

Model Checking of Fault-Tolerant Distributed Algorithms

Part I: Fault-Tolerant Distributed Algorithms

Annu Gmeiner Igor Konnov Ulrich Schmid
Helmut Veith Josef Widder



VTSA 2014, Luxembourg

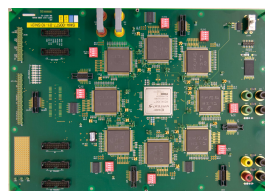
Helmut Veith (www.forsyte.at)

Checking Fault-Tolerant Distributed Algos

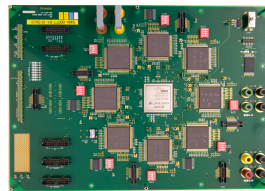
VTSA, October 2014

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Distributed Systems



Distributed Systems



Are they always working?

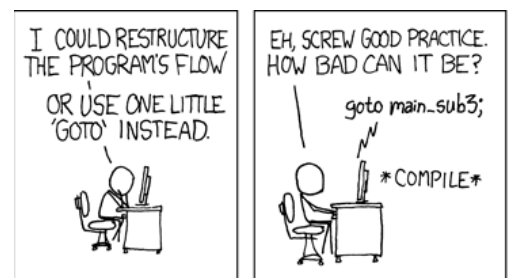
No... some failing systems

- Therac-25 (1985)
 - radiation therapy machine
 - gave massive overdoses, e.g., due to race conditions of **concurrent tasks**
- Quantas Airbus in-flight Learmonth upset (2008)
 - 1 out of 3 **replicated components** failed
 - computer initiated dangerous altitude drop
- Ariane 501 maiden flight (1996)
 - primary/backup, i.e., 2 **replicated** computers
 - both run into the same integer overflow
- Netflix outages due to Amazon's cloud (ongoing)
 - one is not sure what is going on there
 - **hundreds of computers** involved

Why do they fail?

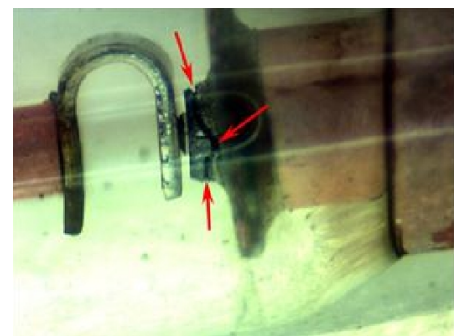
Why do they fail?

- faults at design/implementation phase



- faults at runtime

- outside of control of designer/developer
- e.g., to the right: crack in a diode in the data link interface of the Space Shuttle
⇒ led to erroneous messages being sent



Driscoll (Honeywell)

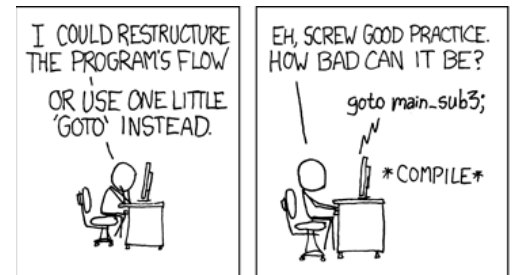
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approach:

