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Getting the right answer despite incorrect hardware[1]

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Outline

Getting the right answer despite incorrect hardware

- Incorrect hardware. . .
  - . . . may expose incorrect arithmetic or storage
  - (to reduce power or improve performance)
  - This may cause silently wrong results, or . . .
  - . . . make algorithms take a long time to fail
  - Software bugs may have the same effect!
- Getting the right answer
  - Our focus: iterative linear solvers ($Ax = b$)
  - Techniques apply to other numerical algorithms
  - Possible generalization to discrete problems
- Through two, mostly algorithmic techniques:
  - Skeptical programming
  - Selective reliability

Why we care about silently wrong results

Simulations for high-consequence decisions

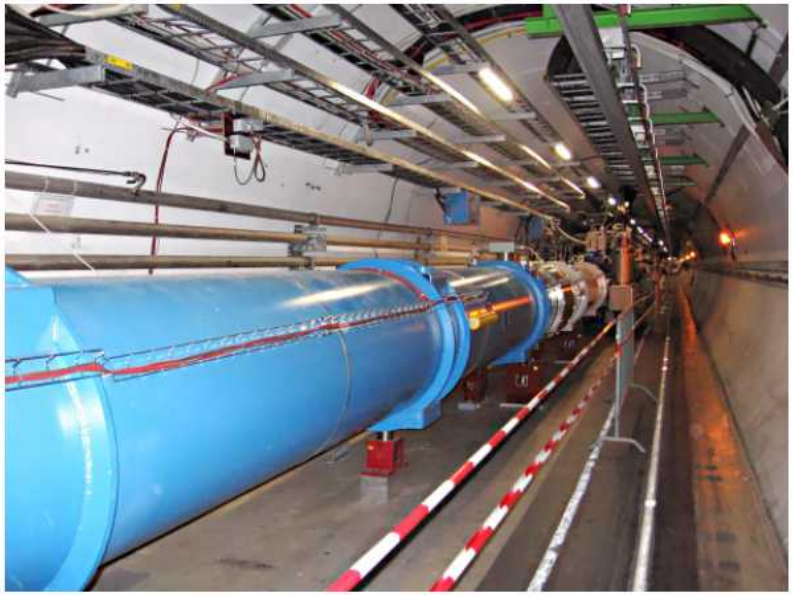
- Decisions like
  - Existential threats
  - Weather disasters
  - Civil engineering
- High fidelity & tight time constraints
- Hard or impossible to validate experimentally

Hurricane Sandy damage (Image credit: US Air Force). Evacuation may kill more than it saves if the weather forecast is incorrect.

High-consequence science & data analysis

Higgs boson: Search for rare event in lots of data

- 1 out of 10^{10} LHC collisions may produce a Higgs boson
- 3×10^{14} collisions analyzed
- 2.5×10^{15} bytes of data / year in 2012
- Expensive; pressure for fast results, but false positive is embarrassing



Large Hadron Collider at CERN.

Definitions: What's a fault?

Fault or failure?

- Fault[3] affects *inside* behavior; failure propagates *outside*
- Definition of "inside" depends on my responsibilities
- Example: bit flip in a defective memory cell
  - DRAM hardware designer:
    - "Fault" if ECC corrects it
    - "Failure" if ECC can't correct it
  - Algorithm developer:
    - "Fault" *only* if it is read
    - "Failure" if code returns wrong result
- This matters because an algorithm might succeed (not fail), despite failure of hardware to correct a fault.

[3] A possible formal definition: B. Parhami, "Defect, fault, error, . . . , or failure?", IEEE Trans. Reliability, 1997.

