Privacy and Reliability in an Untrusted Cloud

A private and secure cloud

Distributing computation onto untrusted machines.

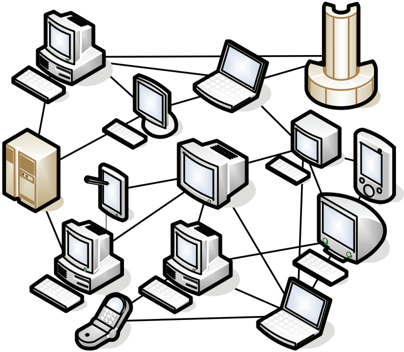
Today's focus on privacy: sTile

sTile

A technique for privately solving computationally-intensive problems (3-SAT) on untrusted computers.

Our approach: intelligent distribution

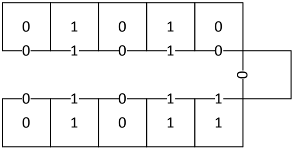
Obstacle: Private computation is hard and inefficient [Childs 2005; Gentry 2009].



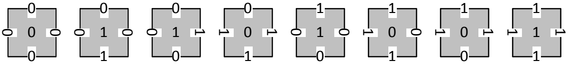
Solution:
1. Divide computation into elemental subcomputations.
2. Distribute subcomputations onto network.

Computing with tiles

Input:



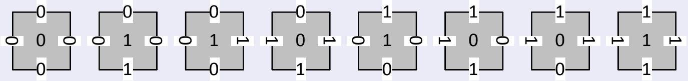
Program:



Computation: Copies of the program tiles self-attach to the input.

Addition with tiles

adding program



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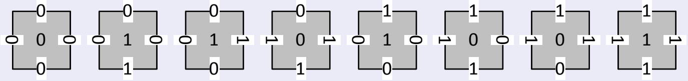
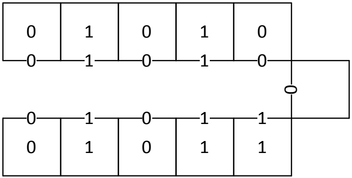


Encode input to add 10 $(= 1010_2)$ and 11 $(= 1011_2)$



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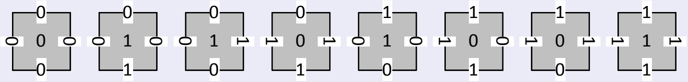
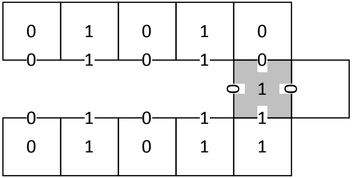


Add the two least significant bits



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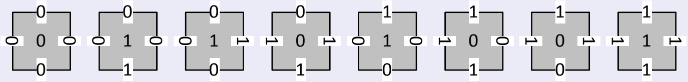
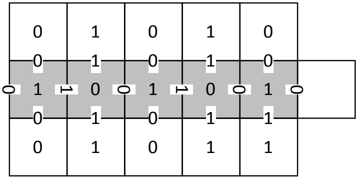


Add the rest of the bits, one at a time: $10 + 11 = 21 (= 10101_2)$



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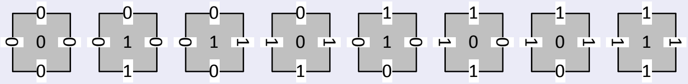
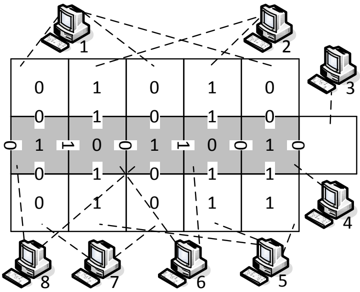