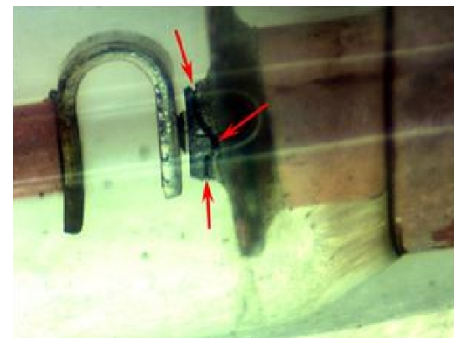
find and fix faults before operation

⇒ model checking



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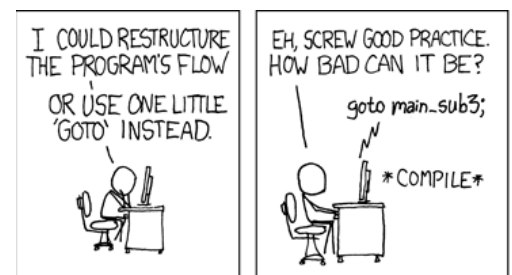
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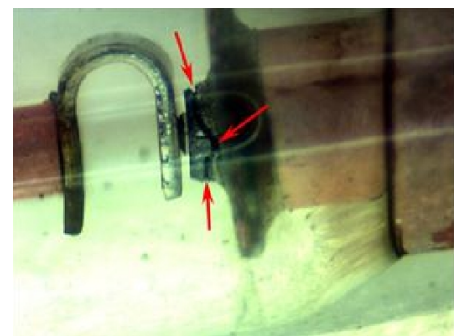
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approach:

keep system operational despite faults

⇒ fault-tolerant distributed algorithms



Driscoll (Honeywell)

Bringing both together

Goal: automatically verified fault-tolerant distributed algorithms

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model checking FTDAs is a research challenge:

- computers run independently at different speeds
- exchange messages with uncertain delays
- faults
- parameterization

... fault-tolerance makes model checking harder

Lecture overview

Part I: Fault-tolerant distributed algorithms

- introduction to distributed algorithms
- details of our case study algorithm
- motivation why model checking is cool

Part II: Modeling fault-tolerant distributed algorithms

- model checking challenges in distributed algorithms
- Promela, control flow automata, etc.
- model checking of small instances with Spin

Lecture overview cont.

Part III: Introduction into Parameterized model checking

- the general problem statement
- well-known undecidability results

Part IV: Parameterized model checking of FTDAs by abstraction

- parametric interval abstraction (PIA)
- PIA data and counter abstraction
- counterexample-guided abstraction refinement (CEGAR)

Igor Konnov:

Part V: Parameterized model checking of FTDAs by BMC

- bounding the diameter
- bounded model checking as a complete method

Part I: Fault-Tolerant Distributed Algorithms

Distributed Systems are everywhere

What they allow to do

- share resources
- communicate
- increase performance
 - speed
 - fault tolerance

Difference to centralized systems

- independent activities (concurrency)
- components do not have access to the global state (only “local view”)

Application areas

buzzwords from the 60ies

- operating systems
- (distributed) data base systems
- communication networks
- multiprocessor architectures
- control systems

New buzzwords

- cloud computing
- social networks
- multi core
- cyber-physical systems

Major challenge

Uncertainty

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challenge in proving them correct

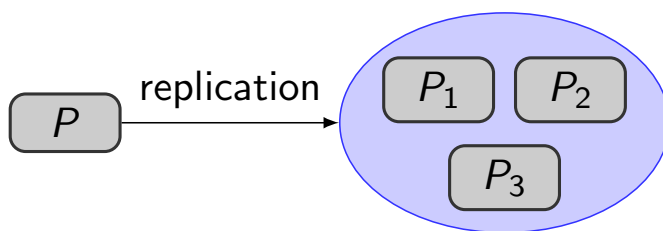
- large degree of non-determinism
⇒ large execution and state space

From dependability to a distributed system



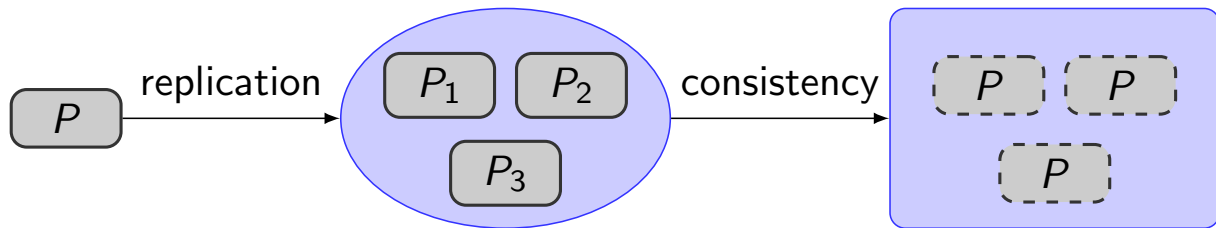
- Process P provides a service. We want to access it reliably
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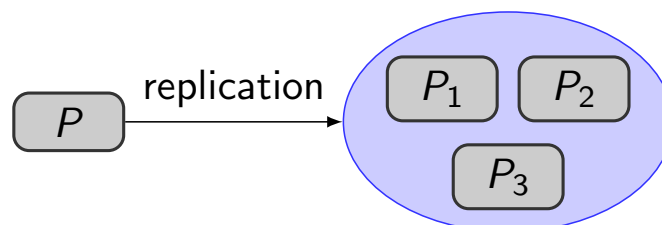
- Process P provides a service. We want to access it reliably
but P may fail
- canonical approach: replication, i.e., several copies of P
Due to non-determinism, the behavior of the copies might deviate
(e.g. in a replicated database, transactions are committed in different
orders at different sites)