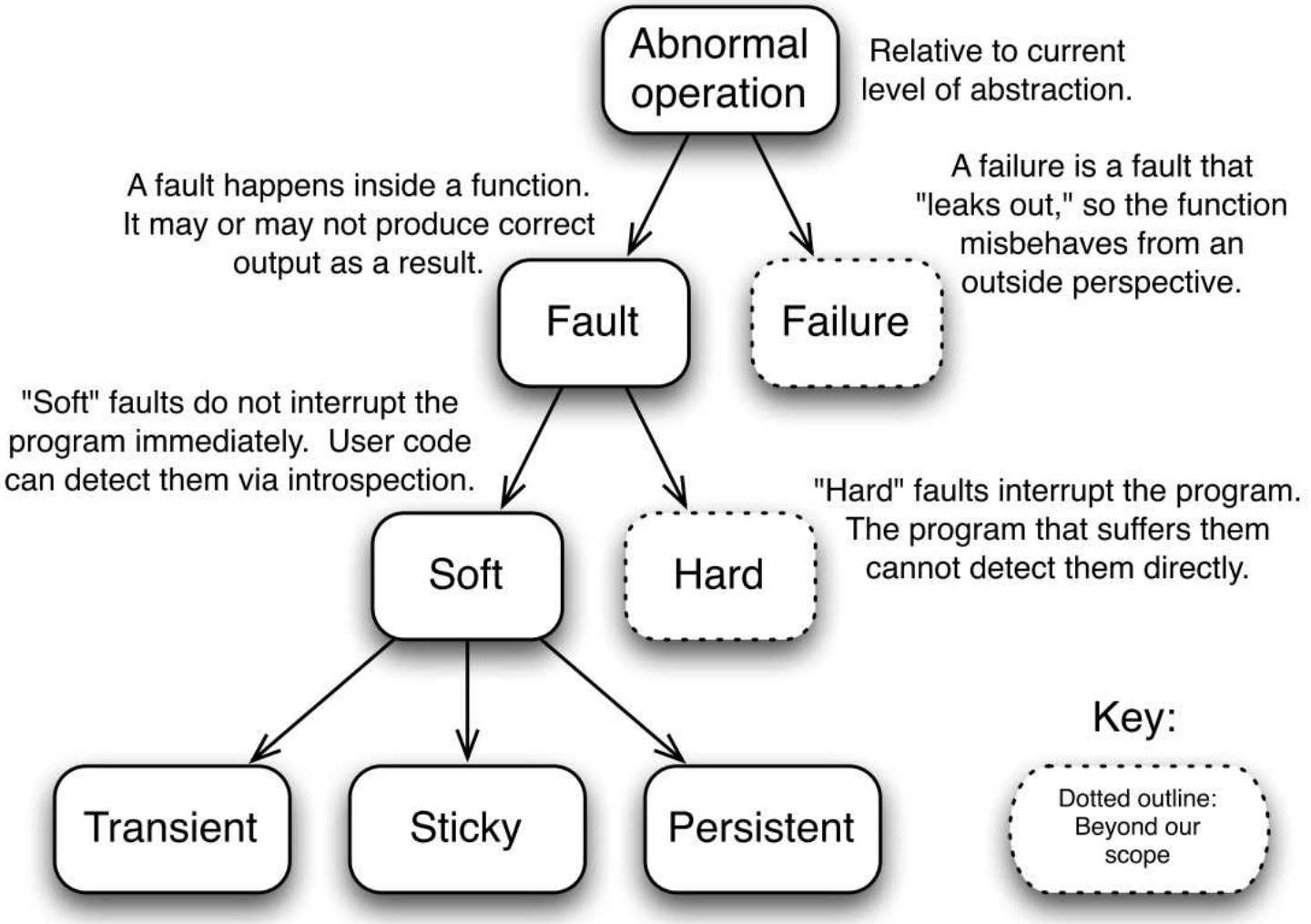
Soft or hard?

- **Hard** breaks "it," **Soft** lets "it" keep going
- What is "it"? Depends on your perspective!
- Hardware designer: "it" = **hardware**
  - "Hard" breaks the hardware permanently
  - "Soft" goes away, perhaps after reset
- Algorithm / application: "it" = **program**
  - "Hard" terminates the program ("crash")
  - "Soft" lets the program keep going
- "Keep going" says nothing about correctness

Transient, "sticky," or persistent?