Suppose computers deployed tiles



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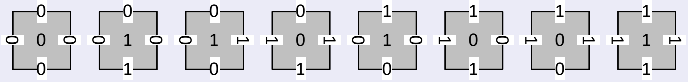
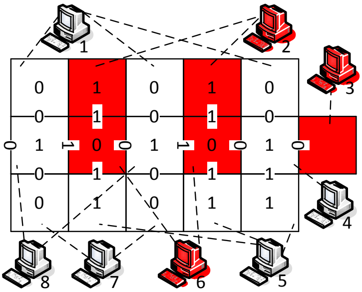
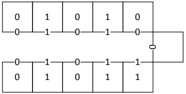


Even if some were compromised, they couldn't learn private data

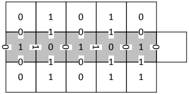


3-SAT with tiles [Winfree 1998]

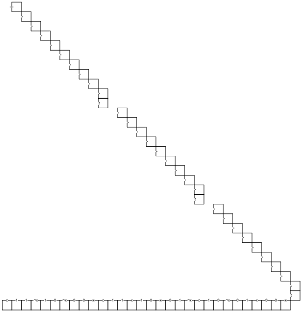
Addition [TCS'07]



→



3-SAT [Nat.Comp.'12]



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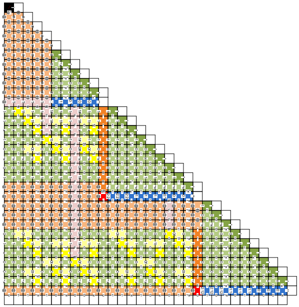
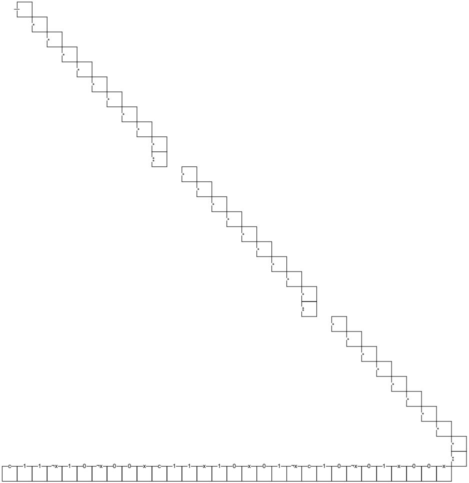


sTile intuition: computers simulate tiles

1. set up the 3-SAT seed



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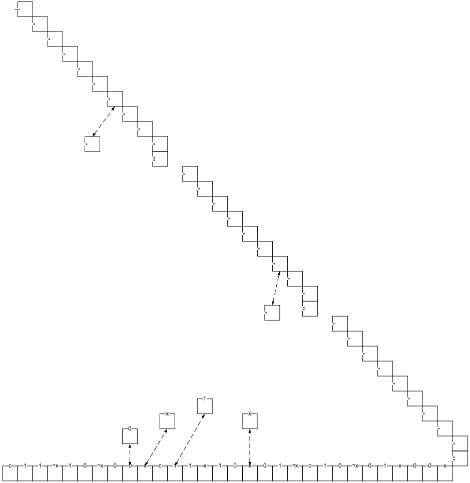
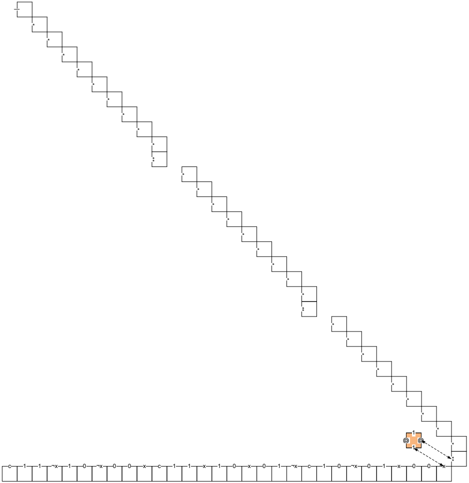
2. the seed self-replicates



discovery algorithm

sTile intuition: computers simulate tiles

3 tiles recruit neighbors



secure multi-party computation [Yao 1986]

