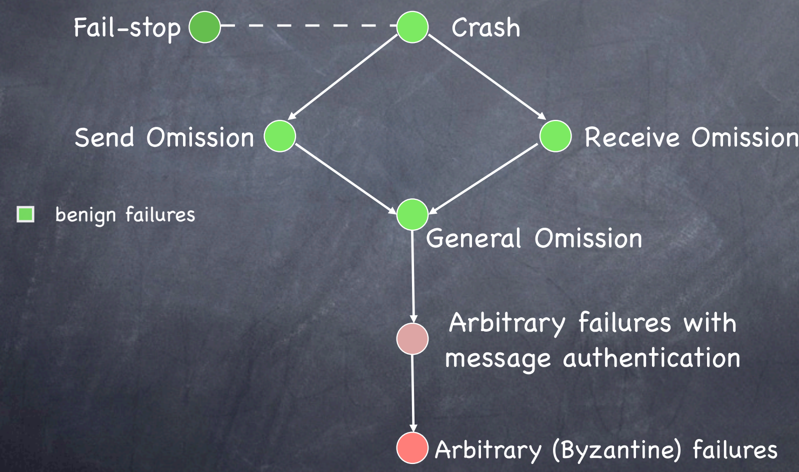
Meet BFT

A hierarchy of failure models



Weird Things Happen in Distributed Systems

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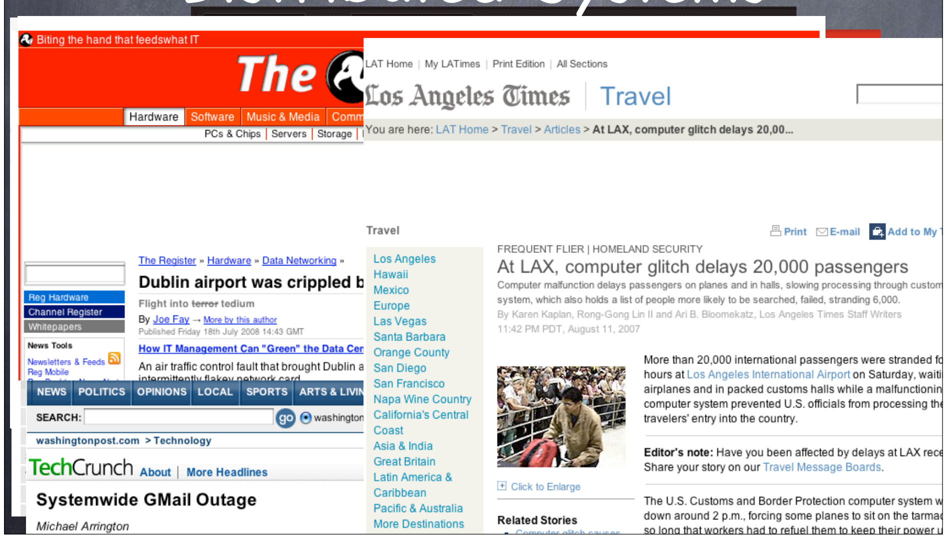
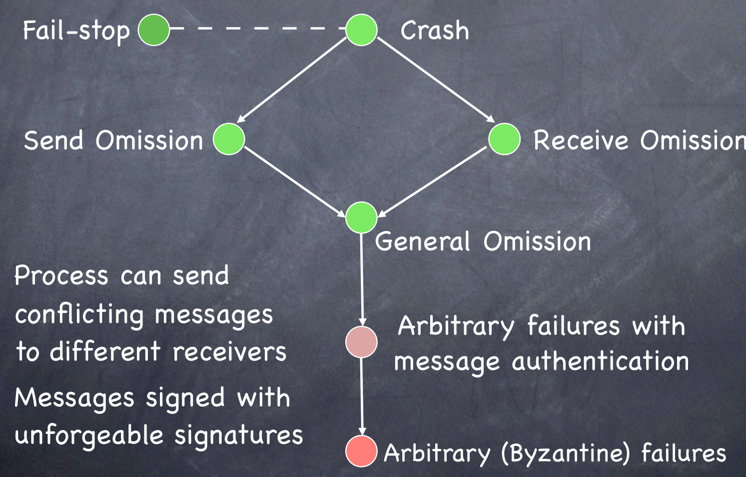


