Computational Science of Computer Systems

Méthodologies d'expérimentation pour l'informatique distribuée à large échelle

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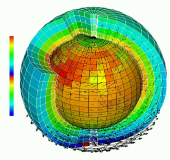
(with the SimGrid Team and others)

October 16th 2014
Mons

What is Science anyway?

Doing Science = Acquiring Knowledge

$$\frac{\partial}{\partial x_j}\left(\frac{\partial \Phi}{\partial x_i}\right) = \frac{\partial}{\partial x_i}\left(\frac{\partial \Phi}{\partial x_j}\right)$$



Experimental Science

- Thousand years ago
- Observations-based
- Can describe
- Prediction tedious

Theoretical Science

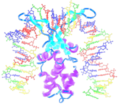
- Last few centuries
- Equations-based
- Can understand
- Prediction long

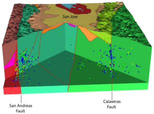
Computational Science

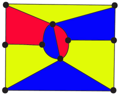
- Nowadays
- Compute-intensive
- Can simulate
- Prediction easier

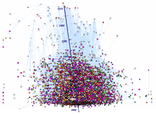
Prediction is very difficult, especially about the future. – Niels Bohr

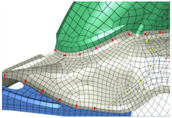
Computational Science

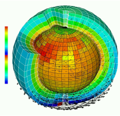




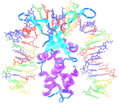


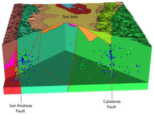


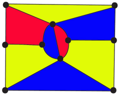


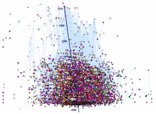


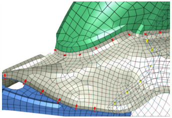
Computational Science

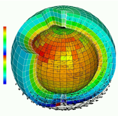




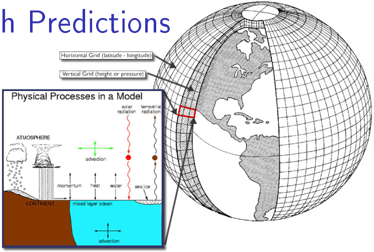




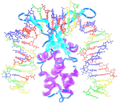
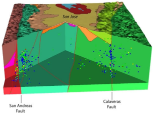


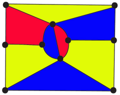
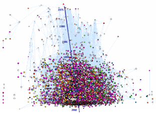
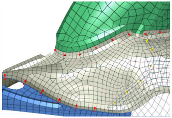
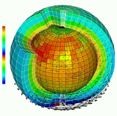


Understanding the Climate Change with Predictions



Computational Science

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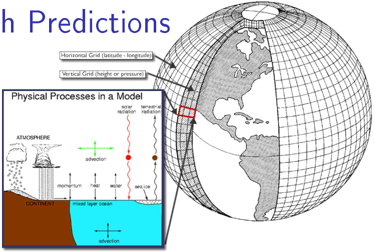
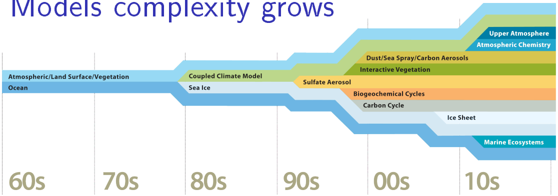


Models complexity grows



this requires
large computers

Modern Computers are Large and Complex

Massive Parallelism

- Cannot miniaturize further (atom limit)
- Cannot increase frequency (energy limit)
- Solution: Multiply compute cores!
- Sequoia, third fastest computer: 1,572,864 cores

ExaScale Systems, used in Computational Science

- Systems doing one Exaflop per second by the end of the decade
- 1 Exaflop = 10^{18} operations. One million million million operations...
  At humanly doable speed, that requires 10 times the age of the universe
- Each node: 20 millions lines of code (10$\times$ Encyclopedia Britannica)

Other very large computer systems in the wide

- Google computers dissipate 300MW on average (150,000 households, $\frac{1}{3}$ reactor)
- Botnets: BredoLab estimated to control 30 millions of zombie computers
- In addition, these systems are heterogeneous and dynamic

So, how do we *study* these beasts?