From dependability to a distributed system



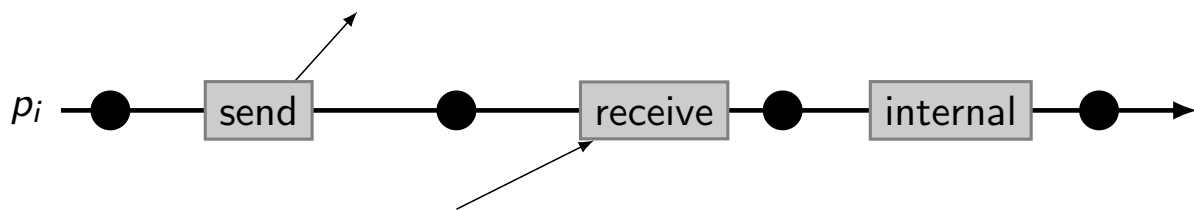
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Due to non-determinism, the behavior of the copies might deviate (e.g. in a replicated database, transactions are committed in different orders at different sites)
- \Rightarrow we have to enforce that the copies “behave as one”.
 \Rightarrow Consistency in a distributed system: what does it mean to *behave as one*.

Replication — distributed systems



Distributed message passing system

multiple distributed processes p_i



- dots represent **states**
- a **step** of a process can be
 - a send step (a process sends messages to other processes)
 - a receive step (a process receives a subset of messages sent to it)
 - an internal step (a local computation)
- steps are the atomic (indivisible) units of computations

Types of Distributed Algorithms: Synchronous vs. Asynchronous

Synchronous

- all processes move in lock-step
- rounds
- a message sent in a round is received in the same round
- idealized view
- impossible or expensive to implement

Asynchronous

- only one process moves at a time
- arbitrary interleavings of steps
- a message sent is received eventually

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We focus on asynchronous algorithms here. . .

Asynchronous system

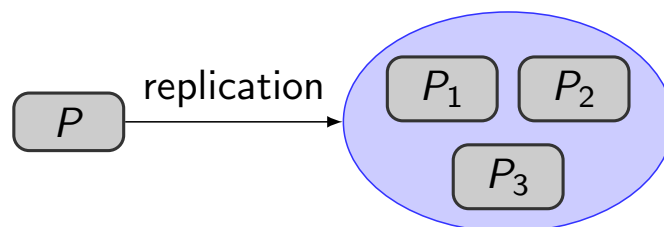
has very mild restrictions on the environment

- interleaving semantics
- unbounded message delays

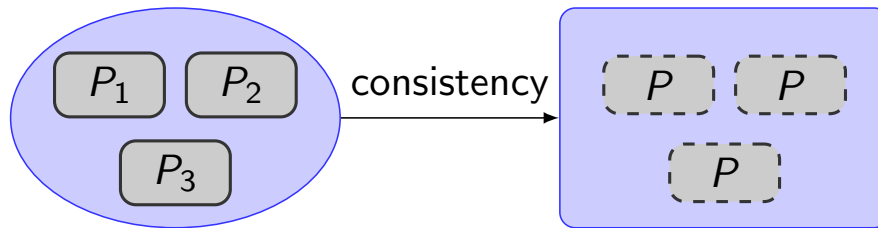
very little can be done. . .