Terminating Reliable Broadcast

Validity	If the sender is correct and broadcasts a message m, then all correct processes eventually deliver m
Agreement	If a correct process delivers a message m, then all correct processes eventually deliver m
Integrity	Every correct process delivers at most one message, and if it delivers $m \neq$ SF, then some process must have broadcast m
Termination	Every correct process eventually delivers some message

Arbitrary failures with message authentication



- Process can send conflicting messages to different receivers
- Messages signed with unforgeable signatures

Valid messages

A valid message m has the following form:

in round 1:

$m : s_{id}$ (m is signed by the sender)

in round r > 1, if received by p from q :

$m : p_1 : p_2 : \ldots : p_r$ where

- p_1 = sender; $p_r = q$
- $p_1, \ldots, p_r$ are distinct from each other and from p
- message has not been tampered with

AFMA: The Idea

- A correct process p discards all non-valid messages it receives
- If a message is valid,
  - it "extracts" the value from the message
  - it relays the message, with its own signature appended
- At round $f+1$:
  - if it extracted exactly one message, p delivers it
  - otherwise, p delivers SF

AFMA: The Protocol

Initialization for process p:
  if p = sender and p wishes to broadcast m then
    extracted := relay := $\{m\}$

Process p in round $k, 1 \leq k \leq f+1$
  for each $s \in$ relay
    send $s : p$ to all
  receive round k messages from all processes
  relay := $\emptyset$
  for each valid message received $s = m : p_1 : p_2 : \ldots : p_k$
    if $m \notin$ extracted then
      extracted := extracted $\cup \{m\}$
      relay := relay $\cup \{s\}$

At the end of round $f+1$
  if $\exists m$ such that extracted = $\{m\}$ then
    deliver m
  else deliver SF

Termination

Initialization for process p:
  if p = sender and p wishes to broadcast m then
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Process p in round $k, 1 \leq k \leq f+1$
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At the end of round $f+1$
  if $\exists m$ such that extracted = $\{m\}$ then
    deliver m
  else deliver SF

In round $f+1$, every correct process delivers either m or SF and then halts

Agreement

Initialization for process p:
  if p = sender and p wishes to broadcast m then
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Process p in round $k, 1 \leq k \leq f+1$
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At the end of round $f+1$
  if $\exists m$ such that extracted = $\{m\}$ then
    deliver m
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Lemma. If a correct process extracts m, then every correct process eventually extracts m

Proof

Let r be the earliest round in which some correct process extracts m. Let that process be p.

- if p is the sender, then in round 1 p sends a valid message to all.

All correct processes extract that message in round 1

- If $r \leq f, p$ will send a valid message

$$m : p_1 : p_2 : \ldots : p_r : p$$

  in round $r+1 \leq f+1$ and every correct process will extract it in round $r+1 \leq f+1$

- If $r = f+1$, p has received in round $f+1$ a message

$$m : p_1 : p_2 : \ldots : p_{f+1}$$

- Each $p_j, 1 \leq j \leq f+1$ has signed and relayed a message in round $j-1 < f+1$
- At most f faulty processes - one p_j is correct and has extracted m before p

CONTRADICTION

Agreement follows directly, since all correct process extract the same set of messages

Validity

Initialization for process p:
  if p = sender and p wishes to broadcast m then
    extracted := relay := $\{m\}$

