Tolerating Byzantine processes in distributed systems: using wormholes to reduce the number of replicas

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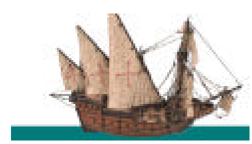
Navigators group



- Group leader: Paulo Veríssimo
- Currently 9 PhDs (6 faculty, 3 post-docs), 7 PhD students, ? MsC students, ? junior researchers
- Projects: 2 EC STREPs (CRUTIAL, HIDENETS), 1 EC NoE (ReSIST), 1 EC CA (ESFORS), 1 ESA, 5 FCT
- CMU-PT partnership – dual degree MsC in Security and PhD in Informatics
- Research Lines
  - ☞ Fault and Intrusion Tolerance in Open Distributed Systems
  - ☞ Timeliness and Adaptation in Dependable Systems
- http://www.navigators.di.fc.ul.pt/

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Outline

- Intrusion Tolerance – motivation
- Hybrid system models and Wormholes
- State machine replication
- 2f+1 atomic multicast
- Consensus
- Conclusions

Intrusion Tolerance – motivation

Motivation for I-T

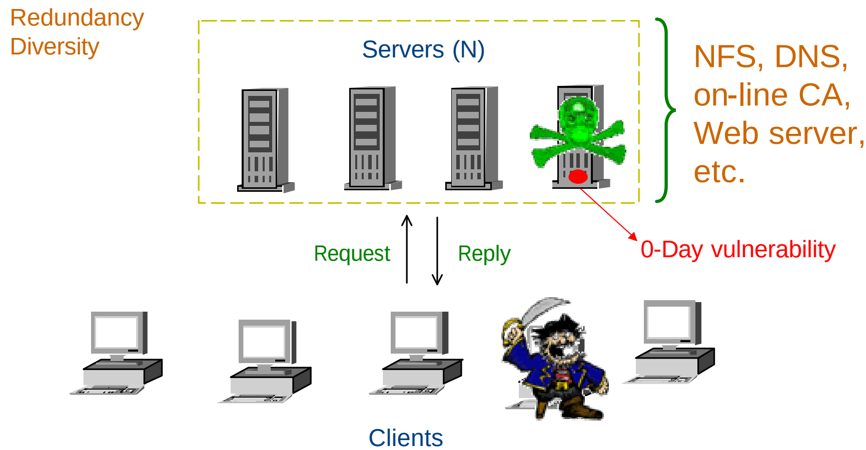
- Every year thousands of new vulnerabilities appear, zillions of attacks and intrusions
  - ☞Doing the best we know/can, using security best practices etc. is not enough
- Systems with very high societal importance are becoming “online”
  - ☞Critical infrastructures: gas, water, electr.,…
  - ☞Controlled by computers indirectly connected to the Internet

Intrusion Tolerance

- To apply the Fault Tolerance paradigm in the domain of Security
- *Do the best we know to protect systems (prevention)*
- *…but vulnerabilities still remain…*
- *Tolerate intrusions that still occur (tolerance)*

I-T: an example

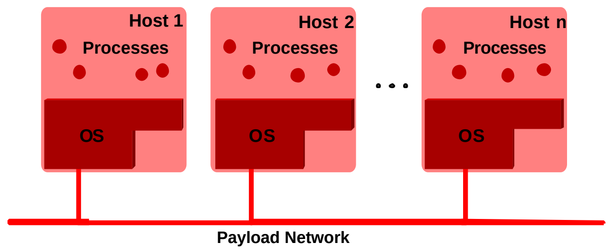
I-T Distributed Service



Hybrid system models and Wormholes

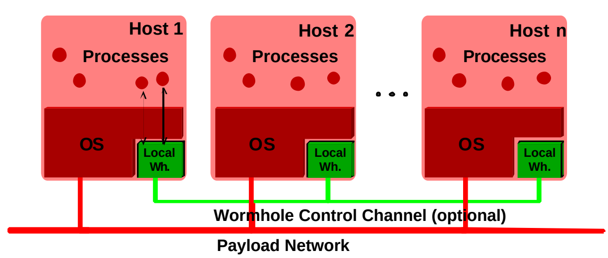
Homogeneous system models

- In Fault and Intrusion Tolerance the system model is usually homogeneous, e.g.:
  - ☞Asynchronous (no bounds on delays)
  - ☞Byzantine (or arbitrary) faults



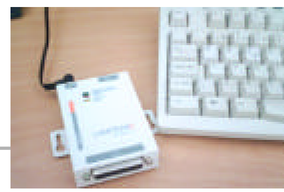
Hybrid system models

- We proposed and are interested on *hybrid* system models. For instance:
  - ☞Asynchronous/Byzantine as before (red) +
  - ☞Secure wormhole (green)



Question 1: reasonable model?

