Simulating authenticated broadcast

For round-based algorithms, a protocol that provides the properties of broadcasting authenticated messages.

T. K. Srikanth and S. Toueg. Simulating authenticated broadcasts to derive simple fault-tolerant algorithms. *Distributed Computing* 2:(80-94), 1987.

Authenticated broadcast

Synchronous-round based

- p broadcasts m in round k: *broadcast*(p, m, k)
- process *accept*(p, m, k) when:
  - receives (p, m, k)
  - verifies p's signature.

Correctness: If correct p broadcasts (p, m, k) in round k then every correct process accepts (p, m, k) in the same round.

Unforgeability: If correct p does not broadcast (p, m, k) then no correct process ever accepts (p, m, k).

Relay: If correct p accepts (p, m, k) in round $r \geq k$, then every correct process accepts (p, m, k) by round $r + 1$.

Authenticated Arbitrary Consensus: I

// $m \in \{0, 1\}$, non-loquacious protocol

process p:

  if ($p == p_1$) *value* = *m;*

  else *value* = 0;

  for r =1 to $t + 1$

    if (*value* == 1 and (p not broadcast in earlier round))

      broadcast(p, 1, r);

      relay the $r - 1$ messages accepted in rounds 1, 2, …, $r - 1$

        that caused *value* to be set to 1;

    if (in rounds $r' \leq r$ *accepted* (p_k, 1, r_k) from r distinct

      processes p_k including the transmitter p_1)

    value = 1;

decide *value*;

Authenticated Arbitrary Consensus: II

- *Validity*
  - $m = 1$
    - p_1 sets *value* to 1 and broadcasts $(p_1, 1, 1)$.
    - By *Correctness* every correct process accepts $(p_1, 1, 1)$ in round 1 and sets *value* to 1.
    - *value* is never set to another value, so decides *value.*
  - $m = 0$
    - p_1 sets *value* to 0 and does not broadcast in round 1.
    - Since *value* = 0, p_1 never broadcasts in other rounds and decides on 0.
    - By *Unforgeability* no correct process ever accepts message from p_1.
    - Hence, no correct process sets *value* to 1, and so decides on 0.

Authenticated Arbitrary Consensus: III

- *Agreement*
  - Some correct p first sets *value* to 1 at the end of round $r < t + 1$:
    - p accepted messages $(p_k, 1, r_k)$ from at least r distinct processes p_k including p_1.
    - In round $r + 1$ p broadcasts $(p, 1, r + 1)$ and relays the $r - 1$ messages that caused p to set *value* to 1.
    - By *Correctness* and *Relay*, in round $r + 1$ all correct processes accept $(p, 1, r + 1)$ and $(p_k, 1, r_k)$ for $1 \leq k \leq r$, and so sets *value* to 1.
  - Some correct p first sets *value* to 1 at the end of round $t + 1$:
    - p accepted $(p_k, 1, r_k)$ from $t + 1$distinct processes, and at least one must be correct. Say was p_i broadcasting $(p_i, 1, r_i)$ where $r_i \leq t + 1$.
    - So p_i set *value* to 1 in round $r_i - 1 < t + 1$.
    - The first case above therefore holds.
  - Otherwise, each correct process has *value* = 0 and decides 0.

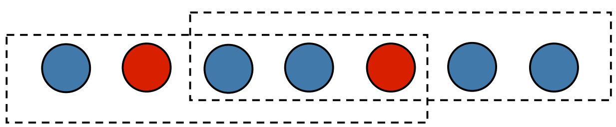
Simulating authenticated broadcast

- Implement a broadcast primitive that provides *Correctness*, *Unforgeability*, and *Relay* without using cryptographic methods
  - To broadcast a message, a set of processes need to *witness* the broadcast.
  - A correct process accepts a message only when it knows that there are sufficient witnesses to this broadcast.
  - Doing so prevents a faulty process from claiming to have received a message that was not sent to it, and to allow a correct process to prove why it accepted a message.
  - Requires $n > 3t$.

Handy Facts about $n > 3t$

- Any subset of $n - 2t$ processes contains at least one correct process.
  - $n - 2t > 3t - 2t = t$.
- The intersection of any two subsets of $n - t$ processes contains at least one correct process.
  - $n - t > 3t - t = 2t$.

Example: $n = 7$, $t = 2$: $n - 2t = 3$, $n - t = 5$.



Basic Idea

- Each round consists of two phases.
- p sends ($init$, p, m, k) to all.
- Any process that receives this message becomes a witness and sends ($echo$, p, m, k).
- Any non-witness process that receives at least $n - 2t$ ($echo$, p, m, k) also becomes a witness and sends ($echo$, p, m, k).
  - Because in any set of $n - 2t$ processes, one must be correct.
- Any process that receives at least $n - t$ ($echo$, p, m, k) accepts the message.
  - Because at least $n - 2t$ correct processes sent the echo, and so eventually all correct processes will echo.