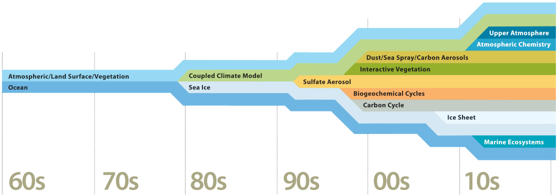
Computational Science of Computer Systems

My Research Field: Methodologies of Experimentation

- Goal: assess the performance and correctness of large-scale computer systems
- Question: Are we really producing scientifically sound results?
- Main contribution: SimGrid, a simulator of large-scale computer system

My approach: I am a physicist

- Empirically consider large-scale computer systems as natural objects
- Eminently artificial artifacts, but complexity reaches "natural" levels
- Other sciences routinely use computers to understand complex systems



Assessing Distributed Applications

Performance Study $\rightsquigarrow$ Experimentation

- Maths: Often not sufficient to fully understand these systems

Correctness Study $\rightsquigarrow$ Formal Methods

- Tests: Unable to provide definitive answers

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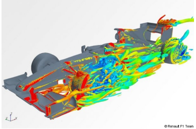


By L. Nussbaum

- Experimental Facilities: Real applications on Real platform *(in vivo)*
- Emulation: Real applications on Synthetic platforms *(in vitro)*
- Simulation: Prototypes of applications on system's Models *(in silico)*

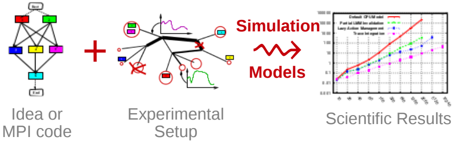
Correctness Study ⇝ Formal Methods

- Tests: Unable to provide definitive answers
- Model-Checking: Exhaustive and automated exploration of state space

Simulating Distributed Systems

Simulation: Fastest Path from Idea to Data

- Get preliminary results from partial implementations
- Experimental campaign with thousands of runs within the week
- Test your scientific idea, don't fiddle with technical subtleties (yet)



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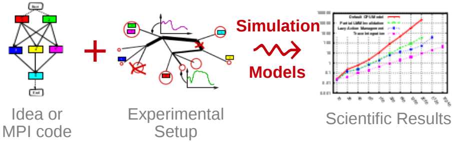
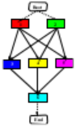


Simulation: Easiest Way to Study Distributed Applications

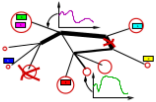
- Everything is actually centralized: Partially mock parts of your protocol
- No heisenbug: (Simulated) time does not change when you capture more data
- Clairevoyance: Observe every bits of your application and platform
- High Reproducibility: No or very few variability
- Capacity planning: Can we save on component? *What if* network were faster
- Don't waste resources to debug and test (up to 50% on some production infra)

Simulation Challenges



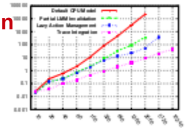
Idea or
MPI code

+

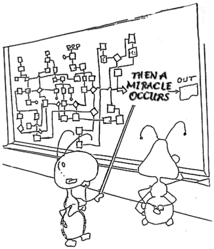


Experimental
Setup

Simulation
⇝
Models



Scientific Results



Challenges for the Tool Makers

- Validity: Get realistic results (controlled experimental bias). That's hard.
- Scalability: *Fast enough* and *Big enough*
- Tooling: runner, post-processing, integrated lab notes

Major Components of any Simulation-based Experiment

- An observation of your application: either a trace, prototype or live application
- A configuration describing the experimental settings
- Models of your platform: CPU, Network, Disk, any other relevant resource

SimGrid: Versatile Simulator of Distributed Apps

Scientific Instrument

- Versatile: Grid, P2P, IaaS Clouds, HPC, Volunteer Computing and others
- Sound: Validated, Scalable, Usable; Modular; Portable
- Ready to use: Integrated to Debian/Ubuntu, self-contained Jar, win installer

