 TB/s	10 TB/s	20 TB/s
MTTI	4 days	19 h 4 min	3 h 52 min	1 h 56 min
Power	6 MW	~10MW	~10 MW	~20 MW

More and more cores
Smaller circuit sizes
Lower voltages
Thermal/voltage var, radiation

XC-40@ECMWF: 7220 nodes, 8PF
15 node failures/month

Chen et al. '17, Boehm et al. '10, C. Engelmann, B. et al. 2021, Agullo et al. '21

Fault-tolerant design

1. How likely is a component/system to fail?

2. How critical is the component/system?

Fault-tolerant design – NWP & Climate

1. How likely is a component/system to fail?

2. How critical is the component/system?

New York Times

Fault-tolerant design – NWP & Climate

1. How likely is a component/system to fail?

2. How critical is the component/system?

3. How expensive is it to make the component/system fault-tolerant?

Tight operational schedules | High computational intensity | Finer resolutions

Taxonomy

Fault - cause of an error

- Hard – permanent and reproducible (broken hardware)
- Soft – transient and non-reproducible (bit flip in memory)

- Detected and corrected – error-correcting codes, replication, re-execution
- Detected and uncorrectable – application crash
- Undetected – silent data corruption

Error - part of state causing → Failure - transition to incorrect service

Nielsen 2018, B. et al. 2021

Existing strategies - Checkpointing

Store system state at regular intervals | restore | recompute on failure

Costly | heavy I/O load | detection latency / checkpoint frequency trade-off

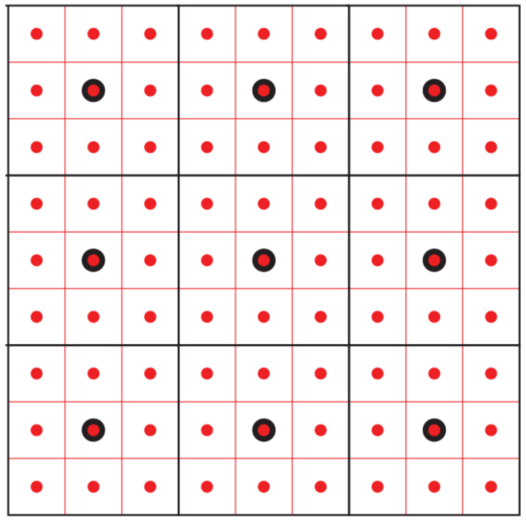
Not viable if $T_{CPR} > MTTI$

For a 10-day forecast @ECMWF: 5 checkpoints written | 1% runtime | FS b/w absorbed

@1km resolution: restart files of several TB across 1000s MPI procs to single FS

Existing strategies - Redundancy

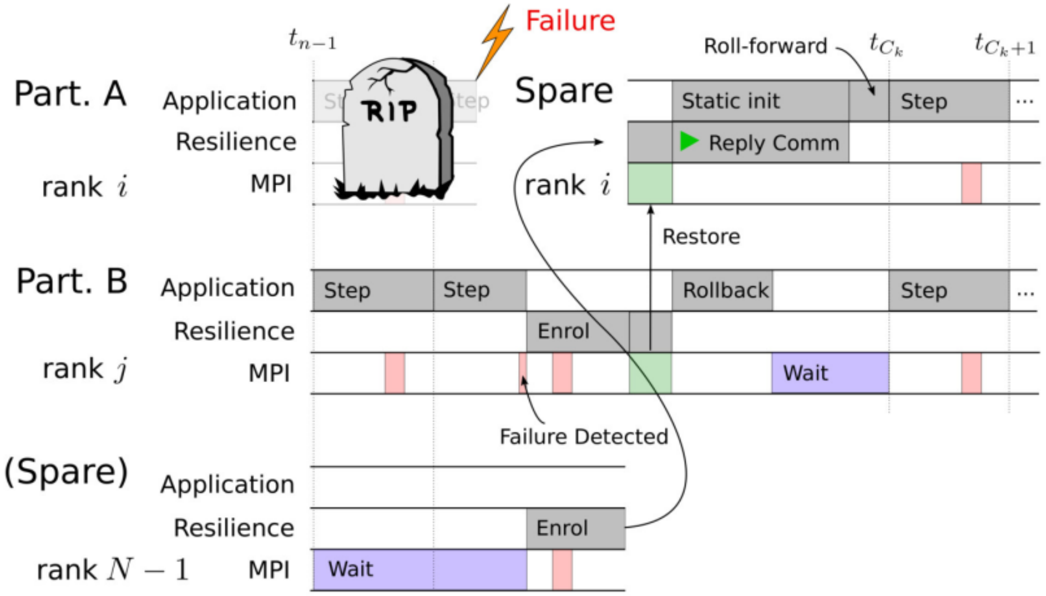
1. Multiple compute clusters/file systems – standard in operational NWP
2. Process replication – clone data and re-run computation
3. Use backup grids where checks are made