Broadcast primitive

Round k:

Phase $2k-1$: p sends ($init$, p, m, k) to all;

Phase $2k$: each process executes:

if received ($init$, p, m, k) from p in phase $2k-1$

send ($echo$, p, m, k) to all;

if received ($echo$, p, m, k) from at least $n-t$ distinct processes in phase $2k$

accept (p, m, k);

Round $r > k$:

Phase $2r-1$, $2r$: each process executes:

if received ($echo$, p, m, k) from at least $n-2t$ distinct processes in previous phases

and not sent ($echo$, p, m, k)

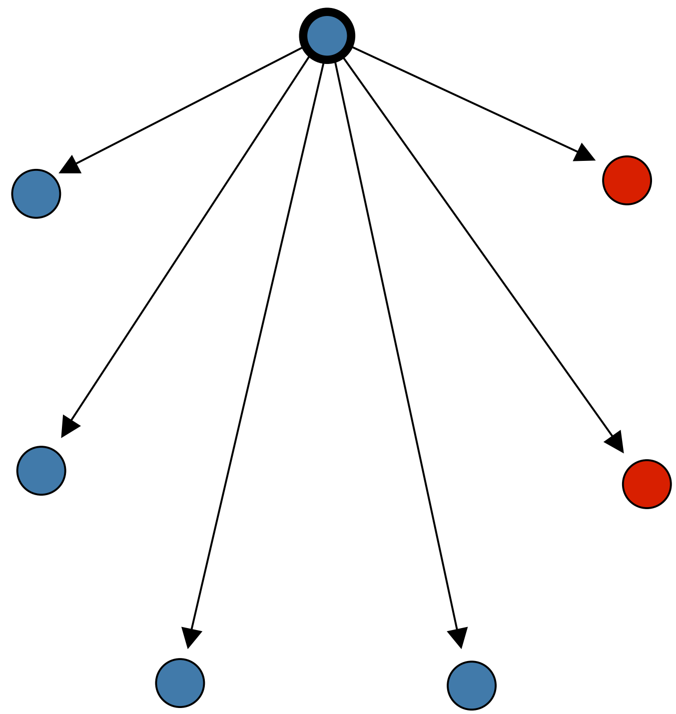
send ($echo$, p, m, k) to all;

if received ($echo$, p, m, k) from at least $n-t$ distinct processes in this and previous phases

accept (p, m, k);

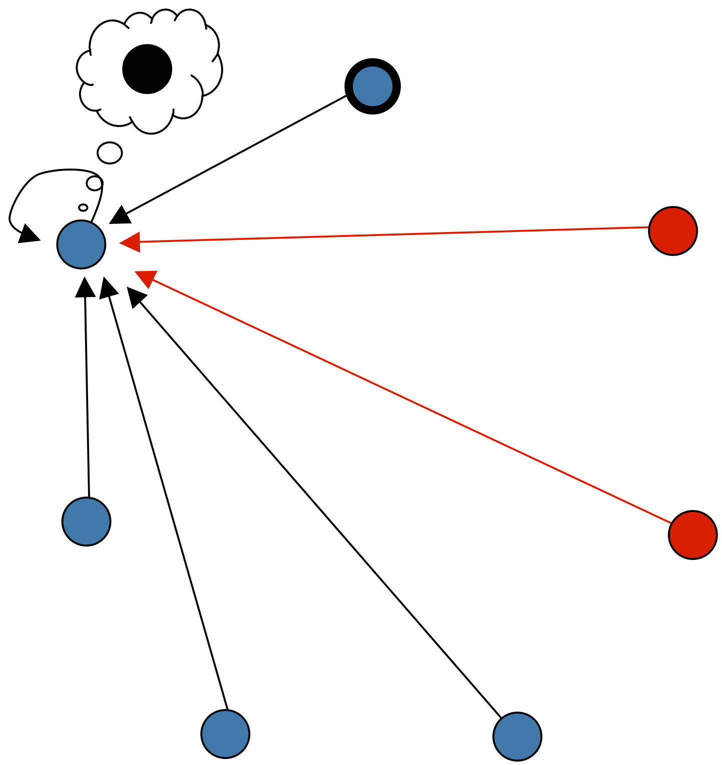
Correct process sends *init* in $2k - 1$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