- Persistently incorrect means broken hardware
  - e.g., Pentium FDIV bug work-around (2× slower)
- Sticky: stays incorrect for a while
  - Goes away after time or an action (e.g., refresh)
  - e.g., uncorrected DRAM / cache bit flips
  - If the original problem got corrupted:
    - Solver will solve $\tilde{A}x = b$, not $Ax = b$
    - Residual $\|b - \tilde{A}\tilde{x}\|$ small, but wrong $\tilde{x}$!
- Transient: happens once, goes away
  - Many existing "resilient" algorithms require transience
  - Transient fault becomes persistent if it corrupts an input
- Can make sticky faults "look transient" by:
  - Recomputing corrupted data (e.g., the matrix)
  - Restoring from a reliable backup

Fault terminology summary



Correct hardware costs performance or power

Correct computer hardware may go away

- The privilege to think of a computer as a *reliable*, *digital* machine for which
  - Arithmetic results are always correct
  - Data in storage always read correctly
- Future hardware may be *silently incorrect*
- Why? *Power & performance*
  - Smaller denser transistors
    - 14nm (Intel KNL) $\approx$ 30 Si atoms (lattice distance)
    - How do we make reliable atom-sized devices?
  - More parallel components (more things to fail)
  - Consumer applications drive hardware development
  - Extreme-scale parallelism is a niche market
  - Improving hardware reliability costs performance or power

Two strategies for handling faults in hardware

Redundancy to detect & correct faults

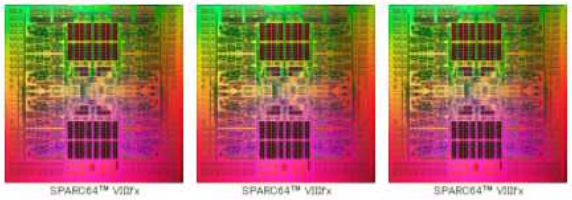


Image credits: Fujitsu, Wikipedia.

Robustness: Absorb fault-causing events

Real hardware combines both, with one of two goals:

- Lower performance, more robust
  - Exotic manufacturing (behind industry performance)
  - Hazardous environments (like outer space)
- Higher performance, higher power
  - Individual components may be less reliable
  - Choice of high-performance computing

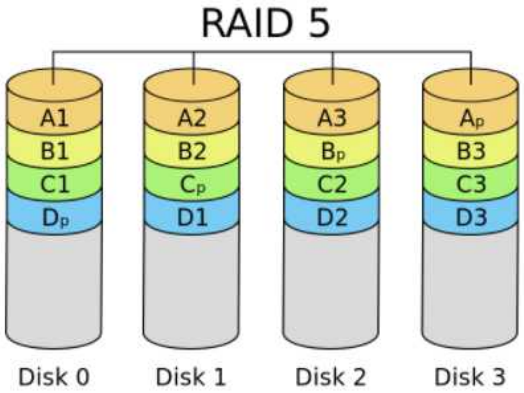
Historical note: Von Neumann and redundancy

- "Probabilistic logics and the synthesis of reliable organisms from unreliable components"
  - *Automata Studies*, 1956
- Sections 7–10
  - Even if each logic gate incorrect with probability ϵ,
  - Can use redundancy to build *arbitrarily* reliable computer
- Practical examples
  - "...a computing machine with 2500 vacuum tubes..."
  - "...a plausible quantitative picture for the functioning of the human nervous system"

John von Neumann (Image credit: Los Alamos Nat. Lab).

Redundancy costs power

- Redundant storage & computation (checksums)
  - ECC (error-correcting) memory
  - RAID (Redundant Arrays of Inexpensive Disks)
  - Software checksums (Algorithm-Based Fault Tolerance)
- Redundant hardware & communication (voting)
  - MPI process replication (in software)
  - Redundant arithmetic units (in hardware)
  - Run it several times ("time replication")



RAID 5 (Image credit: Wikipedia).

Power: hard constraint, decided initially

- Can I power & cool it?
- Often decided first
- For big computers: geography, facilities
- For mobile devices: shape, weight, anatomy
- 2x time / space replication means 2x energy / power

"[S]caling today's systems to an exaflop level would consume more than a gigawatt of power, roughly the output of the Hoover Dam" [1,2]

1. "The opportunities and challenges of exascale computing," Fall 2010, US DOE Office of Science.
2. Image credit: US Bureau of Reclamation.

How much do we need to worry?

- Less reliable hardware may come
- But might not come *soon*
- Vendors work very hard not to sell broken hardware
  - Bad marketing
  - FDIV: $475M recall
  - Legal liability?
- As transistors get *very* small, cosmic rays have *less* effect
- More uncertainty
  - End of CMOS & beyond
  - Vendor trade secrets

Is the sky falling?