Fault detected on coarser backup grid: replace with previous known good value then map to full grid

Düben & Dawson '17

In-memory checkpointing



In-memory storage of distributed solver iterate

On failure

1. Revokes MPI comm
2. Recovers remote in-memory CP
3. Replaces failed process with spare

Computation continues, other procs unaffected

Attractive system resilience option matched with algorithmic fault-tolerance

Cantwell & Nielsen '18

Fault-tolerant linear solvers – FT -GCR

Resilience add-on for linear solver

ESCAPE elliptic solver dwarf

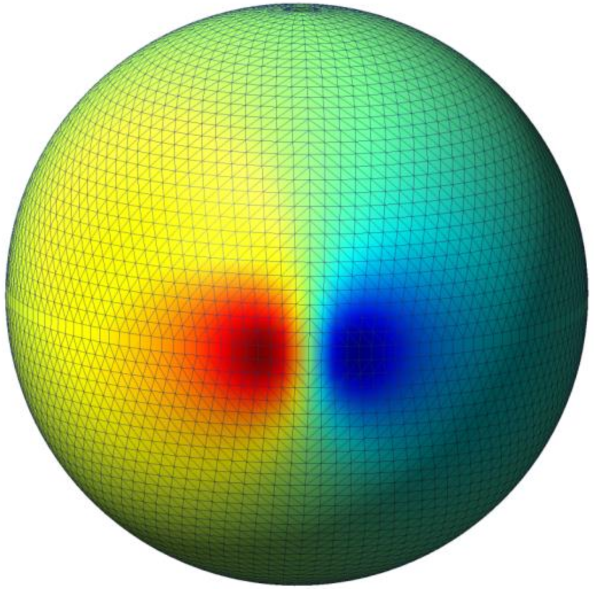
Mirroring IFS-FVM dynamical core solver

Monitor residual norm, if nondecreasing reset iteration in Krylov subspace

Algorithm 1 FT-GCR(k):

For any initial guess, ϕ^0, set $r^0 = \mathcal{L}(\phi^0) - \mathcal{R}$, $p^0 = \mathcal{P}^{-1}(r^0)$; then iterate:
for $n = 1, 2, \ldots$ until convergence **do**
  for $\nu = 0, \ldots, k-1$ **do**
    $\beta = -\dfrac{\langle r^\nu \mathcal{L}(p^\nu)\rangle}{\langle \mathcal{L}(p^\nu)\, \mathcal{L}(p^\nu)\rangle}$
    $\phi^{\nu+1} = \phi^\nu + \beta p^\nu$
    $r^{\nu+1} = r^\nu + \beta \mathcal{L}(p^\nu)$
    if $\|r^{\nu+1}\|_2 \leq \epsilon$ **then**
      exit
    end if
    if $\|r^{\nu+1}\|_2 \geq \|r^\nu\|_2$ **then**
      $n = n - 1$
      reset $[\phi, r, p, \mathcal{L}(p)]^0$ to $[\phi, r, p, \mathcal{L}(p)]^*$
    else if $\nu = 0$ **then**
      set $[\phi, r, p, \mathcal{L}(p)]^*$ to $[\phi, r, p, \mathcal{L}(p)]^0$
    end if
    $e = \mathcal{P}^{-1}(r^{\nu+1})$
    Compute $\mathcal{L}(e)$
    $\alpha_l = -\dfrac{\langle \mathcal{L}(e)\mathcal{L}(p^l)\rangle}{\langle \mathcal{L}(p^l)\, \mathcal{L}(p^l)\rangle} \qquad \forall\, l = 0, \ldots, \nu$
    $p^{\nu+1} = e + \sum_{l=0}^{\nu} \alpha_l p^l$
    $\mathcal{L}(p^{\nu+1}) = \mathcal{L}(e) + \sum_{l=0}^{\nu} \alpha_l \mathcal{L}(p^l)$
  end for
  reset $[\phi, r, p, \mathcal{L}(p)]^k$ to $[\phi, r, p, \mathcal{L}(p)]^0$
end for