Correct processes accept in $2k$

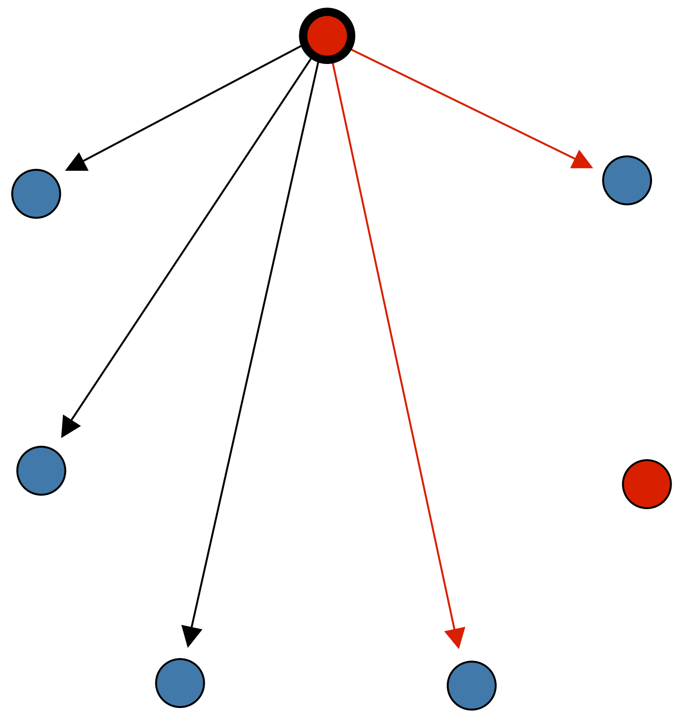
$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



also *Unforgeability*: if correct p does not send (*init*, *p*, *m*, *k*) then each correct process will receive no more than t (*echo*, *p*, *m*, *k*) messages. Since $t < n - 2t$, there will be no more witnesses.

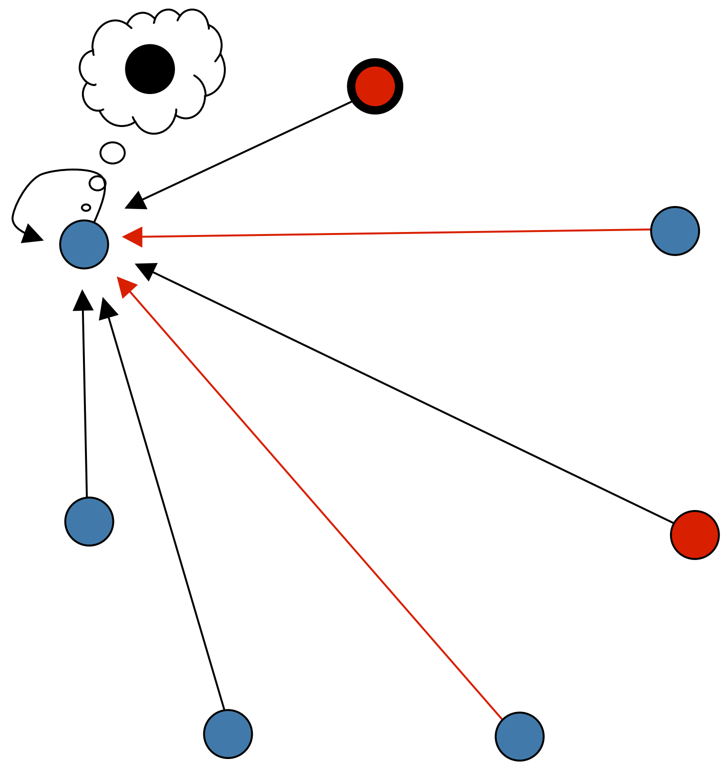
Faulty sends *init* in $2k - 1$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



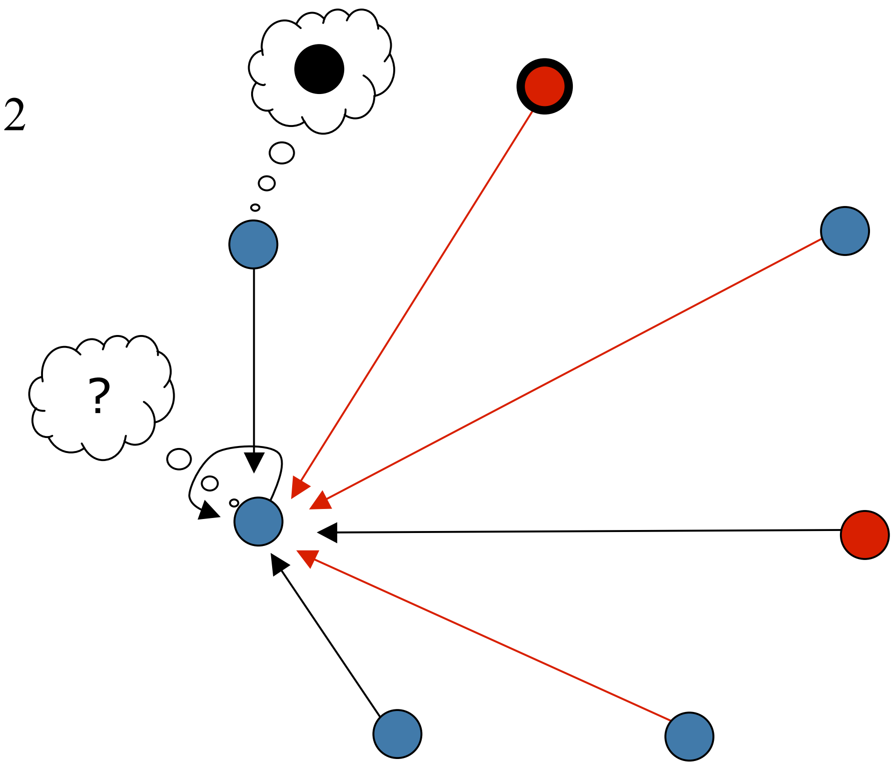
Correct can behave differently in $2k$: I