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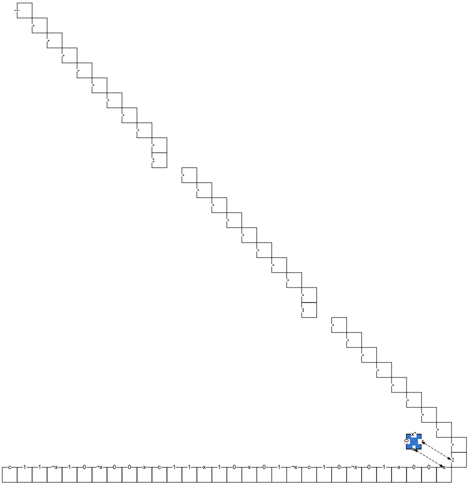

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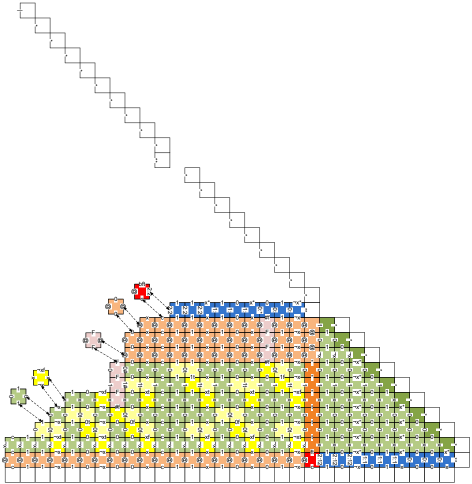

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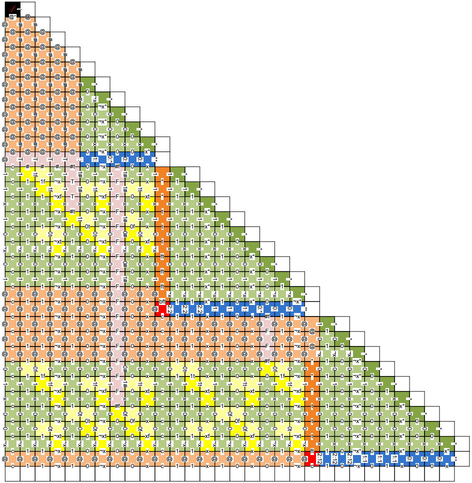
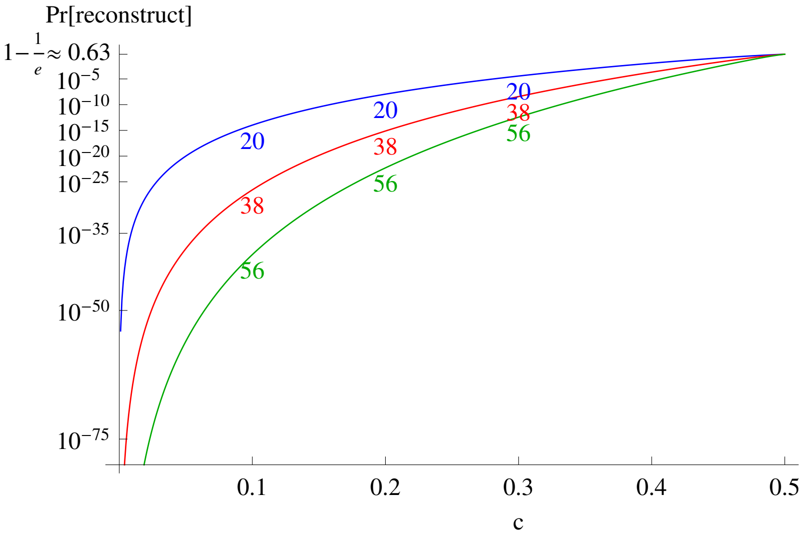
4. report solution to the client



