This Thursday

• Do you like extra credit?

if (true)

come to class Thursday with your computer

else

do it anyway; we'll talk about LIMITS of software

Project Final Presentations

- December 11, 10AM-11:15AM
- CS 150 (in the CS building)
- Think of this as a science fair.
- Each team will get an easel. Bring a poster or printed slides. And laptop for demo.
- Describe and discuss the solution, and demo the implementation.
- Will see (at least) 2 separate judges.
- Chance to see other projects too!

Today

Let's talk about how to automate making high-quality software

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:

Divide computation into elemental subcomputations. Distribute subcomputations onto network.

Computing with tiles



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

adding program



adding program

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \\ 1 \end{bmatrix}$$

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



adding program

Add the two least significant bits



adding program

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



adding program

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

Suppose computers deployed tiles



adding program

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]

















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:

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

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 ${\cal P}$
- ${\ensuremath{\, \circ }}$ Output: Distributed software system to solve P
- Download: http://www.cs.umass.edu/~brun/Mahjong

Experimental Setup

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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



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

Network Delay



Communication is $\sim 100-1000$ 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				
	11	Private Cluster	20.1 sec.	
A		HPCC	19.3 sec.	
		PlanetLab	$18.5 \mathrm{sec.}$	
		Private Cluster	41.6 min.	
B	11	HPCC	41.2 min.	
		PlanetLab	43.9 min.	
Simjong				
Ð	1,000,000	0ms	65 min.	
		10 ms	57 min.	
		100 ms	64 min.	
		500ms	60 min.	
		Gaussian	68 min.	
		Distance-based	59 min.	

Robustness to Network Delay

Problem	# of Nodes	Network Delay	Execution Time
Mahjong			
		Private Cluster	20.1 sec.
A	11	HPCC	19.3 sec.
		PlanetLab	18.5 sec.

Network latency does not affect system throughput

			0ms	65 min.
			10 ms	57 min.
	0	1 000 000	100 ms	64 min.
Ð	1,000,000	500 ms	60 min.	
			Gaussian	68 min.
			Distance-based	59 min.

Scalability: Speed \propto Network Size

Network & Problem	# of Nodes	Execution Time	Speed-up Ratio
Private Cluster	5	43 sec.	
A	10	23 sec.	1.9
HPCC	93	220 min.	
C	186	116 min.	1.9
PlanetLab	50	9.2 min.	
\mathfrak{B}	100	4.8 min.	1.9
Simiona	125,000	8.7 hours	
Sinijong	250,000	4.5 hours	1.9
0	500,000	2.1 hours	2.1
	1,000,000	64 min.	2.0

Scalability: Speed \propto Network Size

Network & Problem	# of Nodes	Execution Time	Speed-up Ratio
Private Cluster	5	43 sec.	
21	10	23 sec.	1.9

System speed scales almost linearly with network size

Simjong	$\begin{array}{c c} 125,000 \\ 250,000 \end{array}$	8.7 hours 4.5 hours	1.9
Ð	500,000	2.1 hours	2.1
	1,000,000	64 min.	2.0

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

${\sf sTile}$

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

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sTile

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

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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Example

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

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]

Assume (for now) we know average node reliability

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node reliability: 0.7 desired system reliability: 0.97

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• If we ask 3 nodes, the system reliability will be: $1-0.3^3-3\left(0.3^2
ight)0.7pprox0.84$

Assume (for now) we know average node reliability

node reliability: 0.7 desired system reliability: 0.97

• If we ask 3 nodes, the system reliability will be:

$$1 - 0.3^3 - 3(0.3^2) 0.7 \approx 0.84$$

• 19 nodes have to vote to get 0.97 reliability:

$$1 - \sum_{i=10}^{19} {19 \choose i} 0.3^i 0.7^{19-i} \approx 0.97$$

Smart redundancy



main idea: only deploy jobs if you need them

ansv	vers	reliability	
1	0		0.70

ans	swers	reliability	
1	0		0.70
2	0	$\frac{\left(0.7^2\right)}{(0.7^2) + (0.3^2)}$	pprox 0.84

ans	swers	reliability	/
1	0		0.70
2	0	$\frac{\left(0.7^2\right)}{(0.7^2) + (0.3^2)}$	≈ 0.84
3	0	$\frac{\left(0.7^3 ight)}{\left(0.7^3 ight)+\left(0.3^3 ight)}$	pprox 0.93

answers		reliability	
1	0		0.70
2	0	$\frac{\left(0.7^2\right)}{(0.7^2) + (0.3^2)}$	pprox 0.84
3	0	$\frac{\left(0.7^3\right)}{(0.7^3) + (0.3^3)}$	pprox 0.93
3	1	$\frac{3(0.7^3)0.3}{3(0.7^3)0.3+3(0.3^3)0.7}$	pprox 0.84

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3	1	$\frac{3(0.7^3)0.3}{3(0.7^3)0.3+3(0.3^3)0.7}$	pprox 0.84
4	0	$\frac{\left(0.7^4\right)}{(0.7^4) + (0.3^4)}$	pprox 0.97
4	1	$\frac{4(0.7^4)0.3}{4(0.7^4)0.3+4(0.3^4)0.7}$	pprox 0.93
5	1	$\frac{5(0.7^5)0.3}{5(0.7^5)0.3+3(0.3^5)0.7}$	pprox 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.

room 1

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

room 2

room 1

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

room 2

$$\frac{\binom{1004}{504} \left(0.7^{504}\right) 0.3^{500}}{\binom{1004}{504} \left(0.7^{504}\right) 0.3^{500} + \binom{1004}{500} \left(0.3^{504}\right) 0.7^{500}}$$

room 1

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

room 2

$$\underbrace{\begin{pmatrix} 1004 \\ 504 \end{pmatrix} \left(0.7^{504}\right) 0.3^{500}}_{\left(504 \atop 504 \right) \left(0.7^{504}\right) 0.3^{500} + \left(\frac{1004}{500}\right) \left(0.3^{504}\right) 0.7^{500}}$$

room 1

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

room 2

$$\underbrace{\frac{\binom{1004}{504} \left(0.7^{504}\right) \overline{0.3^{500}}}{\binom{1004}{504} \left(0.7^{504}\right) \overline{0.3^{500}} + \binom{1004}{500} \left(0.3^{500}\right) \left(0.3^{500}\right)}}_{500}$$

room 1

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

room 2

$$\frac{\binom{1004}{504}(0.7^{504})\overline{0.3^{500}}}{\binom{1004}{504}(0.7^{504})\overline{0.3^{500}} + \binom{1004}{500}(0.3^{500})}$$

room 1

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

room 2



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.

$$\frac{\left(0.7^{4}\right)}{\left(0.7^{4}\right) + \left(0.3^{4}\right)} = \frac{\left(1004}{\left(504\right)} \left(0.7^{304}\right) 0.3^{500}}{\left(1004\right) \left(0.7^{304}\right) 0.3^{500} + \left(1004\right) \left(0.3^{304}\right) 0.7^{500}}$$

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

Inject redundancy only when it is needed



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] cost factor



Empirical analysis confirms theoretical predictions

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

cost factor



Response time cost

response time SR 3 SR SR 2.5 SŦ 2 SŘ 1.5 VR **VR** VR **VR** ₩R 1 0 5 10 15 20 25

cost factor

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
- Using history to improve resource use (non-Byzantine)
- Crowdsourcing

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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