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



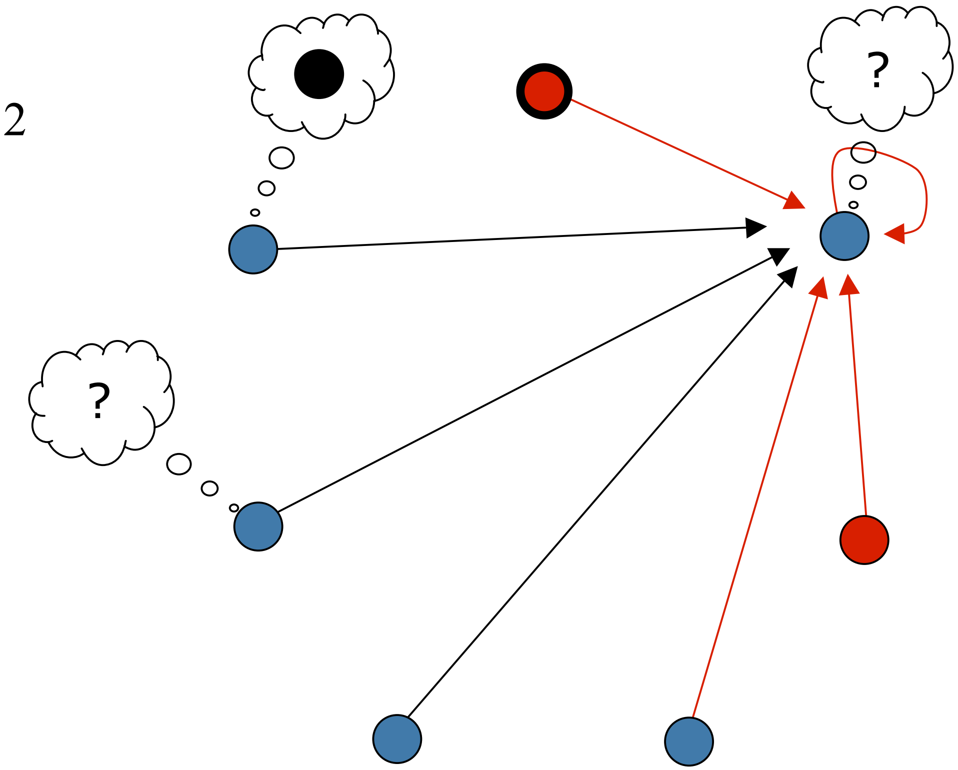
Correct can behave differently in $2k$: II

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



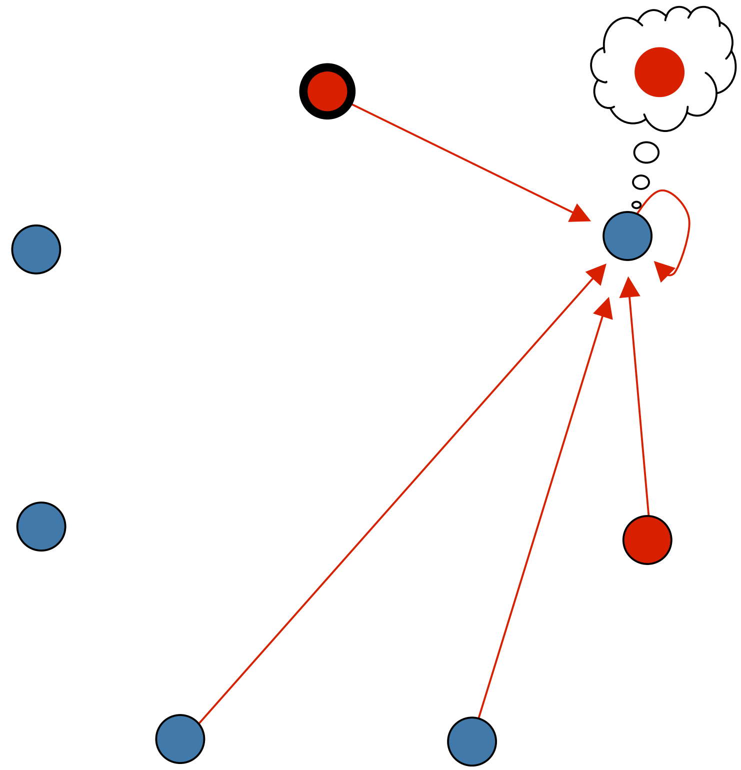
Correct can behave differently in 2*k*: III