- there is no distributed algorithm that solves consensus in the presence of one faulty process
(as we will see, consensus is the paradigm of consistency)
- folklore explanation:
“you cannot distinguish a slow process from a crashed one”
- real explanation:
see intricate proof by Fischer, Lynch, and Paterson (JACM 1985)

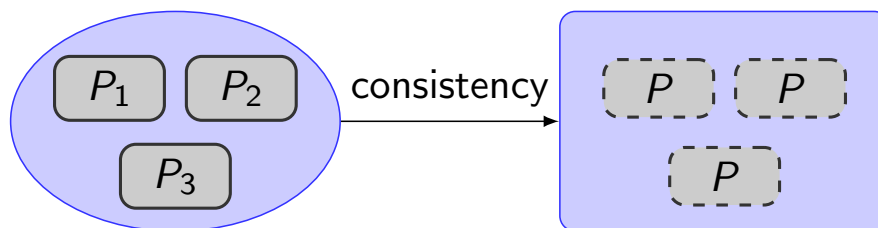
Where we stand



What we still need...

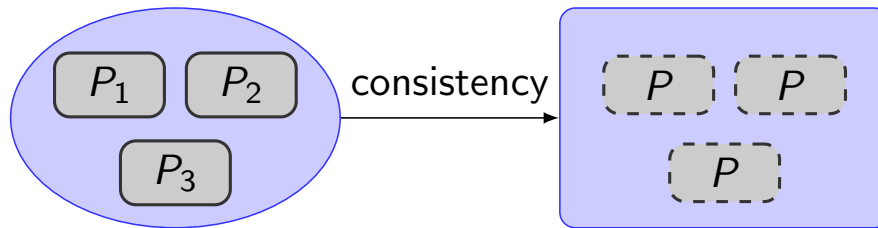


What we still need...



- consistency requirements have been formalized under several names, e.g.,
 - consensus
 - atomic broadcast
 - Byzantine Generals problem
 - Byzantine agreement
 - atomic commitment
- definitions are similar but may have subtle differences

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- consistency requirements have been formalized under several names, e.g.,
 - consensus
 - atomic broadcast
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- definitions are similar but may have subtle differences
- We use the famous Byzantine Generals to introduce this problem domain...

Fault tolerance – The Byzantine generals problem

Wiktionary:

Byzantine: adj. of a devious, usually stealthy manner, of practice.

Fault tolerance – The Byzantine generals problem

Lamport (this year's Turing laureate), Shostak, and Pease wrote in their *Dijkstra Prize in Distributed Computing* winning paper (Lamport et al., 1982):

[...] several divisions of the Byzantine army are camped outside an enemy city, each division commanded by its own general. [...] However, some of the generals may be traitors [...]

- if the divisions of loyal generals attack together, the city falls
- if only some loyal generals attack, their armies fall
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The Byzantine generals problem:

- the loyal generals have to agree on whether to attack.
- if all want to attack they must attack, if no-one wants to attack they must not attack

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metaphor for a distributed system where correct processes (loyal generals) act as one in the presence of faulty processes (traitors)

Byzantine generals problem cont.

In the absence of faults it is trivial to solve:

- send proposed plan (“attack” or “not attack”) to all
- wait until received messages from everyone
- if a process proposed “attack” decide to attack
- otherwise, decide to not attack

Byzantine generals problem cont.

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In the presence of faults it becomes tricky

- if a process may crash, some processes may not receive messages from everyone (but some may)
- if a process may send faulty messages, contradictory information may be received, e.g.,
“A tells B that C told A that C wants to attack, while C tells B that C does not want to attack”

Byzantine generals problem cont.

