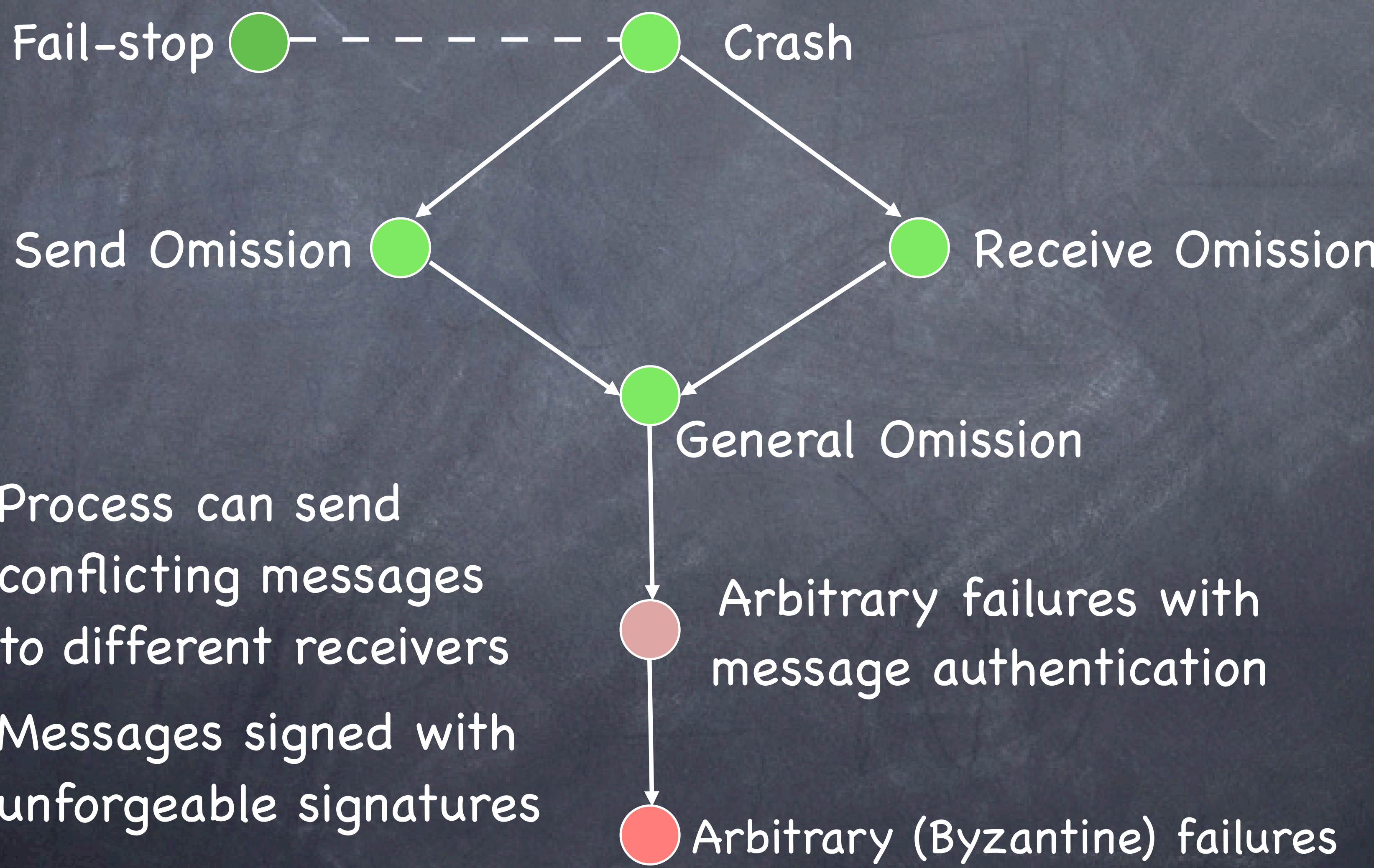
Arbitrary failures with message authentication



- 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
    extracted := relay := $\{m\}$

Process p in round k, $1 \leq k \leq f+1$
  for each $s \in$ relay
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  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

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

extracted := relay := $\{m\}$

Process p in round k, $1 \le k \le f+1$

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

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 $r \le f$, p will send a valid message

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

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

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

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

- Each $p_j, 1 \le j \le f+1$ 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:
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    extracted := relay := $\{m\}$