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



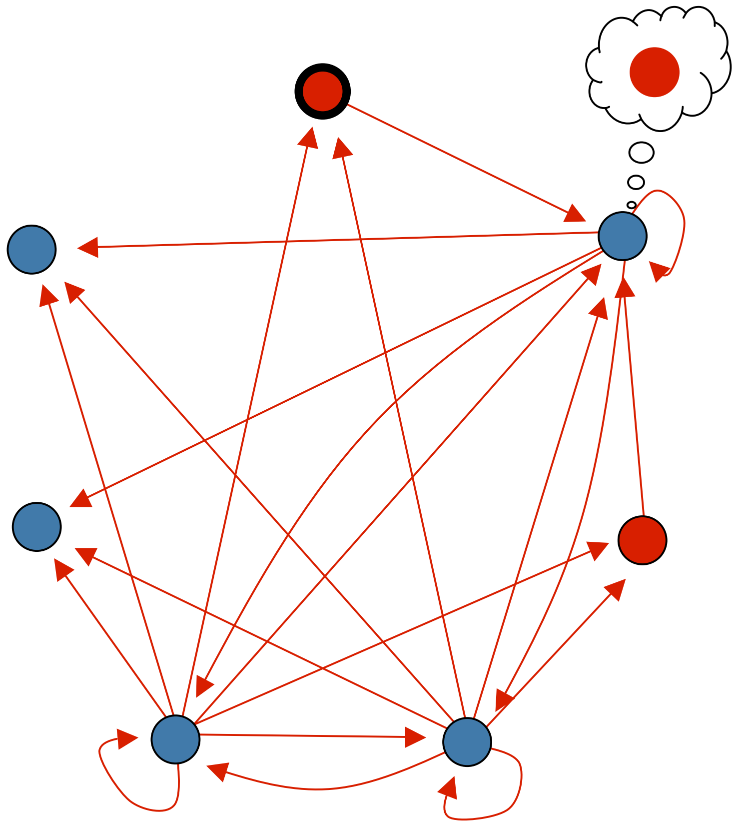
Relay: phase i

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



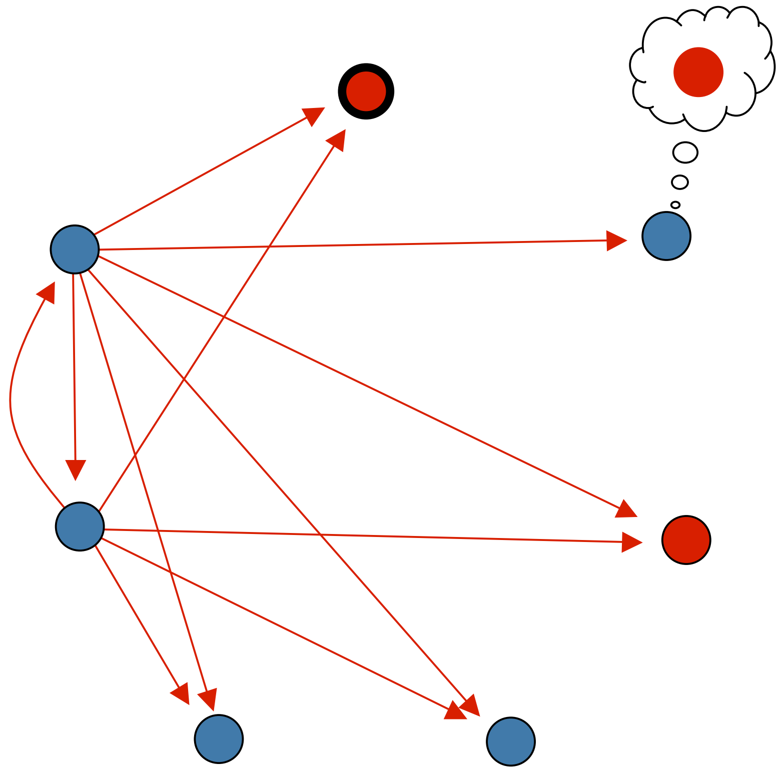
Relay: phase i

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