How can algorithm developers cope?

- Given uncertainty, seek least invasive solution
  - Avoid asymptotically slower algorithms
  - Use familiar algorithmic ideas & pieces
  - Prefer changes that are always helpful
- Avoid committing to invasive programming models
  - Assume minimum help from system & hardware
  - But influence systems as much as possible
- Our two strategies
  - Skeptical programming
  - Selective reliability

Skeptical programming

Computer generated results need to be treated with some enlightened skepticism. No system or microprocessor can be expected to produce results which are absolutely reliable.

– Prof. Thomas R. Nicely (discovered Pentium FDIV bug)

- Model faults as incorrect intermediate results
- Distrust & check intermediate results, cheaply
- Detect "bad" faults & roll back
- "Converge through" all other faults if possible

Fault model: Incorrect intermediate results

- Any computational kernel could return the wrong answer
- *Not* random bit flips!
  - Binary number representation is not uniform
    - "Expected value" of a bit flip: huge / infinite
    - 52 / 64 bits of `double`: change $\leq 1/2$
  - Bit flips just change values; why flip bits?
  - We lack a good model for hardware faults
- Assumes transience
  - Read-only state external to function not corrupted
  - Can simulate transience by recomputing or rereading

Distrust & check intermediate results

- Numerical algorithms have natural nested structure
  - Iterative eigenvalue solve with shift and invert
    - Large sparse linear solve inside
    - LAPACK & BLAS calls inside that
  - Time-dependent partial differential equation
    - Nonlinear equation at each time step
    - Linear equation at each nonlinear iteration
- Why do you trust software written by humans?
- Can check solution to any equation $f(x) = 0$
- But don't take too long to check!

Selective reliability

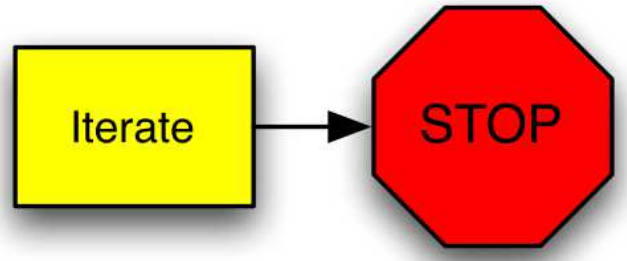
Reliability model lets us prove algorithms correct

- Reliability model: when & where faults may occur
- If faults can happen anywhere or anytime:
  - Can't prove algorithms correct
  - Can't even do time replication (esp. if faults "sticky")
- Analogy: rounding error in floating-point arithmetic
  - IEEE 754 & 854 provide invariants (e.g., exact rounding)
  - Invariants let me bound my algorithm's error
  - Language lets me control error (by declaring precision)
- Programmers cannot provide invariants themselves!
  - Just like IEEE 754, the hardware & system must help

"Floating-point code is just like any other code: it helps to have provable facts on which to depend" (David Goldberg).

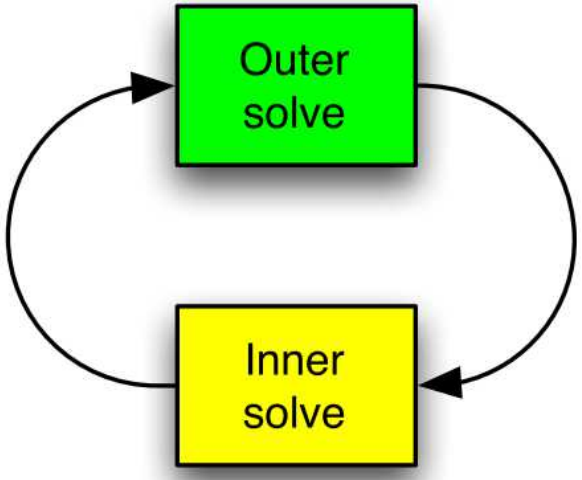
Reliability models

Current model: Fail-stop



- System tries to detect all soft faults
- Turn all detected soft faults into hard faults
- Detected local faults become global
- Checkpoint / restart is the only recovery model