Scientific Object

- Allows comparison of network models on non-trivial applications
- High-Performance Simulation on realistic workload
- Full model checker of distributed applications; Emulator under way

Open Project with a Large Community

- Community-driven: 30 contributors (5 not affiliated), 5 contributed tools, GPL
- Impact: 120 publications (110 distinct authors, 5 continents), 4 PhD
- Started in 1998 at UCSD; Now collab accross many individuals and institutions
- 7 partners, 20+ researchers (CNRS, Universities, Inria)
- Public funding (≈ 3M€ ANR/Inria); Community based (User days, hackfests)

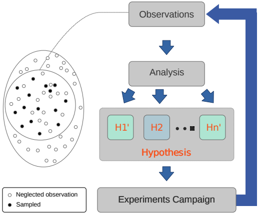
Simulation Validity

SotA: Models in most simulators are either simplistic, wrong or not assessed

- PeerSim: discrete time, application as automaton;
- GridSim/CloudSim: naive packet level or buggy flow sharing
- OptorSim, GroudSim: documented as wrong on heterogeneous platforms
- Dimemas: aim at performance trends and bottleneck identification

SimGrid: 10-years effort on validity

- Same methodology than physicist: try to (in)validat our models
- Observe, analyze, hypothesis, test

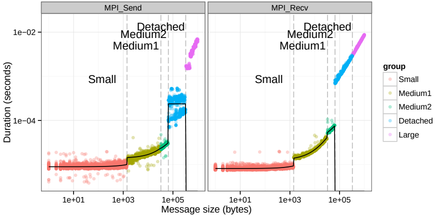


SimGrid provides several Network Models

- Flow-based: Contention, Slow-start, TCP congestion, Cross-traffic effects
- Constant time: A bit faster, but no hope of realism
- Coordinate-based: Easier to instantiate in P2P scenarios
- Packet-level: NS3 bindings

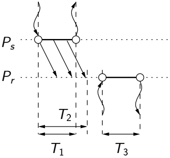
SimGrid Network Model

Measurements

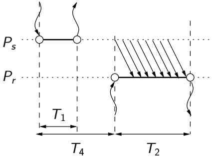


Model hybridizing LogP...

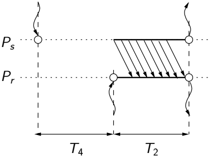
Asynchronous ($k \leqslant S_a$)



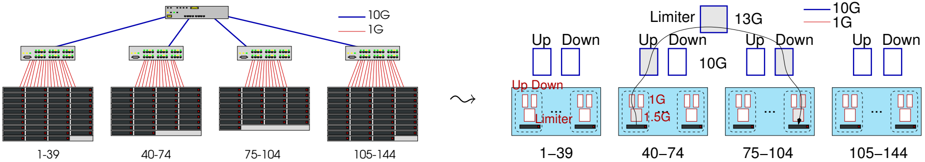
Detached ($S_a < k \leqslant S_d$)



Synchronous ($k > S_d$)



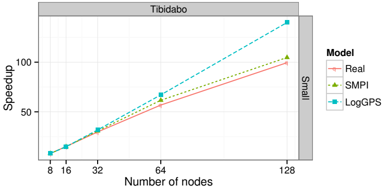
...and Fluid model: account for contention and network topology



SimGrid Validity Limits

Sometimes, it work rather well

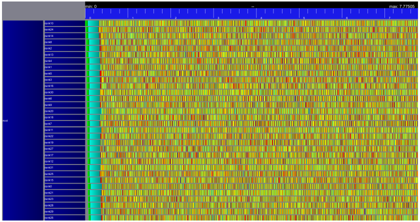
App: BigDFT (physics)
Host: Tibidabo (ARM + Ethernet 10G)