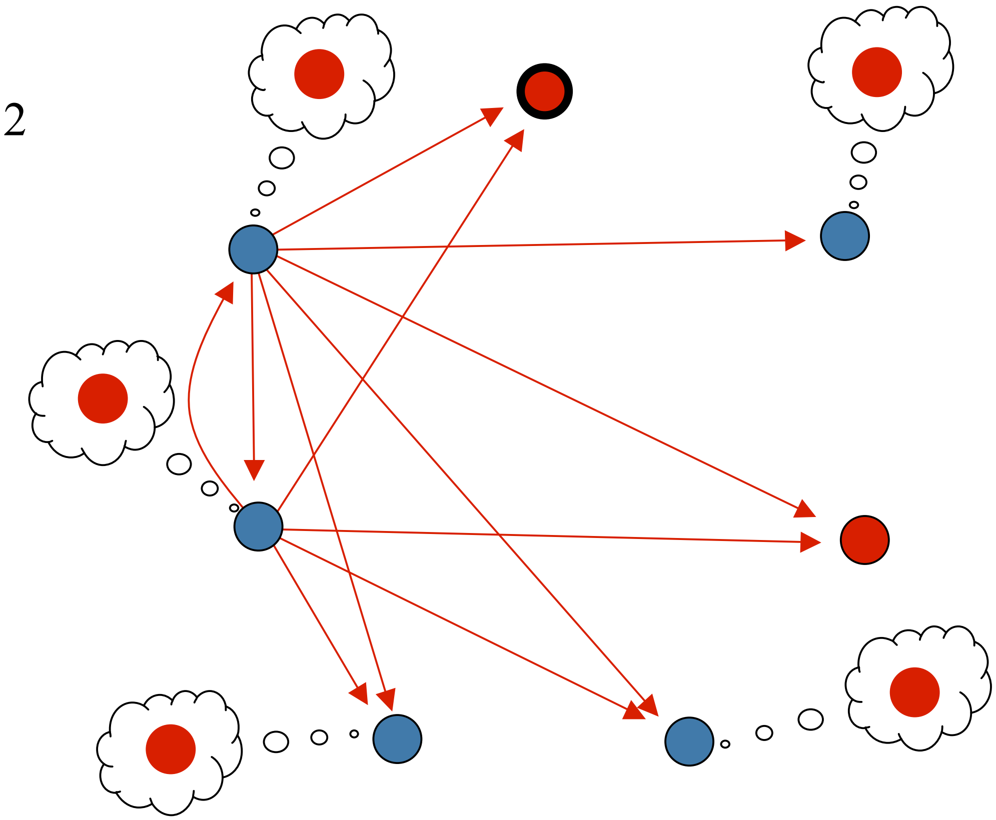
Relay: phase $i + 1$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



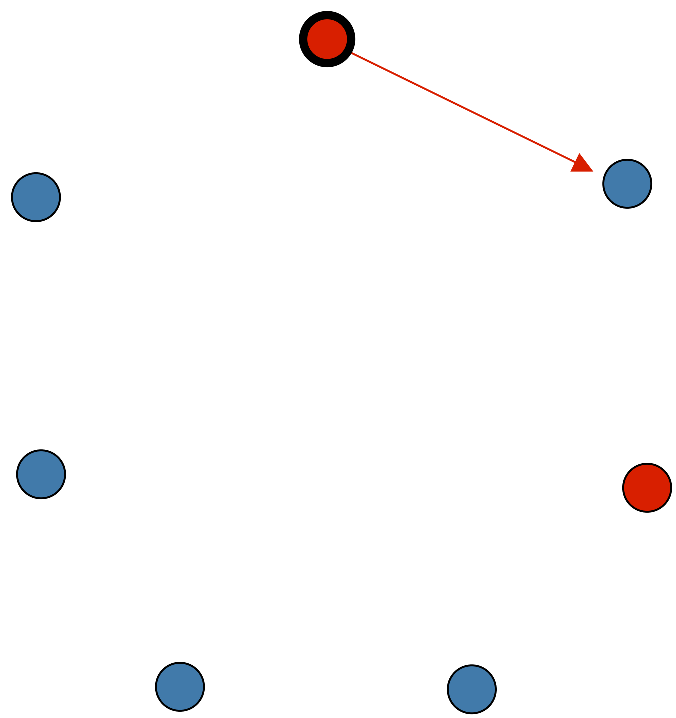
Relay: phase $i + 1$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