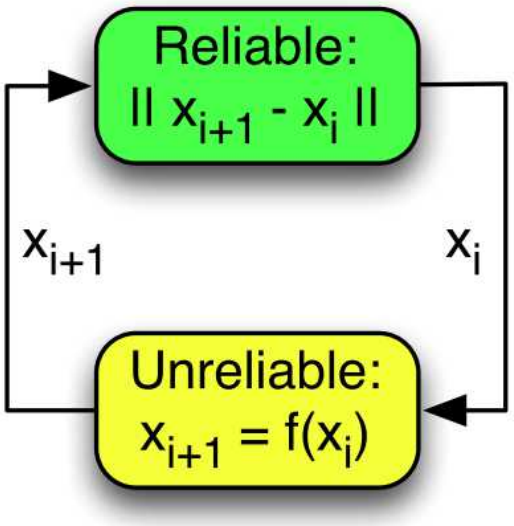
Better model: Sandbox



- Isolate unreliable data & computation in a box
- Reliable code invokes box
- Local faults stay local
- App gets flexibility to define recovery model

Example: Sandbox model for fixed-point iteration

- Solve $f(x) = x$: iterate $x_{i+1} = f(x_i)$ until $\|x_{i+1} - x_i\| < \epsilon$
- If faults can happen anywhere, can't trust convergence test
- Protect convergence test & put f evaluation in sandbox
  - If convergence test passes, we know x_{i+1} is correct
  - If enough iterations pass without a fault, we will converge
  - If f time-consuming, then most time in unreliable mode
- This generalizes to nearly any iterative algorithm!



Improvements on sandbox model

- Detection: report faults to application
  - Detection often cheaper than correction
  - Hardware (e.g., DRAM) can already do this
  - Operating system doesn't expose this (yet)
- Transience: make faults not "stick"
  - Sticky faults more harmful to algorithms
  - Example: $\|b - Ax_k\|_2$ when A is wrong
  - Refresh or recompute unreliable data periodically
  - Algorithm must expose what data need refreshing
- None necessary; all useful
  - Detection allows approximate correction (see later).

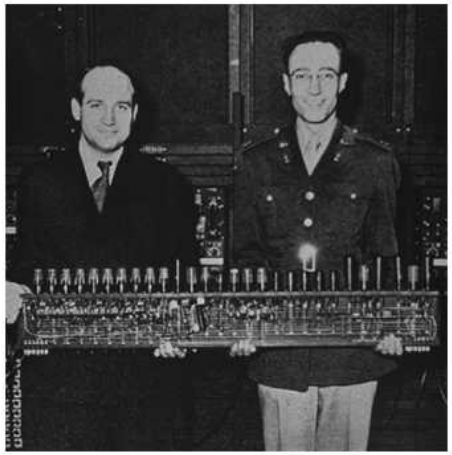
Algorithms

Rounding error analysis gives us hope

Example: Gaussian elimination

- Pessimistic worst-case theory (Hotelling 1943)
- Yet tolerates rounding errors in both theory and practice
- They succeeded for rounding error; hardware faults?

James H. Wilkinson



John von Neumann & Herman Goldstine

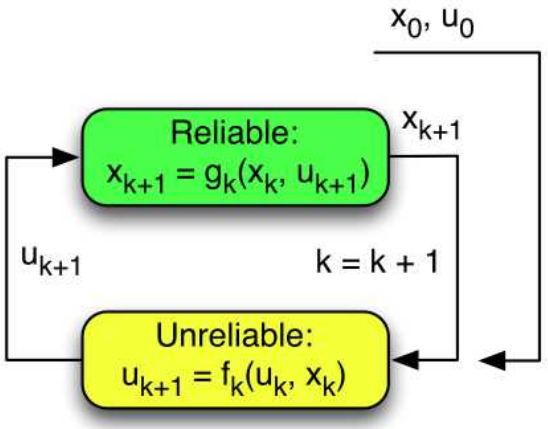
Alan Turing

Desired properties of a fault-tolerant iteration

- Exploit reliability model for predictable behavior
- Converge eventually, or detect & indicate failure
  - Not true of iterative refinement!
- Convergence degrades gradually as fault rate increases
  - Easy to trade between reliability and extra work
- Require as little reliable computation as possible
- Avoid global communication / synchronization
  - If faults are local, recover locally
  - Recover locally first, even if approximate
  - Defer exact, possibly global recovery

How can we guarantee convergence?