- Yes, it models several current systems:
- PCs with Trusted Platform Modules
  - ☞ https://www.trustedcomputinggroup.org/
- PCs with SmartCards
- DIY: PCs with virtual machines (Xen, VMWare)
- DIY: PCs with hardware appliances



Question 2: why model?

- Why not do research about PCs + SmartCards or TPMs or…?
- Science vs. engineering; we want:
  - ☞ *Expressive models of reality*
  - ☞ *Sound theoretical basis for proofs of correctness*
  - ☞ *Enablers of concepts for building new algorithms*
- For practical minds: we can do things that cannot be done with SmartCards or TPMs…
  - ☞ See rest of the talk

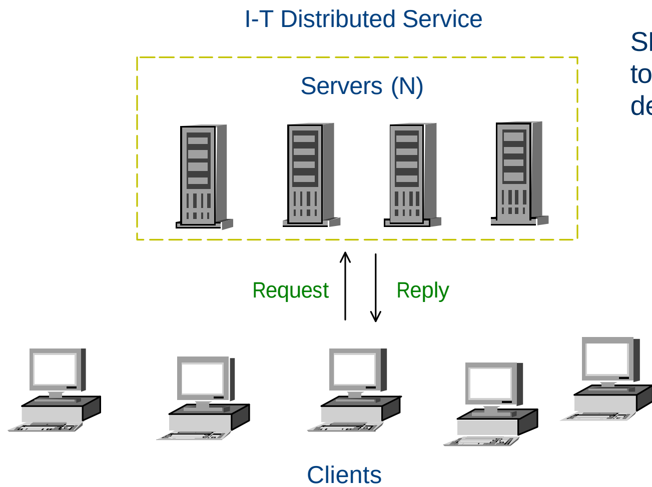
Question 3: model what?

- Not necessarily "*insecure system + secure subsystem"*
- Some of us have been working with "*untimely system + timely subsystem"*
  - ☞A. Casimiro, P. Veríssimo, Timely Computing Base
- on hybrid models and wormholes:

  P. Veríssimo, "Travelling through Wormholes: a new look at Distributed Systems Models"
  ACM SIGACT News 2006

State machine replication

SMR basics



SMR is a mechanism to implement <u>any</u> deterministic service

A server or client is said to be **faulty** if it deviates from its correct behaviour, e.g., because there is an intrusion or it crashes

SMR definition

- Servers are state machines:
  - ☞state variables, commands
- All correct servers follow the same history of states iff:
  - ☞*Initial state:* all servers start in the same state
  - ☞*Agreement:* all servers execute the same commands
  - ☞*Total order:* all servers execute the commands in the same order
  - ☞*Determinism:* the same command executed in the same initial state generates the same final state

Atomic multicast (covers Agreement and Total order)

I-T Atomic Multicast

- There is a maximum number **f** of servers that can be faulty for the system to remain correct
- With an homogeneous system model (asynchronous Byzantine):
  - Minimum: **N=3f+1** servers
  - 4 to tolerate 1 faulty, 7 to tolerate 2 faulty,…
- With a hybrid system model (secure wormhole in servers; not in clients):
  - Minimum: **N=2f+1** servers
  - 3 to tolerate 1 faulty, 5 to tolerate 2 faulty,…
  - This reduction has a huge impact on the system costs due to the need for diversity

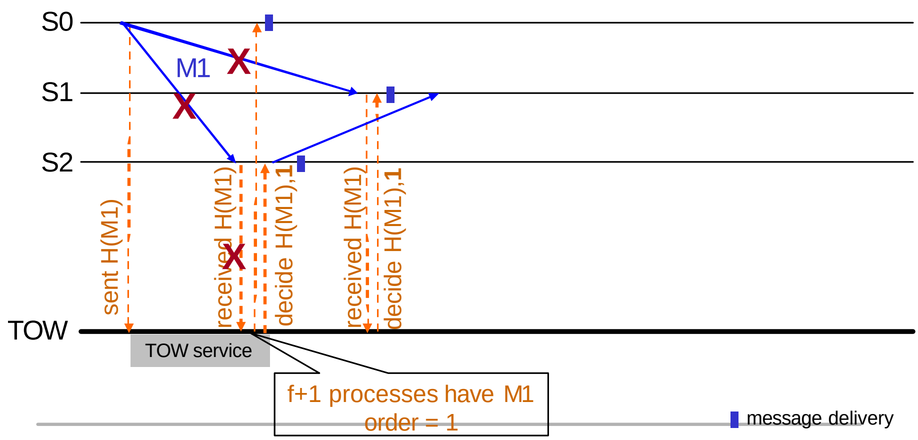
Trusted Ordering Wormhole

- The **TOW** is a wormhole that serves specifically to implement a 2f+1 I-T atomic multicast
- Provides a single service with two purposes:
  - Says when a message can be delivered (which is *when f+1 servers have it*)
  - Says the order in which it must be delivered
- API:
  - TOW_sent – "I sent a message"
  - TOW_received – "I received a message"
- Output:
  - TOW_decide – "You can deliver the message, order is *n*"