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At the end of round $f+1$
  if $\exists m$ such that extracted = $\{m\}$ then
    deliver m
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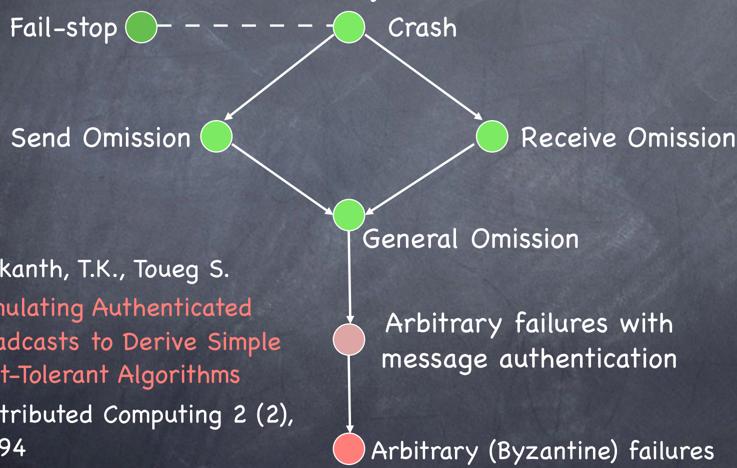
From Agreement and the observation that the sender, if correct, delivers its own message.

TRB for arbitrary failures



Srikanth, T.K., Toueg S.
Simulating Authenticated Broadcasts to Derive Simple Fault-Tolerant Algorithms
Distributed Computing 2 (2), 80-94

AF: The Idea

- Identify the essential properties of message authentication that made AFMA work
- Implement these properties without using message authentication

AF: The Approach

- Introduce two primitives

  broadcast(p, m, i) (executed by p in round i)
  accept(p, m, i) (executed by q in round $j \geq i$)

- Give axiomatic definitions of broadcast and accept
- Derive an algorithm that solves TRB for AF using these primitives
- Show an implementation of these primitives that does not use message authentication

Properties of broadcast and accept

- Correctness   If a correct process p executes broadcast(p, m, i) in round i, then all correct processes will execute accept(p, m, i) in round i
- Unforgeability   If a correct process q executes accept(p, m, i) in round $j \geq i$, and p is correct, then p did in fact execute broadcast(p, m, i) in round i
- Relay   If a correct process q executes accept(p, m, i) in round $j \geq i$, then all correct processes will execute accept(p, m, i) by round $j+1$

AF: The Protocol - 1

sender s in round 0:
0: extract m

sender s in round 1:
1: broadcast$(s, m, 1)$
Process p in round $k, 1 \leq k \leq f+1$
2: if p extracted m in round $k-1$ and $p \neq$ sender then
4: broadcast(p, m, k)
5: if p has executed at least k accept(q_i, m, j_i) $1 \leq i \leq k$ in rounds 1 through k
(where (i) q_i distinct from each other and from p, (ii) one q_i is s, and
(iii) $1 \leq j_i \leq k$) and p has not previously extracted m then
6: extract m
7: if $k = f+1$ then
8: if in the entire execution p has extracted exactly one m then
9: deliver m
10: else deliver SF
11: halt

Termination

sender s in round 0:
0: extract m
sender s in round 1:
1: broadcast$(s, m, 1)$
Process p in round $k, 1 \leq k \leq f+1$
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Validity

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- A correct sender executes broadcast$(s, m, 1)$ in round 1
- By CORRECTNESS, all correct processes execute accept$(s, m, 1)$ in round 1 and extract m
- In order to extract a different message m', a process must execute accept$(s, m', 1)$ in some round $i \leq f+1$
- By UNFORGEABILITY, and because s is correct, no correct process can extract $m' \neq m$
- All correct processes will deliver m

Agreement - 1

sender s in round 0:
0: extract m
sender s in round 1:
1: broadcast$(s, m, 1)$
Process p in round $k, 1 \leq k \leq f+1$
2: if p extracted m in round $k-1$ and $p \neq$ sender then
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(where (i) q_i distinct from each other and from p, (ii) one q_i is s, and (iii) $1 \leq j_i \leq k$)
and p has not previously extracted m then
6: extract m
7: if $k = f+1$ then
8: if in the entire execution p has extracted exactly one m then
9: deliver m
10: else deliver SF
11: halt

Lemma
If a correct process extracts m, then every correct process eventually extracts m