A more generic iteration for solving some equation $g(x) = x$:



- x_k is current approximate solution; u_k is auxiliary
- Initial guesses x_0, u_0
- for k in $0, 1, 2, \ldots$:
  - $u_{k+1} = f_k(u_k, x_k)$
  - $x_{k+1} = g_k(x_k, u_{k+1})$

- f_k may experience faults; g_k may not
- g_k must converge eventually, for any sequence of f_k, or clearly detect if it can't converge
- Monotonic convergence would help gradual degradation

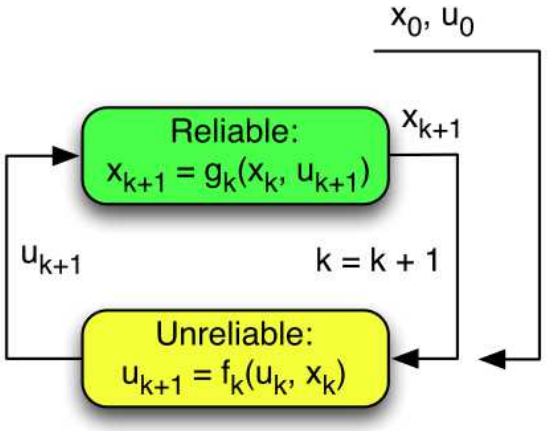
Brief review of iterative linear solvers

- Solve linear system $Ax = b$
  - Gaussian elimination not feasible / too expensive
  - Can compute matrix-vector products $v = Au$
  - Have M ("preconditioner") with $AM \approx I$

1. Pick initial guess x_0, compute $r_0 = b - Ax_0$
2. x_k is x_0 plus linear combination of $(AM)^k r_0$
3. Compute search directions via matrix-vector products
4. Repeat until norm of $r_k = b - Ax_k$ is small

How does this map to solving $Ax = b$?

Imagine generic iteration as an iterative solver for $Ax = b$:



- for k in $0, 1, 2, \ldots$:
  - $u_{k+1} = f_k(u_k, x_k)$
  - $x_{k+1} = g_k(x_k, u_{k+1})$

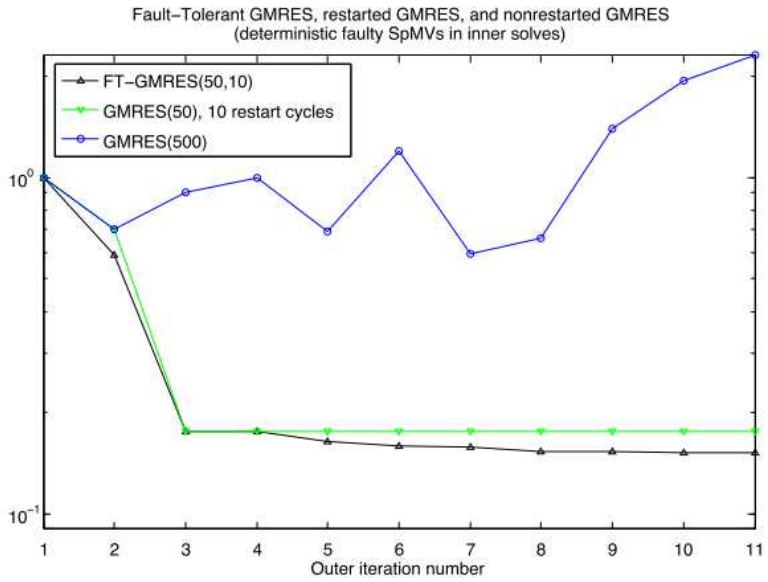
- f_k: apply the preconditioner
  - May be different each k, perhaps because of faults
- $\Rightarrow$ Need a "flexible" method
- Monotonic convergence $\Rightarrow$ (Flexible) GMRES