Evaluation plan

- Formally prove privacy
- Empirically demonstrate robustness to network delay
- Empirically demonstrate scalability

Probability of reconstructing a 20-, 38-, and 56-bit input



sTile provides highly-probable privacy

Threat model:

A Byzantine fraction of the cloud attempts to reconstruct private data.

sTile guarantee:

$$\boxed{P_{\text{compromise}}(c, n, s) = 1 - (1 - c^n)^s}$$

c — compromised fraction n — bits in input s — number of seeds

TeraGrid example

Controlling $\frac{1}{8}$ of TeraGrid's 100,000 machines yields a probability of 10^{-10} of data compromise of a 17-variable formula.

Experimental Setup

- Mahjong: sTile implementation framework
  - Java, 3K LoC, builds on Prism-MW [Malek et al. 2005]
  - Input: NP-c problem instance P
  - Output: Distributed software system to solve P
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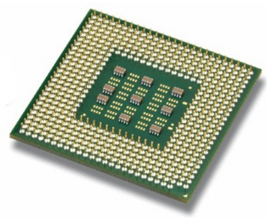
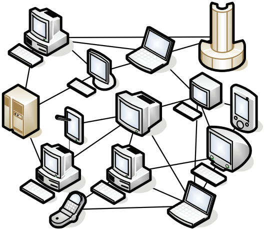
- Networks
    - 11-node private cluster (P4 1.5GHz, 512MiB, WinXP/2000)
    - 186-node USC HPCC cluster [High Performance Computing and Communications] (P4 Xeon 3GHz, Linux)
    - 100-node PlanetLab [Peterson et al. 2003] (global, varying speeds and resources)

Network Delay



vs.



Communication is ∼100–1000 times faster in a CPU than on a network.

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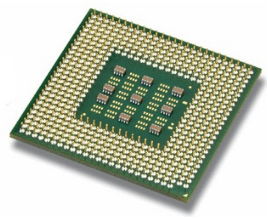

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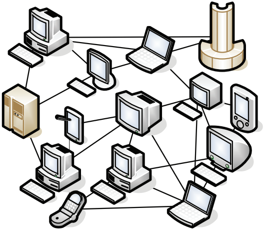

Communication is ∼100–1000 times faster in a CPU than on a network.

But latency is not throughput!

Robustness to Network Delay

Problem	# of Nodes	Network Delay	Execution Time
Mahjong			
$\mathfrak{A}$	11	Private Cluster	20.1 sec.
		HPCC	19.3 sec.
		PlanetLab	18.5 sec.
$\mathfrak{B}$	11	Private Cluster	41.6 min.
		HPCC	41.2 min.
		PlanetLab	43.9 min.
Simjong			
$\mathfrak{D}$	1,000,000	0ms	65 min.
		10ms	57 min.
		100ms	64 min.
		500ms	60 min.
		Gaussian	68 min.
		Distance-based	59 min.

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Network latency does not affect system throughput

Scalability: Speed $\propto$ Network Size

Network & Problem	# of Nodes	Execution Time	Speed-up Ratio
Private Cluster	5	43 sec.	
$\mathfrak{A}$	10	23 sec.	1.9
HPCC	93	220 min.	
$\mathfrak{C}$	186	116 min.	1.9
PlanetLab	50	9.2 min.	
$\mathfrak{B}$	100	4.8 min.	1.9
Simjong	125,000	8.7 hours	
	250,000	4.5 hours	1.9
$\mathfrak{D}$	500,000	2.1 hours	2.1
	1,000,000	64 min.	2.0

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System speed scales almost linearly with network size