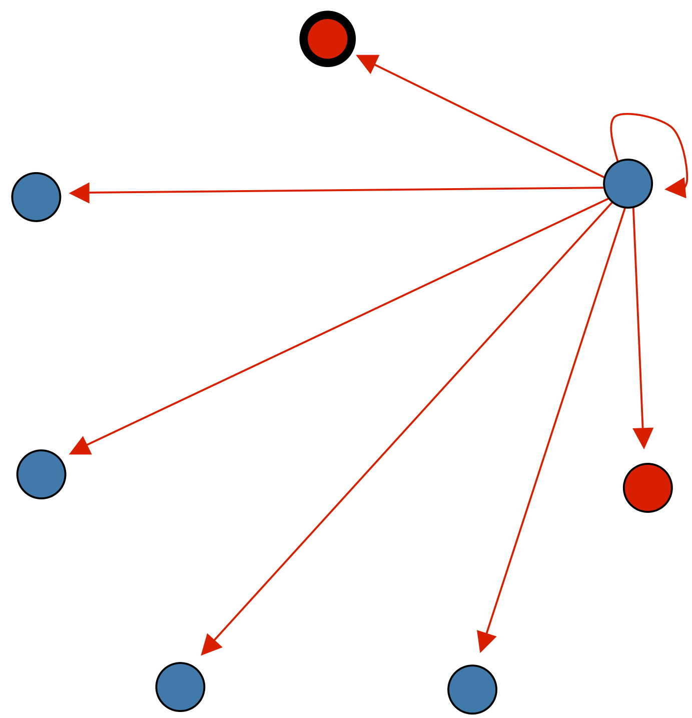
Delaying accept arbitrarily long: $2k$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



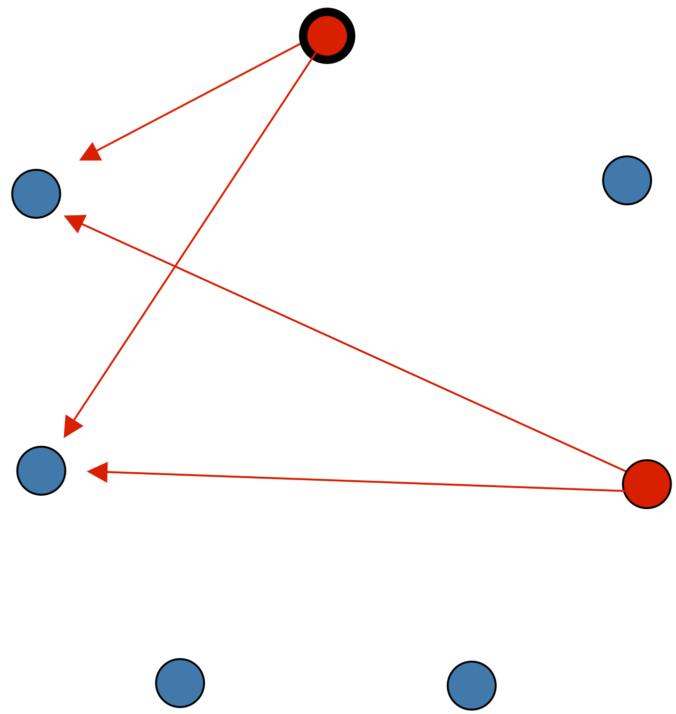
Delaying accept arbitrarily long: $2k + 1$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