Fault-Tolerant GMRES

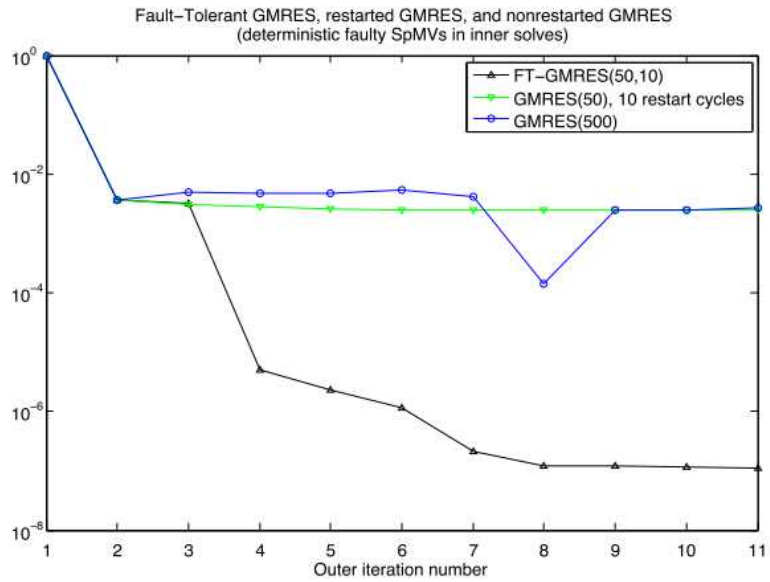
- "Outer solver" g_k is Flexible GMRES, run reliably
  - Converges eventually (or tells you otherwise)
    - Detect failure cheaply and locally
    - ($O(k^2)$ arithmetic operations at iteration k)
    - Same failure condition as without faults
  - Flexible: Allows arbitrary preconditioner changes
    - Any bit in floating-point word may flip
    - Fault = "changing" preconditioner
- "Inner solver" f_k: your current solver & preconditioner
  - Should take most of the time
  - Preconditions the outer solver
- Can reuse existing software stack for inner solver

FT-GMRES can run through faults

- FT-GMRES can run through faults and still converge.
- Standard GMRES, with or without restarting, cannot.



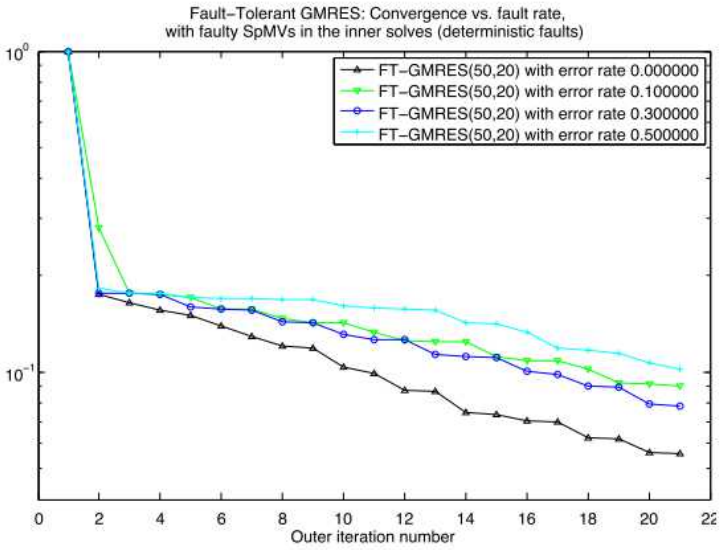
FT-GMRES vs. GMRES on Ill_Stokes (an ill-conditioned discretization of a Stokes PDE).



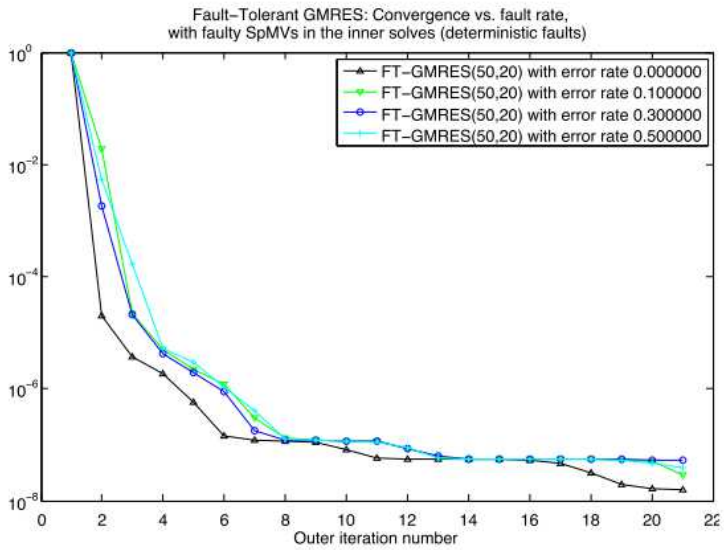
FT-GMRES vs. GMRES on mult_dcop_03 (a Xyce circuit simulation problem).