Related Work

- Private computation in quantum computing through entanglement [Childs 2005]
- Homomorphic encryption for private computation [Gentry 2009]
- Plethora of non-private distributed computation work [BOINC 2009; Korpela et al. 1996; Larson et al. 2002; Rosetta@home; Dean and Ghemawat 2004; Chakravarti and Baumgartner 2004]
- . . . and fault-tolerant computation work [Sarmenta 2002; Bondavalli et al. 1993, 2002; Felber and Schiper 2001; Koren and Krishna 2007; Hwang and Kesselman 2003]
- . . . and private storage and access [Ateniese et al. 2006; Wang et al. 2011; Yang et al. 2011; Yu et al. 2010]

Contributions

sTile

- Distribution can result in privacy
- A bound on the cost of privacy

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For more, see "Entrusting Private Computation and Data to Untrusted Networks" by Y. Brun and N. Medvidovic. In IEEE Transactions on Dependable and Secure Computing (TDSC), 10(4):225–238, 2013. `http://dx.doi.org/10.1109/TDSC.2013.13`

How do I compute a function using Byzantine machines?

How do I send you a message over a noisy channel?

Environment model

A pool of network nodes

- some nodes are Byzantine
- Byzantine node identity and rate are unknown
- nodes may join, leave, fail, and become reliable

Smart redundancy: maximize task reliability for a given resource cost

Applicable to problems with many independent subtasks that can be executed out of order.

Example

- MapReduce / Hadoop [Dean and Ghemawat 2004]
- Globus Grid Toolkit [Foster et al. 2001]
- BOINC [Korpela et al. 1996]

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Crowdsourcing applications too

- reCAPTCHA [von Ahn et al. 2008]
- ESP Game [von Ahn and Dabbish 2004]
- FoldIt [Baker 2009]
- software verification [Schiller and Ernst 2010]
- AutoMan [Barowy et al. 2012]

Voting redundancy

Assume (for now) we know average node reliability

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Voting redundancy

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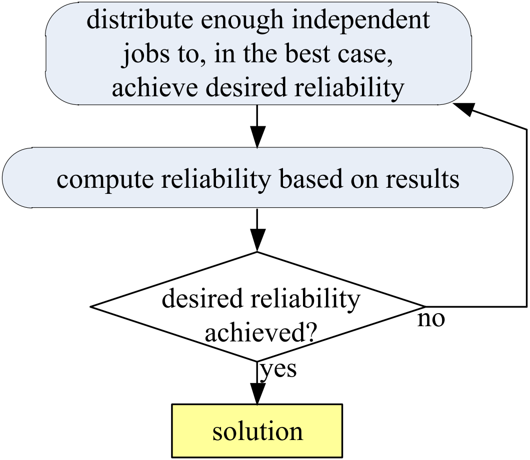
- If we ask 3 nodes, the system reliability will be:
  $1 - 0.3^3 - 3\left(0.3^2\right)0.7 \approx 0.84$
- 19 nodes have to vote to get 0.97 reliability:
  $1 - \sum_{i=10}^{19} \binom{19}{i} 0.3^i 0.7^{19-i} \approx 0.97$

Smart redundancy



main idea: only deploy jobs if you need them

Smart redundancy example execution

answers		reliability
1	0	0.70

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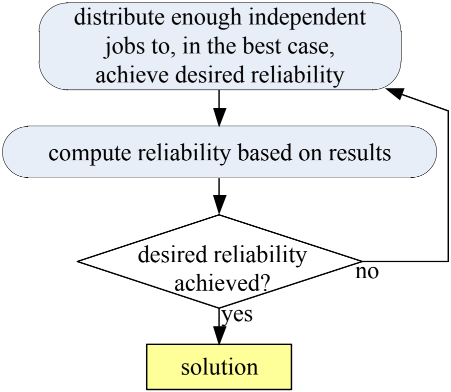