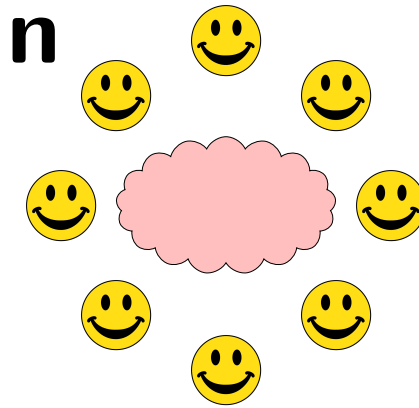
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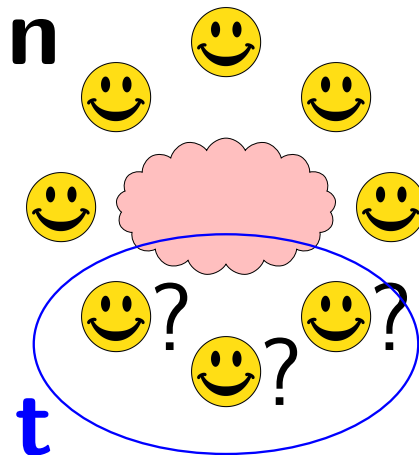
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Who is lying to whom?

Fault-tolerant distributed algorithms



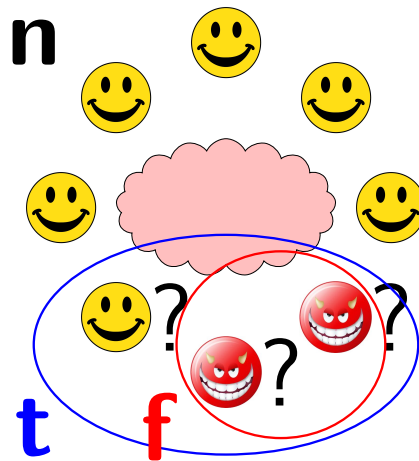
- n processes communicate by messages (reliable communication)
- all processes know that at most t of them might be faulty
- f are actually faulty
- resilience conditions, e.g., $n > 3t \wedge t \geq f \geq 0$
- no masquerading: the processes know the origin of incoming messages

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Fault models—abstractions of reality

- clean crashes: least severe
faulty processes prematurely halt after/before “send to all”
- crash faults:
faulty processes prematurely halt (also) in the middle of “send to all”
- omission faults:
faulty processes follow the algorithm, but some messages sent by them might be lost
- symmetric faults:
faulty processes send arbitrarily to all or nobody
- Byzantine faults: most severe
faulty processes can do anything
encompass all behaviors of above models

Fault models—the ugly truth

A photo of a Byzantine fault:

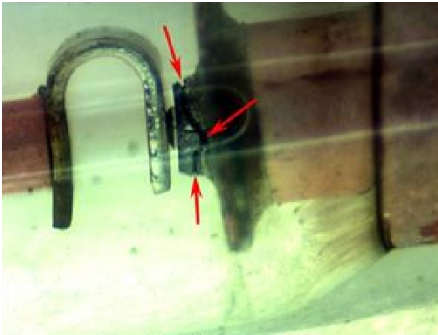


photo by Driscoll (Honeywell)

he reports Byzantine behavior on the Space Shuttle computer network

other sources of faults: bit-flips in memory, power outage, disconnection from the network, etc.

Model vs. reality: impossibilities

Hence, we would like the weakest assumptions possible. But there are theoretical limits on how weak assumptions can be made:

- consensus is impossible in asynchronous systems if there may be a crash fault, i.e., $t = 1$ (Fischer *et al.*, 1985)
- consensus is possible in synchronous systems in the presence of Byzantine faults iff $n > 3t$ (Lamport *et al.*, 1982)
- consensus is impossible in (synchronous) round-based systems if $\lfloor n/2 \rfloor$ messages can be lost per round (Santoro & Widmayer, 1989)
- fast Byzantine consensus is solvable iff $n > 5t$ (Martin & Alvisi, 2006)
- 32 different “degrees of synchrony” and whether consensus can be solved in the presence of **how many** faults investigated in (Dolev *et al.*, 1987)

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arithmetic resilience conditions play crucial role!

After this excursion to faults, let's
go back to the problem of defining
consistency

(asynchronous systems)

Defining consistency — e.g., binary consensus

Every process has some initial value $v \in \{0, 1\}$ and has to decide **irrevocably** on some value in concordance with the following properties:

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- termination.** Every correct process eventually decides.
at some point negotiations must be over

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Interplay of safety and liveness makes the problem hard. . .

What if only two properties have to be satisfied?

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Give an algorithm that solves validity and termination!