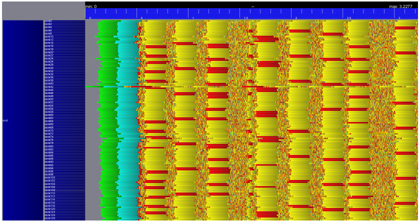


Sometimes, Simulation sucks

- Model limits, Bad instanciation, Applicative model faulty

Sometimes, Reality sucks





- NAS PB benchmark. Left: simulation; Right real execution
- Discrepancy: Reality experiences timeouts that are probably due to TCP RTO

Agenda

- Introduction
- Modern Large Computing Facilities
- Computational Science of Computer Systems (CS^2)
- Simulation Models
- Dynamic Verification of Distributed Applications
- Conclusion

Assessing the Correctness of HPC codes?

Writing Distributed Apps is notoriously difficult, but:

The Good Old Days

- MPI codes circumvented the difficulty with rigid communication patterns

- Correctness established through testing
- Only performance matters anyway:
  - Most prefer a fast code that rarely fail-stop to a slow code that always work
  - (at least, that's my feeling for most of the numerical applications)

These Days are Now Over

- But rigid patterns do not scale! We now have to release the grip
- But this is dangerous! We now have to explicitly seek for correctness

Slowly, old ignored problems resurface. . .

Model Checking and Dynamic Verification

These are Automated Formal Methods

- Try to assess the correctness of a system by actively searching for faults
- If you find a fault, then you have something to work on
- If don't find any after an exhaustive search, correctness experimentally proved
- Dynamic Verification: Model Checking applied to real applications

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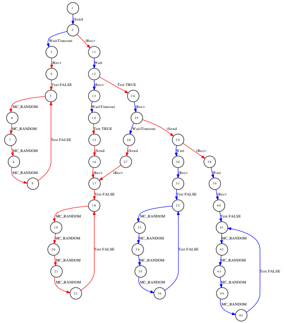
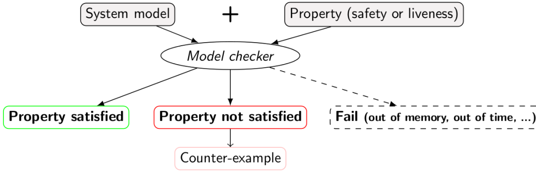
Exhaustive Exploration



Model Checking: the Big Idea



- My preferred outcome: a counter-example
  If not, I fear my property to be wrongly expressed
- We tend to bug finding, not certification

Formal Properties

Safety Properties

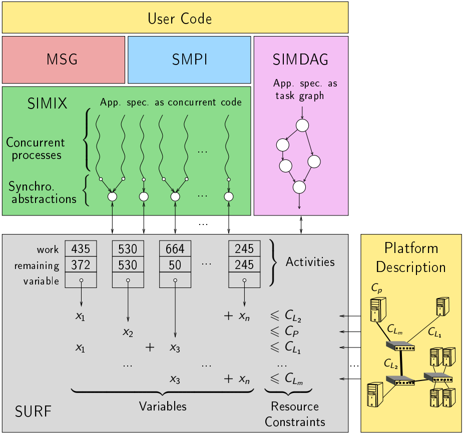
- "A given bad behavior never occurs"
- Can be expressed as boolean (assertion): no deadlock, $x \neq 0$, ...
- Work on all states separately
- Counter example: a faulty state

Liveness Properties

- "An expected behavior will happen in all cases"
- Example: Any process that asks a resource will obtain it eventually
- Must be expressed in a temporal logic such as CTL (safety ones *could* too)
- Work on execution path
- Counter example: an infinite path (ie, a cycle) that violates the property

Liveness properties are much more challenging to verify in practice

SimGrid and SMPI

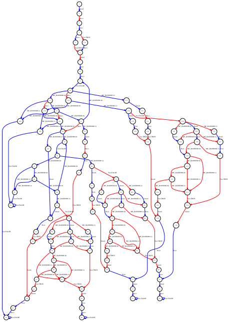


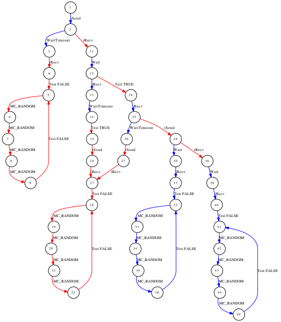
- SMPI can run complex C/C++/Fortran applications on top of SimGrid
- Let's leverage this unconventional virtualization layer for verification!
- + collective code scavenging $\rightsquigarrow$ verify even runtime's collectives