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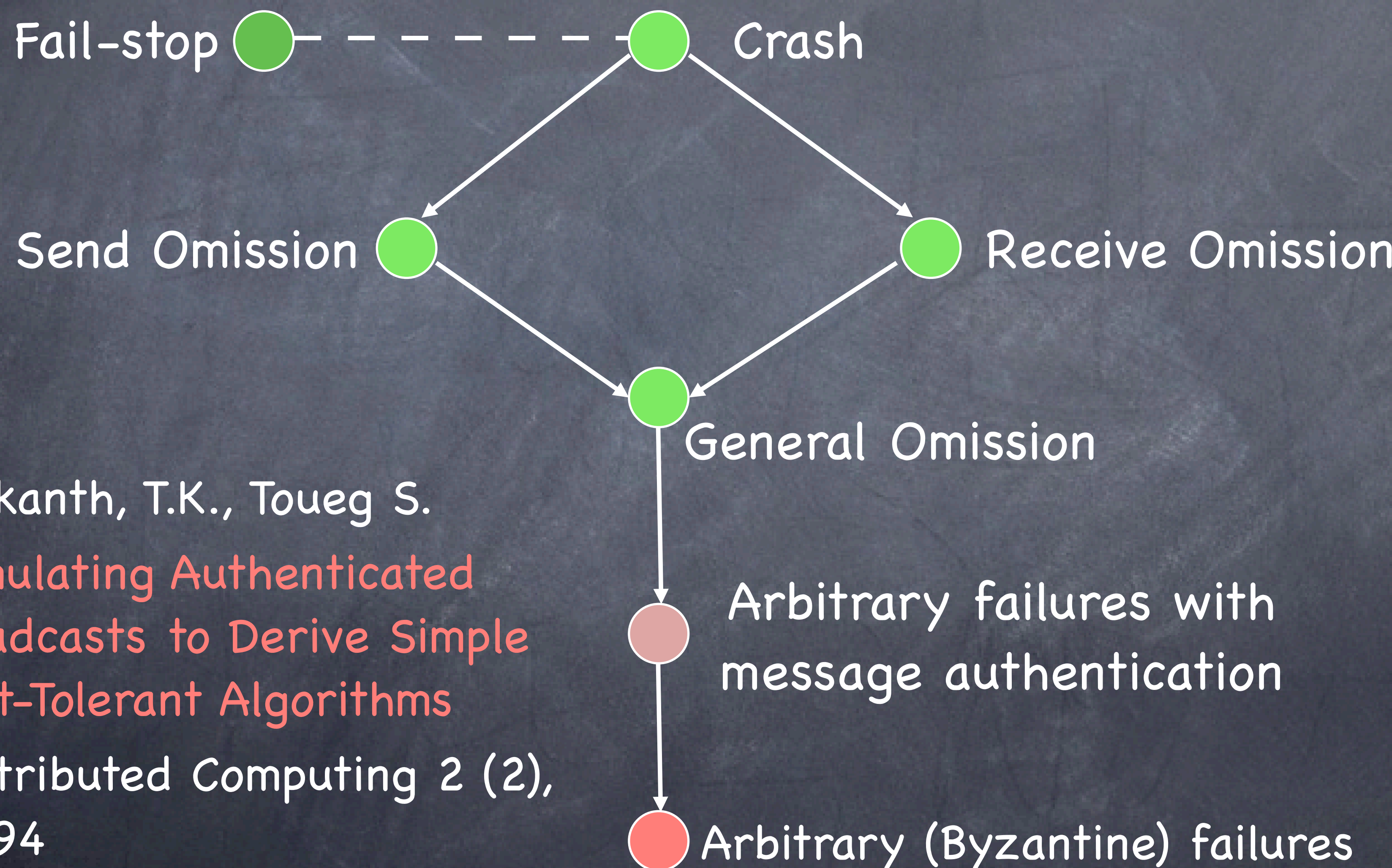
  for each $s \in$ relay
    send $s : p$ to all
  receive round k messages from all processes
  relay := $\emptyset$
  for each valid message received $s = m : p_1 : p_2 : \ldots : p_k$
    if $m \notin$ extracted then
      extracted := extracted $\cup \{m\}$
      relay := relay $\cup \{s\}$

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

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 signatures

AF: The Approach

accept ≠ deliver!