Potential flow test on the sphere



$$\mathbf{v} = \mathbf{v_a} - \nabla\phi$$
$$\nabla \cdot (\rho\mathbf{v}) = 0$$

$\Rightarrow$

$$\mathcal{L}(\phi) = \mathcal{R}$$

Fault simulation: injecting bit flips

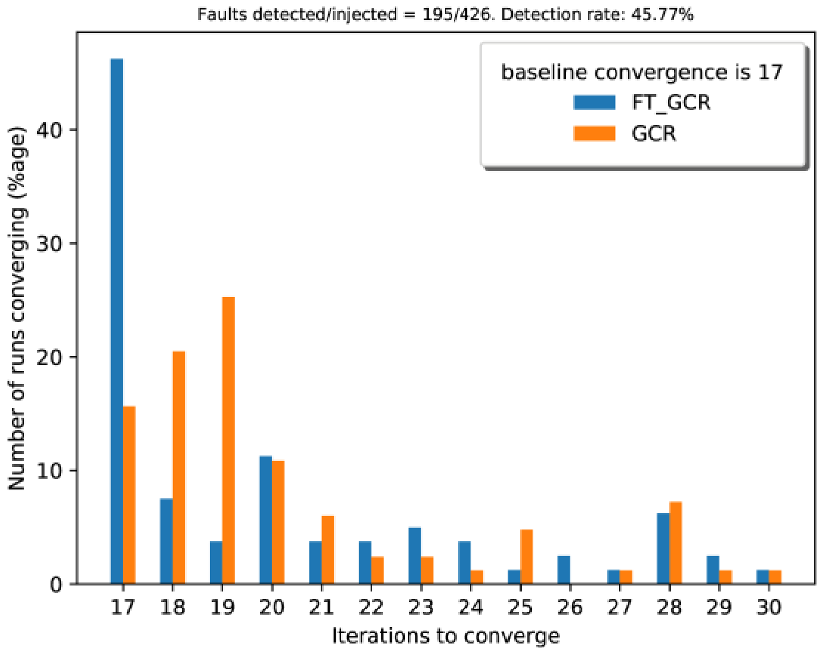
Comparing FT-GCR with unprotected GCR

O40 (~220 km) to O640 (~15 km) grids

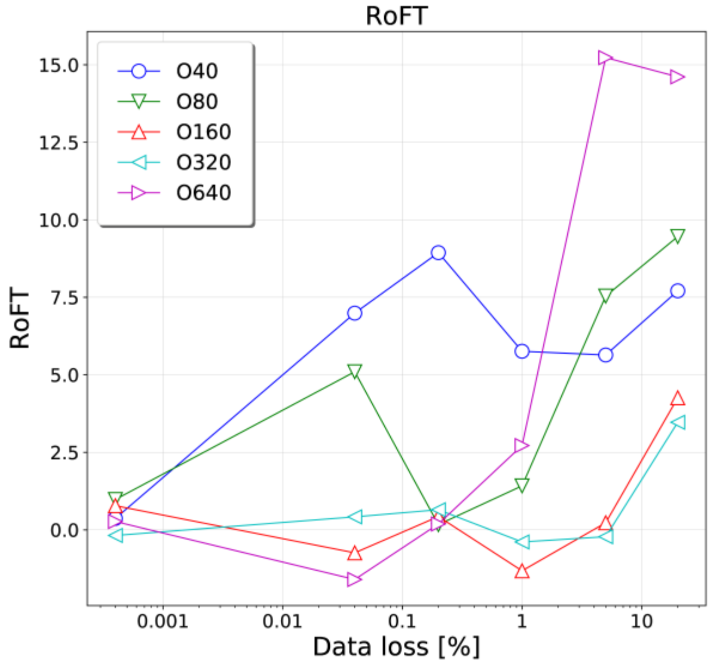
On up to 3240 MPI processes

Thomas et al. 2003

Results



O80 grid , 1% data loss



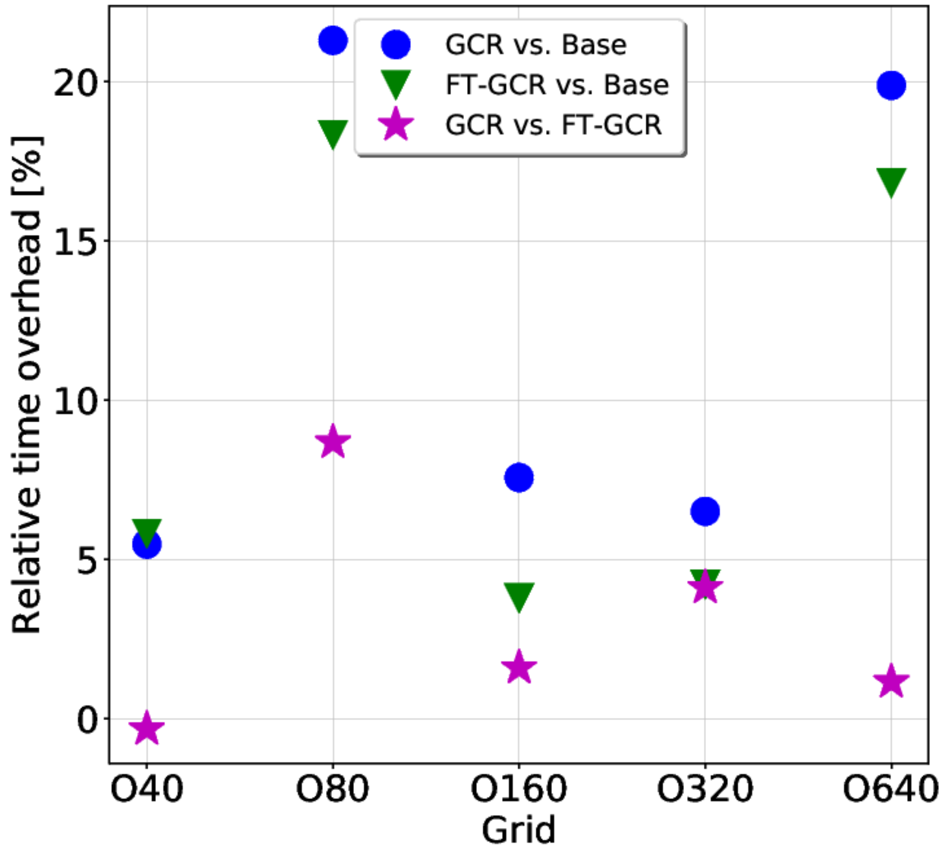
$$\mathrm{RoFT} = \frac{\mathrm{GCR} - \mathrm{FT\text{-}GCR}}{\mathrm{baseline}}$$

1. Protected runs converge in fewer iterations

2. Return on Fault Tolerance grows with > Larger data corruption
   > Higher detection rates

Gillard & B. '21

Results - Timings & costs



Faults have impact

GCR vs. Baseline > FT-GCR vs. Baseline

FT-GCR up to 10% faster than unprotected GCR

Memory overhead < ~20%

Gillard & B. '21

Limitations

Benchmarking of proposed solutions needs extension

Data size per process O(10-100) smaller than operational configs

Tests with set fault frequencies, limited testing on real systems

Take-home messages and next steps

Resilience techniques in NWP/climate models not future-proof

Lightweight novel approaches to be explored

Trials possible on exascale demonstrators such as ESCAPE-2 dwarfs

Future: performance trade-off studies on operational data volumes

Work with vendors to testing fault frequency on future HPC

Questions?

- Benacchio, T., Bonaventura, L., Altenbernd, M., Cantwell, C.D., Düben, P. D.,Gillard, M., Giraud, L., Göddeke, D., Raffin, E., Teranishi, K., Wedi, N. (2021), *Resilience and fault-tolerance in high-performance computing for numerical weather and climate prediction*, The International Journal of High Performance Computing Applications, Vol. 35, pp. 285-311

- Agullo, E., Altenbernd, M., Anzt, H., Bautista-Gomez, L., Benacchio, T., et al. (2021), *Resiliency in Numerical Algorithm Design for Extreme Scale Simulations*, accepted, https://arxiv.org/abs/2010.13342

- Gillard, M., Benacchio, T. (2021), *FT-GCR: a fault-tolerant generalized conjugate residual elliptic solver*, under revision, https://arxiv.org/abs/2103.07210

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