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Solution: decide my own proposed value. (no need to agree)

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Solution: decide 0. (no relation to initial values required)

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Solution: do nothing (doing nothing is always safe)

Wrap-up: Intro to FTDAs

- distributed systems
- replication and consistency
- synchronous vs. asynchronous
- fault models
- example for an agreement problem: Byzantine Generals

Our case study...

Asynchronous FTDAs

In this lecture we consider methods for asynchronous FTDAs that either

- solve problems that are less hard than consensus:

reliable broadcast. termination required only for specific initial state (Srikanth & Toueg, 1987). [Verified in Parts II, III, V]

condition-based consensus properties required only in runs from specific initial states (Mostéfaoui *et al.*, 2003)

[Verified in Part II]

The Paxos idea fault-tolerant distributed algorithms that are **safe** and make **progress** only if you are “lucky” (Lamport, 1998)

[Serious challenge]

- are asynchronous but use “information on faults” as a black box

failure detector based atomic commitment. distributed databases (Raynal, 1997)

[Challenge]

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We use the algorithm from (Srikanth & Toueg, 1987) as running example

Asynchronous Reliable Broadcast (Srikanth & Toueg, 87)

The **core** of the classic broadcast algorithm from the DA literature.

```
1  Variables of process i
2   $v_i: \{0, 1\}$  initially 0 or 1
3   $accept_i: \{0, 1\}$  initially 0
4
5  An atomic step:
6  if  $v_i = 1$ 
7  then send (echo) to all;
8
9  if received (echo) from at least
10  $t + 1$  distinct processes
11 and not sent (echo) before
12 then send (echo) to all;
13
14 if received (echo) from at least
15  $n - t$  distinct processes
16 then  $accept_i := 1$ ;
```

Assumptions from (Srikanth & Toueg, 87)

- asynchronous interleaving
- reliable message passing (no bounds on message delays)
- at most t Byzantine faults
- resilience condition: $n > 3t \wedge t \geq f$

The spec of our case-study

Unforgeability. If $v_i = \text{FALSE}$ for all correct processes i , then for all correct processes j , accept_j remains FALSE forever.

Completeness. If $v_i = \text{TRUE}$ for all correct processes i , then there is a correct process j that eventually sets accept_j to TRUE.

Relay. If a correct process i sets accept_i to TRUE, then eventually all correct processes j set accept_j to TRUE.

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if no loyal general wants to attack, then traitors should not be able to force one.

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If all loyal generals want to attack, there shall be an attack.

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These are the specs as given in literature: they can be formalized in LTL

Reliable broadcast vs. Consensus

Reliable broadcast: Completeness. If $v_i = \text{TRUE}$ for all correct processes i , then there is a correct process j that eventually sets accept_j to TRUE .

Consensus: Termination. Every correct process eventually decides.

Difference:

- Completeness requires to “do something” only if $\forall i. v_i = \text{TRUE}$, i.e., only for one specific initial state
- Termination requires to “do something” in all runs (from all initial states)
- weakening of spec makes reliable broadcast solvable in async, while consensus is not solvable

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Threshold-Guarded Distributed Algorithms

Standard construct: quantified guards ($t=f=0$)