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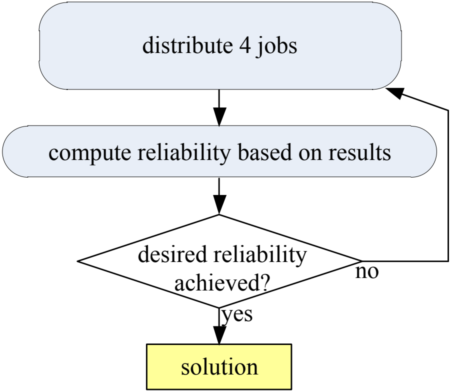

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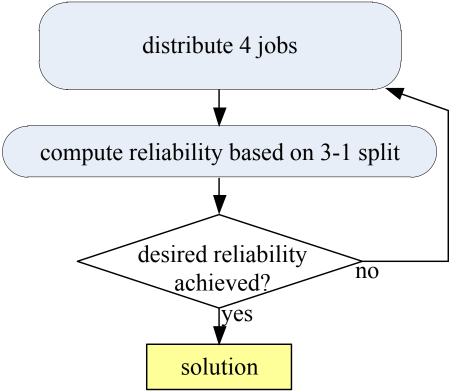

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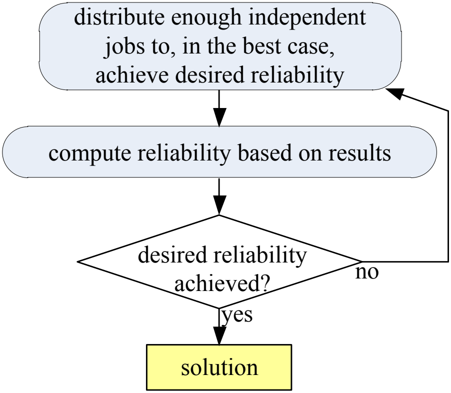

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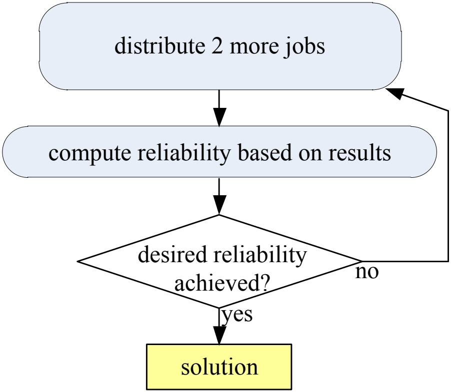

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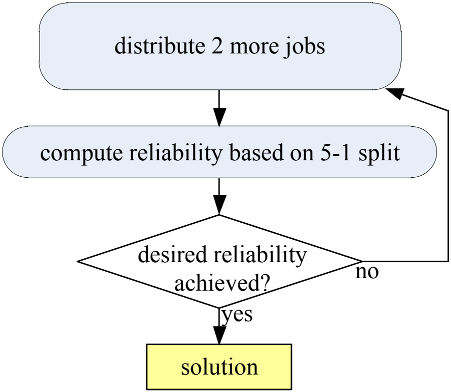
Smart redundancy example execution



answers		reliability	
1	0		0.70
2	0	$\frac{(0.7^2)}{(0.7^2)+(0.3^2)}$	≈ 0.84
3	0	$\frac{(0.7^3)}{(0.7^3)+(0.3^3)}$	≈ 0.93
3	1	$\frac{3(0.7^3)0.3}{3(0.7^3)0.3+3(0.3^3)0.7}$	≈ 0.84
4	0	$\frac{(0.7^4)}{(0.7^4)+(0.3^4)}$	≈ 0.97
4	1	$\frac{4(0.7^4)0.3}{4(0.7^4)0.3+4(0.3^4)0.7}$	≈ 0.93
5	1	$\frac{5(0.7^5)0.3}{5(0.7^5)0.3+3(0.3^5)0.7}$	≈ 0.97

smart redundancy
(1) assumes best case and asks the minimum number of nodes
(2) asks more after learning how reality differs from best case.

How many jobs to distribute?

room 1

Flip a 70% / 30% coin 4 times
get 4 heads and 0 tails.

room 2

Flip a 70% / 30% coin 1004 times
get 504 heads and 500 tails.