SimGridMC: Formal Methods in SimGrid

Verify any application that would run in SimGrid

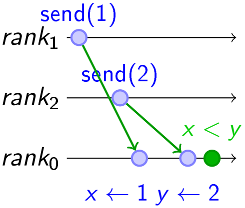
- Replace the simulation kernel underneath with a model checker
- Tests all causally possible orders of events to dynamically verify the app
- Reuse the mediation mechanism that base the simulator
- System-level checkpoints the app to then rewind and explore another path
- Works with SMPI, and MSG (our simple API for the study of CSP algorithms)



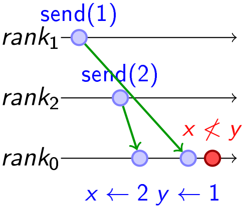


Example: Out of order receive

- Two processes send a message to a third one
- The receiver expects the message to be in order
- This may happen. . . or not




```
if (MPI_rank() == 0) {
  MPI_Recv(&x , MPI_ANY_SOURCE);
  MPI_Recv(&y , MPI_ANY_SOURCE);
  MC_assert(x < y);
} else {
  MPI_Send (&rank , 0);
}
```




```
*************************
*** PROPERTY NOT VALID ***
*************************
Counter-example execution trace:
[(1)recver] iRecv (dst=recver, buff=(verbose only), size=(verbose only))
[(3)sender] iSend (src=sender, buff=(verbose only), size=(verbose only))
[(1)recver] Wait (comm=(verbose only) [(3)sender -> (1)recver])
[(1)recver] iRecv (dst=recver, buff=(verbose only), size=(verbose only))
[(2)sender] iSend (src=sender, buff=(verbose only), size=(verbose only))
[(1)recver] Wait (comm=(verbose only) [(2)sender -> (1)recver])
```

Mitigating the State Space Explosion

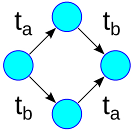
Many execution paths are redundant $\rightsquigarrow$ cut exploration when possible

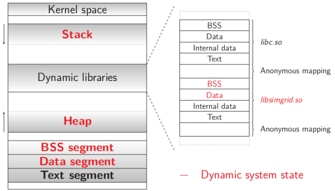
Dynamic Partial Ordering Reduction (DPOR)

- Works on histories: test only one transitions' interleaving if independent
- *Independence theorems:* Local events are independent; iSend+iRecv also; ...
- Must be conservative (exploration soundness at risk!)
- It works well (for safety properties)

System-Level State Equality

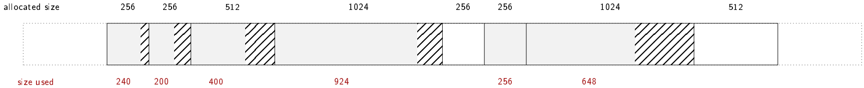
- Works on states: detect when a given space was previously explored
- Complementary to DPOR (but not compatible yet)
- Introspect the C/C++/Fortran app just like `gdb` (+some black magic)





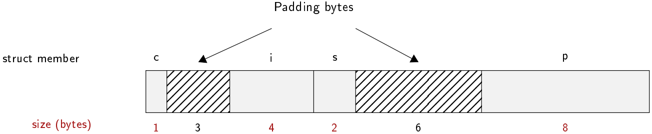
OS-level Challenges of State Equality Detection

- Memory over-provisioning

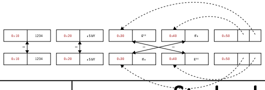


- Padding bytes: Data structure alignment

```
struct foo {
char c;
int i;
short s;
void *p;
}
```



- Irrelevant differences: system-level PID, fd, . . .
- Syntactic differences / semantic equalities:



Solutions

Issue	Heap solution	Stack solution
Overprovisioning	memset 0 (customized `mmalloc`)	Stack pointer detection
Padding bytes	memset 0 (customized `mmalloc`)	DWARF + libunwind
Irrelevant differences	Ignore explicit areas	DWARF + libunwind + ignore
Syntactic differences	Heuristic for semantic comparison	N/A (sequential access)

Some Results

Wild safety bug in our Chord implementation (≈ 500 lines of C)

- Simulation: bug on large instances only; MC finds small trace (1s with DPOR)

Mocked liveness bug

- Buggy centralized mutual exclusion: last client never obtains the CS
- About 100 lines – state snapshot size: 5Mib
- Verified with up to 7 processes (12,000 states, 9 minutes, 45Gb).

Verifying MPICH3 complience tests

- Looking for assertion failures, deadlocks and non-progressive cycles
- 6 tests; ≈ 1300 LOCs (per test) – State snapshot size: ≈ 4MB
- With no reduction: no test concluded in a few hours
- With state equality: Exhaustive exploration up to 10 procs, but no error found
- With memory compaction: use only dozen of Gb in RAM, not hundreds
- We verified several MPI2 collectives too ☺ (but all good so far ☹)

Verification of Protocol-wide Properties

Motivation

- Clever checkpoint algorithms exist, provided that the application is nice enough
- *On communication determinism in parallel HPC applications*, F. Cappello, A. Guermouche and M. Snir (2010)
  - Manual inspection of 27 HPC applications, seeking for such properties

Protocol-wide properties

- deterministic: On each node, send and receive events are always in same order
- send deterministic: $\forall$ node, send are always the same, no matter the recv order
- Not liveness, not even LTL: quantifies for all execution paths within property

Status report: we can verify such properties in SimGrid

- Explore one path to learn the communication order, deduce the property
- Enforce that this order holds on all other execution path
- We reproduced the conclusions of previous paper on several benchmarks
  - All good ☹

More on Formal Verification

We've built a really cool tool

- We can verify many unmodified MPI applications (C/C++/Fortran)
- State space reduction: DPOR or State equality (not together yet)
- Properties: safety, liveness or protocol-wide

Many remaining Research Leads

- Other reductions, HPC-specific properties, statistical model-checking, . . .
- Interactive tool to get gdb-like info on each state in the execution graph

We need more use cases

- We are done with all the ones provided by the practitioners we know
- We could make it even better with really relevant use cases
- We don't know what properties are relevant

Agenda

- Introduction
- Modern Large Computing Facilities
- Computational Science of Computer Systems (CS^2)
- Simulation Models
- Dynamic Verification of Distributed Applications
- Conclusion

Much more to say about SimGrid (too little time)

Hybrid Network Models

- Fluid model: model contention in steady state for large messages
- LogOP model: model intra-node delays and synchronization
- Also: MPI collectives, TCP (slow-start, cross-traffic), soon IB

Realistic Emulation

- SMPI: Study real MPI applications within SimGrid
- Simterpose: Study real arbitrary applications (ongoing)

High Performance Simulation

- Fast Enough: Innovative PDES; Efficient algorithms and implementations
- Big Enough: Scalable and versatile platform representation

Formal Verification of Distributed Apps

- Safety, Liveness or CTL properties, with DPOR or state equality

Take Away Messages

SimGrid will prove helpful to your research

- Versatile: Used in several communities (scheduling, GridRPC, HPC, P2P, Clouds)
- Accurate: Model limits known thanks to validation studies
- Sound: Easy to use, extensible, fast to execute, scalable to death, well tested
- Open: User-community much larger than contributors group; AGPL
- Around since over 10 years, and ready for at least 10 more years

Welcome to the Age of (Sound) Computational Science

SIMGRID

- Discover: `http://simgrid.gforge.inria.fr/`
- Learn: 101 tutorials, user manuals and examples
- Join: user mailing list, #simgrid on irc.debian.org
  We even have some open positions ;)

`apt-get install simgrid` now! (or get the jarfile)