2f+1 Atomic multicast w/TOW

N=3 f=1

H(M) – a collision-resistant hash function



Performance of I-T SMR

- In nice runs

	Algorithm	Latency ComSteps	SignCP	VerifCP	Throughput MesgTot	SignTot	VerifTot
1	Rampart	8	3	$2(n-f)+n$	$4n \oplus 3(n-1)$	$n \oplus (n-1)$	$(n-f)n \oplus (n-f)(n-1)$
2	BFT	5	0	0	$2n \oplus (n-1)(2n-1)$	0	0
3	HQ	4	2	$2(n-f)$	$4n$	$(n+1)$	$(n+1)(n-f)$
4	BFT2F	5	2	$2f$	$2n \oplus (n-1)(2n-1)$	$(n+1) \oplus 0$	$n(2f+1) \oplus 0$
5	Our alg.	5	0	0	$2n\,[+(n^3+n^2-n)]$	0	0

- Bad runs

	Algorithm	Bad run	Consequence
1	Rampart	Long communication delays or faulty coordinator	One or more coordinator elections
2	BFT	Same as Rampart	Same as Rampart
3	HQ	Same as Rampart/BFT if there is contention	Change to BFT and run BFT
4	BFT2F	Same as Rampart/BFT	Same as Rampart/BFT
5	Our alg.	Nothing (outside the wormhole)	Not affected (outside the wormhole)

Consensus

Consensus problem

- "How can some distributed processes achieve agreement on a value despite a number of them being faulty?"
  - ☞Important since related to many other distributed problems
- FLP impossibility result [Fischer et al. 85]
  - ☞Consensus is impossible to solve deterministically in a completely asynchronous system (with faults)
  - ☞For the problem to be solved, this result must be "circumvented" (i.e., system model modified): failure detectors, partial synchrony, randomization, wormholes!

Consensus and atomic multicast

- The 2 problems have been proved to be equivalent in several system models
  - Asynchronous, crash faults, failure detectors
  - Asynchronous, Byzantine, failure detectors
  - Asynchronous, Byzantine, randomization
  - …
- What about asynchronous Byzantine with TOW?

Consensus and atomic multicast

- Two definitions of Byzantine consensus:

  Either or:
  - *Validity 1.* If all correct processes propose the same value *v*, then any correct process that decides, decides *v*.
  - *Validity 2.* If a correct process decides *v*, then *v* was proposed by some process.
  - *Agreement.* No two correct processes decide differently.
  - *Termination.* Every correct process eventually decides.
- It is trivial to use the AM presented to implement consensus with Validity 2
  - Each process atomic multicast its value
  - The decision is the first value delivered
- It is simple to see that it is not possible to use the AM presented to obtain consensus with Validity 1

Conclusions

Conclusions (1)

- First solution for intrusion-tolerant state-machine replication in practical distributed systems with only **2f+1** replicas
- Interesting impact since each additional replica has a considerable cost
- Circumvents FLP without synchrony assumptions on the asynchronous part of the system
  - ☞ all synchrony is encompassed in the TOW
- Good performance:
  - ☞ Low time complexity
  - ☞ No asymmetric cryptography
  - ☞ No leader elections

Conclusions (2)

- This work showed clear benefits of using a *hybrid system model* and *wormholes*
- Later: necessity of using wormholes (Paulo Sousa)

Questions?

- Some related publications:

  - M Correia, NF Neves, LC Lung, P Veríssimo. Worm-IT - A Wormhole-based Intrusion-Tolerant Group Communication System. Journal of Systems & Software, vol. 80, n. 2, February 2007
  - P Veríssimo, Travelling through Wormholes: a new look at Distributed Systems Models. SIGACT News, vol. 37, n. 1, 2006.
  - NF Neves, M Correia, P Veríssimo. Solving Vector Consensus with a Wormhole. IEEE Transactions on Parallel and Distributed Systems, vol. 16, n.12, Dec. 2005
  - M Correia, NF Neves, LC Lung, P Veríssimo. Low Complexity Byzantine-Resilient Consensus. Distributed Computing, vol. 17, n. 3, March 2005
  - M Correia, NF Neves, P Veríssimo. **How to Tolerate Half Less One Byzantine Nodes in Practical Distributed Systems**. In Proc. 23rd IEEE Symposium on Reliable Distributed Systems, October 2004 (journal version to appear)

- More info and papers:
  - http://www.navigators.di.fc.ul.pt/
  - http://www.di.fc.ul.pt/~mpc/