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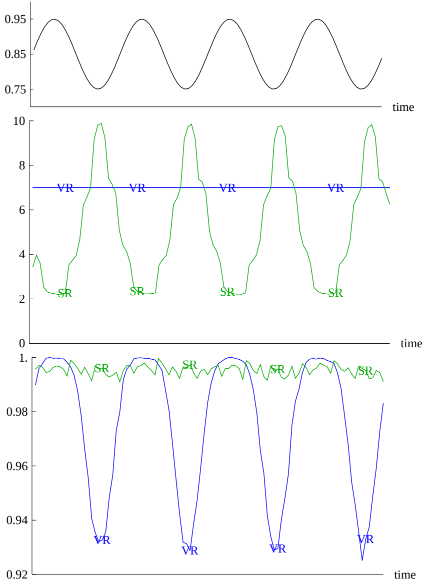
Bayes theorem implies that given an a-b split of answers, only the difference affects the reliability.

Inject redundancy only when it is needed

node reliability:

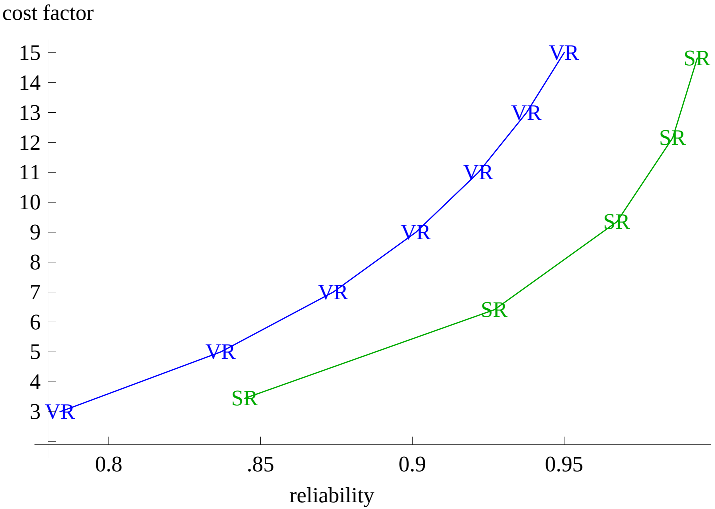
cost factor:

system reliability:



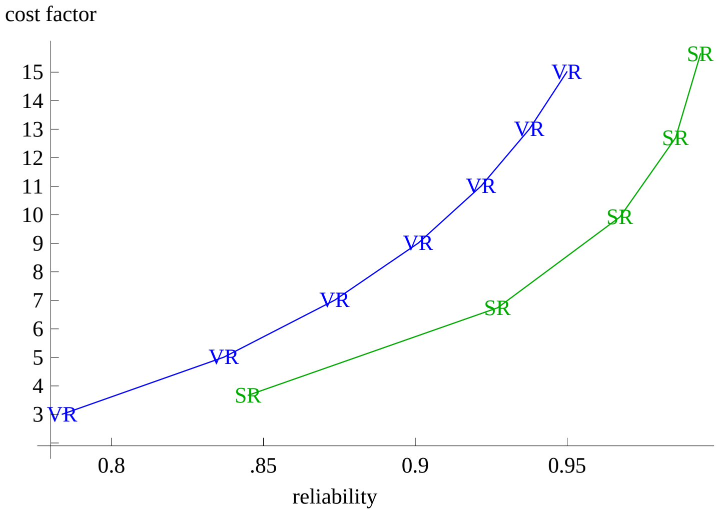
Smart always outperforms voting redundancy