- 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
  - just state some properties we assume of them!
- Derive an algorithm that solves TRB for AF using these primitives
- Show an implementation of these primitives that does not use signatures

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:
extract m
sender s in round 1:
broadcast$(s, m, 1)$

Process p in round $k, 1 \leq k \leq f+1$
if p extracted m in round $k-1$ and $p \neq$ sender then
    broadcast(p, m, k)
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
        extract m
if $k = f+1$ then
    if in the entire execution p has extracted exactly one m then
        deliver m
    else deliver SF
    halt

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

Validity

sender s in round 0:

extract m

sender s in round 1:

broadcast$(s, m, 1)$

Process p in round $k, 1 \leq k \leq f+1$

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

  extract m

if $k = f+1$ then

  if in the entire execution p has extracted exactly one m then

   deliver m

  else deliver SF

  halt

- 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:
    extract m
sender s in round 1:
    broadcast(s, m, 1)

Process p in round k, 1≤k≤f+1
    if p extracted m in round k−1 and p ≠ sender then
        broadcast(p, m, k)
    if p has executed at least k accept(q_i, m, j_i) 1≤i≤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≤j_i≤k )
      and p has not previously extracted m then
            extract m
    if k = f+1 then
        if in the entire execution p has extracted exactly
                one m then
            deliver m
        else deliver SF
        halt
```

Lemma

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

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    extract m
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      and p has not previously extracted m then
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    if k = f+1 then
        if in the entire execution p has extracted exactly
                one m then
            deliver m
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        halt
```

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 $r=0$, then $p=s$ and p will execute broadcast$(s, m, 1)$ in round 1. By CORRECTNESS, all correct processes will execute **accept**$(s, m, 1)$ in round 1 and extract m

Agreement - 1

sender s in round 0:
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Process p in round $k, 1 \leq k \leq f+1$
if p extracted m in round $k-1$ and $p \neq$ sender then
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  and p has not previously extracted m then
    extract m
if $k = f+1$ then
  if in the entire execution p has extracted exactly
      one m then
    deliver m
  else deliver SF
  halt

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 $r = 0$, then $p = s$ and p will execute broadcast$(s, m, 1)$ in round 1. By CORRECTNESS, all correct processes will execute **accept**$(s, m, 1)$ in round 1 and extract m
- if $r > 0$, the sender is faulty. Since p has extracted m in round r, p has accepted at least r triples with properties (i), (ii), and (iii) by round r

Agreement - 1

```
sender s in round 0:
    extract m
sender s in round 1:
    broadcast(s, m, 1)

Process p in round k, 1≤k≤f+1
    if p extracted m in round k−1 and p ≠ sender then
        broadcast(p, m, k)
    if p has executed at least k accept(q_i, m, j_i)  1≤i≤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≤j_i≤k )
      and p has not previously extracted m then
            extract m
    if k = f+1 then
        if in the entire execution p has extracted exactly
                one m then
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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 $r=0$, then $p=s$ and p will execute broadcast$(s,m,1)$ in round 1. By <u>CORRECTNESS</u>, all correct processes will execute **accept**$(s,m,1)$ in round 1 and extract m
- if $r>0$, the sender is faulty. Since p has extracted m in round r, p has accepted at least r triples with properties (i), (ii), and (iii) by round r
  - $r \leq f$ By <u>RELAY</u>, all correct processes will have accepted those r triples by round $r+1$
  - p will execute broadcast$(p,m,r+1)$ in round $r+1$
  - By <u>CORRECTNESS</u>, any correct process other than $p, q_1, q_2, \ldots, q_r$ will have accepted $r+1$ triples $(q_k, m, j_k), 1 \leq j_k \leq r+1$, by round $r+1$
  - $q_1, q_2, \ldots, q_r, p$ are all distinct
  - every correct process other than $q_1, q_2, \ldots, q_r, p$ will extract m
  - p already extracted m; what about $q_1, q_2, \ldots, q_r$?

Agreement - 2

```
sender s in round 0:
    extract m
sender s in round 1:
    broadcast(s, m, 1)

Process p in round k, 1≤k≤f+1
    if p extracted m in round k−1 and p ≠ sender then
        broadcast(p, m, k)
    if p has executed at least k accept(q_i, m, j_i)  1≤i≤k in
        rounds 1 through k
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      and p has not previously extracted m then
            extract m
    if k = f+1 then
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                one m then
            deliver m
        else deliver SF
        halt
```

Claim: $q_1, q_2, \ldots, q_r$ are all faulty

- Suppose q_k were correct
- p has accepted (q_k, m, j_k) in round $j_k \leq r$
- By UNFORGEABILITY, q_k executed broadcast (q_k, m, j_k) in round j_k
- q_k extracted m in round $j_{k-1} < r$

CONTRADICTION (r was supposed to be the earliest round!)

- Case 2: $r = f+1$
    - Since there are at most f faulty processes, some process q_l in $q_1, q_2, \ldots, q_{f+1}$ is correct
    - By UNFORGEABILITY, q_l executed broadcast (q_l, m, j_l) in round $j_l \leq r$
    - q_l has extracted m in round $j_{l-1} < f+1$

CONTRADICTION