Observed gradual degradation of convergence

- Empirical observation: FT-GMRES convergence slows gradually as fault rate increases.
- FT-GMRES only; vary fault rate in inner solves' $A \cdot x$.



Ill_Stokes problem.



mult_dcop_03 problem.

Future work

Future work

- Do we even need to worry about linear solves?
  - Linear $\rightarrow$ nonlinear $\rightarrow$ ODE $\rightarrow$ optimization $\rightarrow$ UQ
  - Some levels robust to incorrect results at lower levels
  - Do we expect a fault in several of the linear solves?
- Comparing cost of different resilience approaches
  - Would it have been cheaper just to start over?
  - Should I let the level above (or below) me handle faults?
  - Checkpointing every 5 CG iterations is ridiculous
- What about discrete problems?
  - Easy checks (e.g., did sorting work?) help if faults rare
  - Relax into continuous optimization problem?
  - Learn to tolerate approximate results?

Conclusions

- Algorithms can prepare for incorrect hardware right now
- This also protects them against incorrect software
- Promising correctness requires a fault model
- Extreme-scale computing cannot succeed without codesign
- Lots of problems left to solve
  - Algorithms: nonlinear, preconditioners, ...
  - Programming models and system support
- Algorithm developers must talk to systems researchers

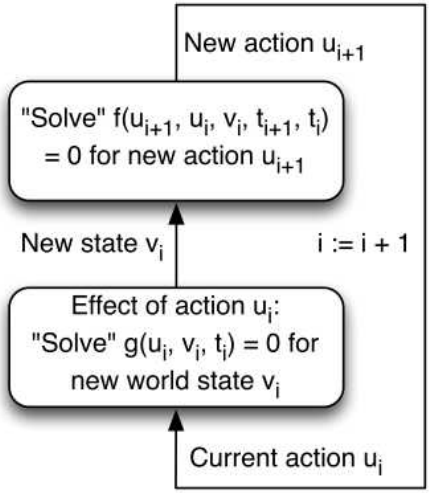
Thanks for listening!

Bill Gates at COMDEX on 20 April 1998.

Extra slides

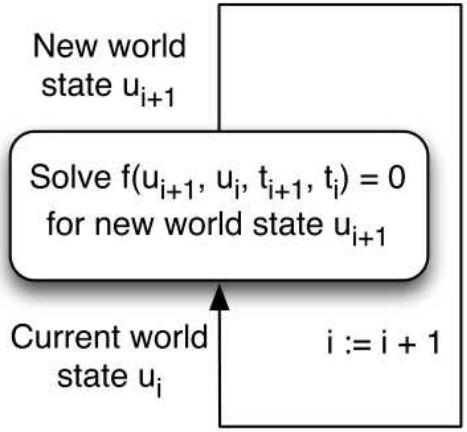
Real-time control system vs. PDE discretization

Real-time control system



The world always computes physical laws correctly. Negative feedback may reduce effect of $f(\dots) = 0$ errors.

Time-dependent PDE discretization



No physical feedback. $f(\dots) = 0$ solve must be correct or mistakes will accumulate.

Detect bad errors and roll back

- We define "bad" errors by their cost
  - Cause solver to fail completely
  - Increase iteration count by too much
- We may not be able to catch all bad errors
- Roll back: Prefer transactional semantics
  - Don't need fancy transactional memory
  - Write code so it has no side effects if it fails
  - C++ calls this the *strong exception guarantee*
  - "[N]ever let go of a piece of information before we can store its replacement" (Stroustrup)