Theoretical results



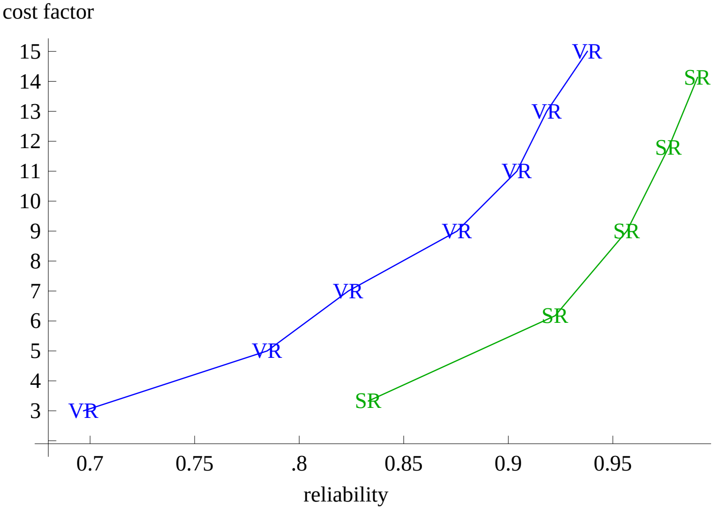
Simulation analysis confirms theoretical predictions

Simulated 1,000,000 task executions on 10,000 nodes using the XDEVS simulator [Edwards 2010]

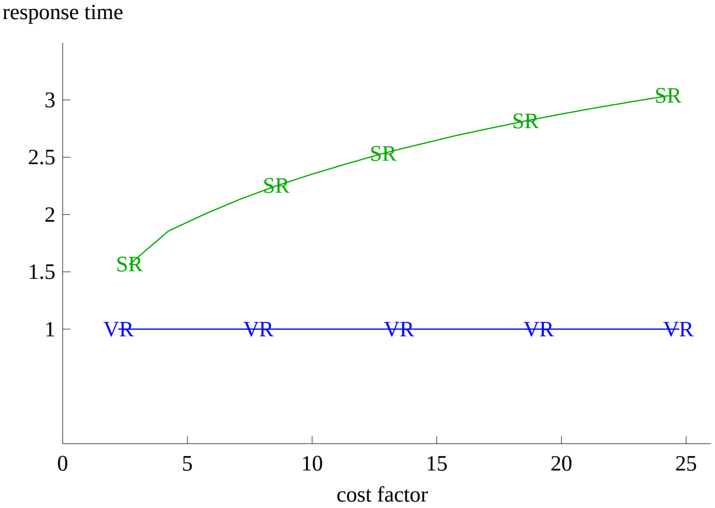


Empirical analysis confirms theoretical predictions

Deployed a SAT solver using BOINC [Anderson 2004]
on PlanetLab [Peterson et al. 2003]



Response time cost



Iterating increases individual task response time

Related work

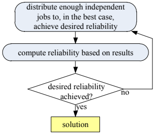
other redundancy techniques

- self-configuring optimistic programming [Bondavalli et al. 2002]
- credibility-based fault tolerance [Sarmenta 2002]
- checkpointing [Priya et al. 2007]
- crowdsourcing [Barowy et al. 2012]
- Byzantine faults in service-based computing (ZZ [Wood et al. 2011])

complementary

- primary backup [Budhiraja et al. 1993]
- active replication [Schneider 1990]
- developer-defined fault detection [Hwang and Kesselman 2003]

Contributions and Future Projects

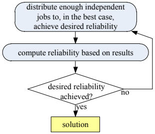


smart redundancy: using resources optimally to boost reliability

What's next?

- Channels with more bandwidth than 1 bit
- Using history to improve resource use (non-Byzantine)
- Crowdsourcing

Contributions and Future Projects



smart redundancy: using resources optimally to boost reliability

What's next?

- Channels with more bandwidth than 1 bit
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For more, see "Smart redundancy for distributed computation" by Y. Brun et al. In the 31st International Conference on Distributed Computing Systems (ICDCS), 665-676, 2011. `http://dx.doi.org/10.1109/ICDCS.2011.25`

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