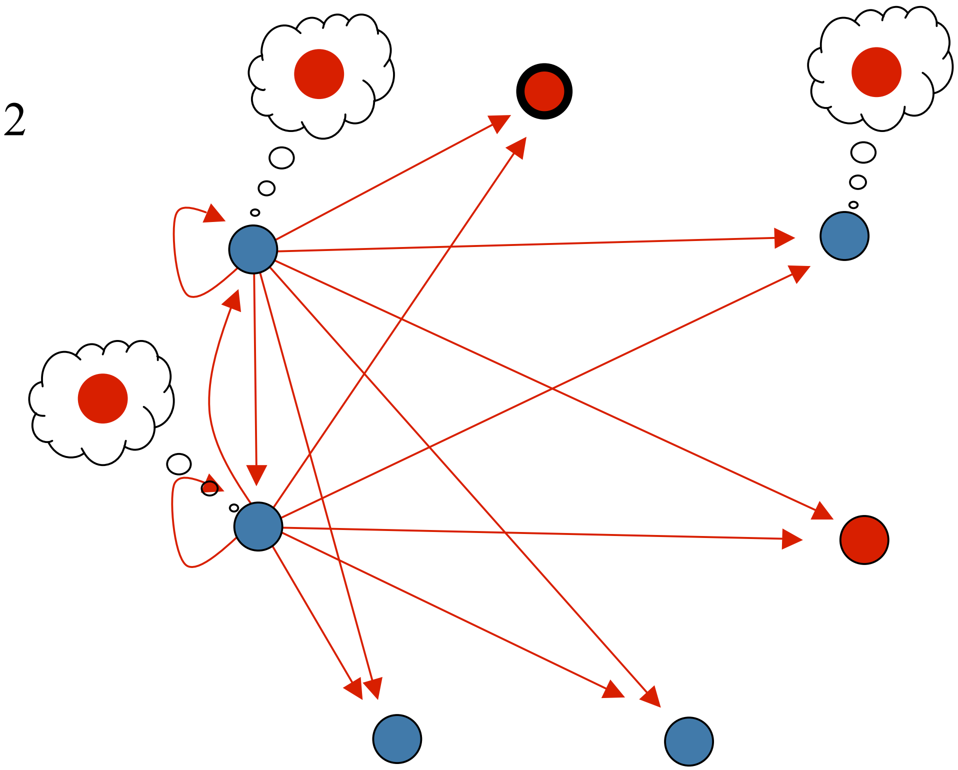
Arbitrarily later… phase i

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



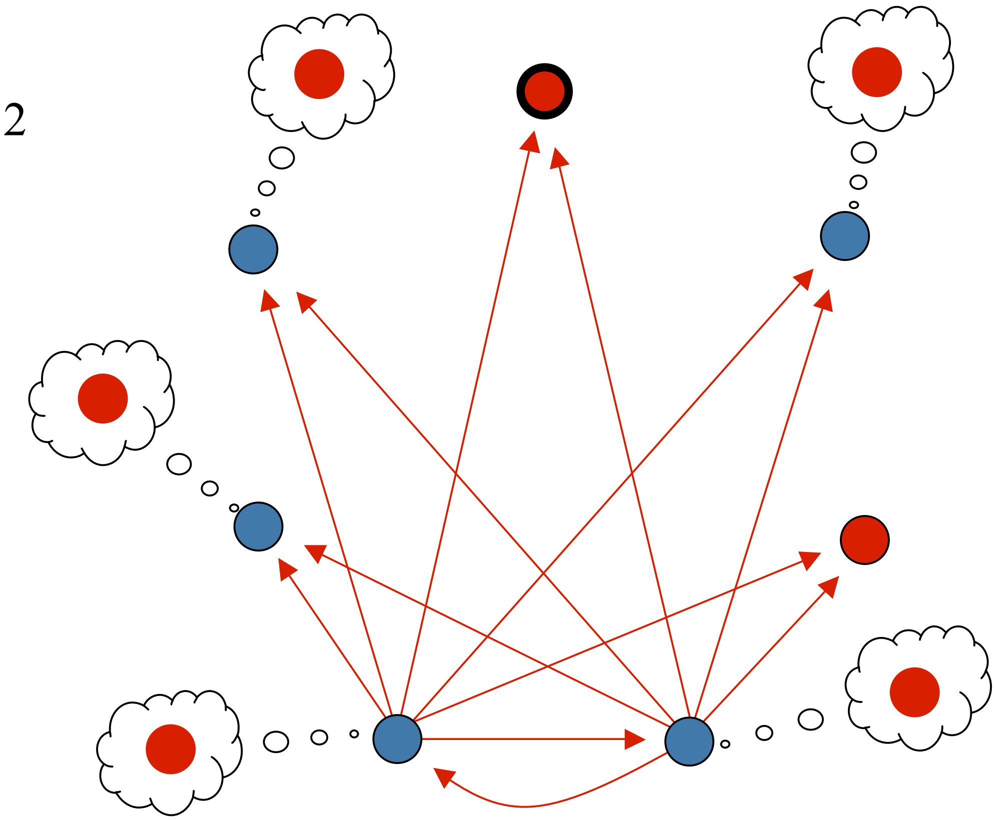
Arbitrarily later… phase $i + 1$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



Arbitrarily later… phase $i + 2$

$n = 7, t = 2$
$n - t = 5$
$n - 2t = 3$



Nonauthenticated Arbitrary Consensus

// $m \in \{0, 1\}$, nonloquacious protocol

process p:

  if ($p == p_1$) $value = m$;

  else $value = 0$;

  for r =1 to $t + 1$

    if ($value == 1$ and (p not broadcast in earlier round))

      broadcast(p, 1, r);

    if (in rounds $r' \le r$ *accepted* (p_k, 1, r_k) from r distinct

      processes p_k including the transmitter p_1)

    $value = 1$;

decide *value*;

Other results from this approach

- Multivalued agreement
- Voting
- Asynchronous randomized agreement
- Clock synchronization