- Existential Guard
if received m from *some* process then ...
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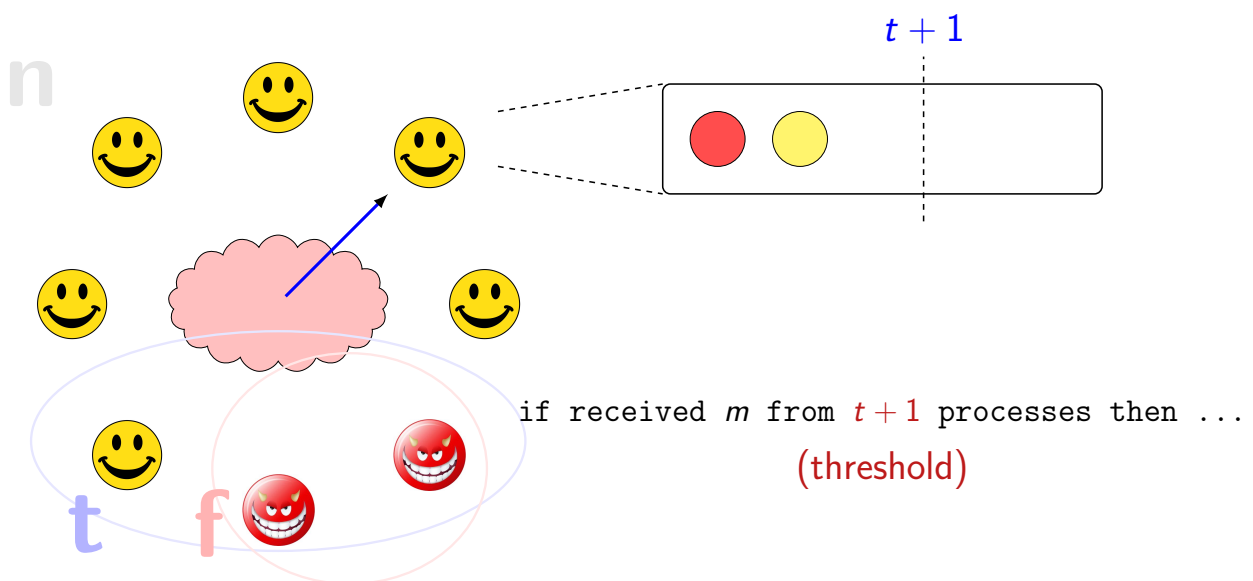
what if faults might occur?



Fault-Tolerant Algorithms: n processes, at most t are Byzantine

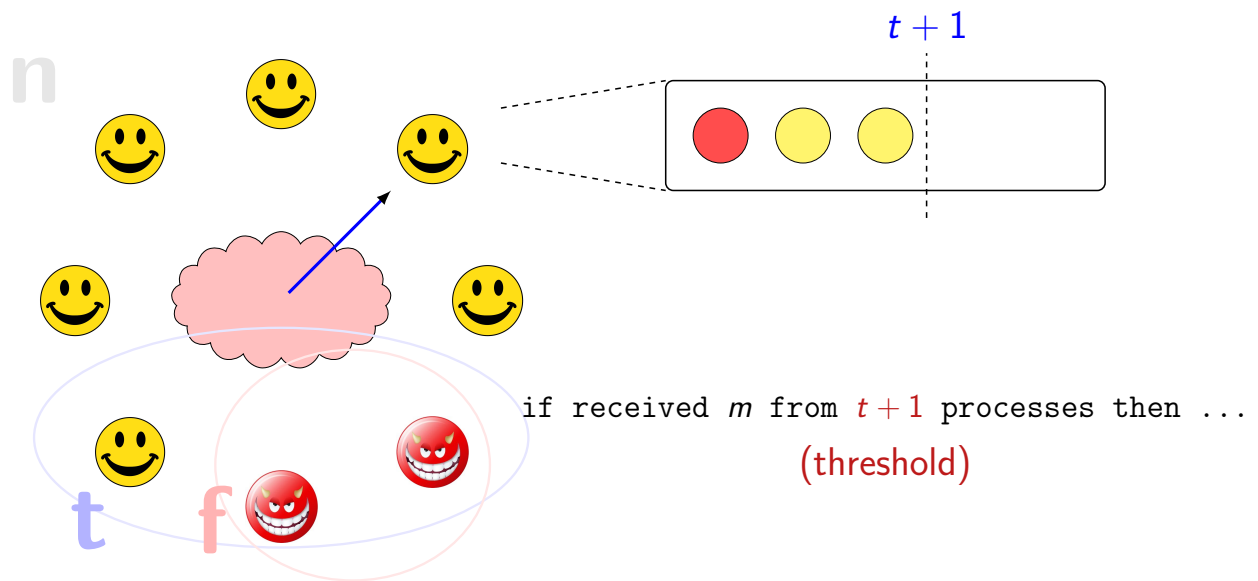
- Threshold Guard
if received m from $n - t$ processes then ...
- (the processes *cannot refer to f !*)

Basic mechanisms used by the algorithm: thresholds



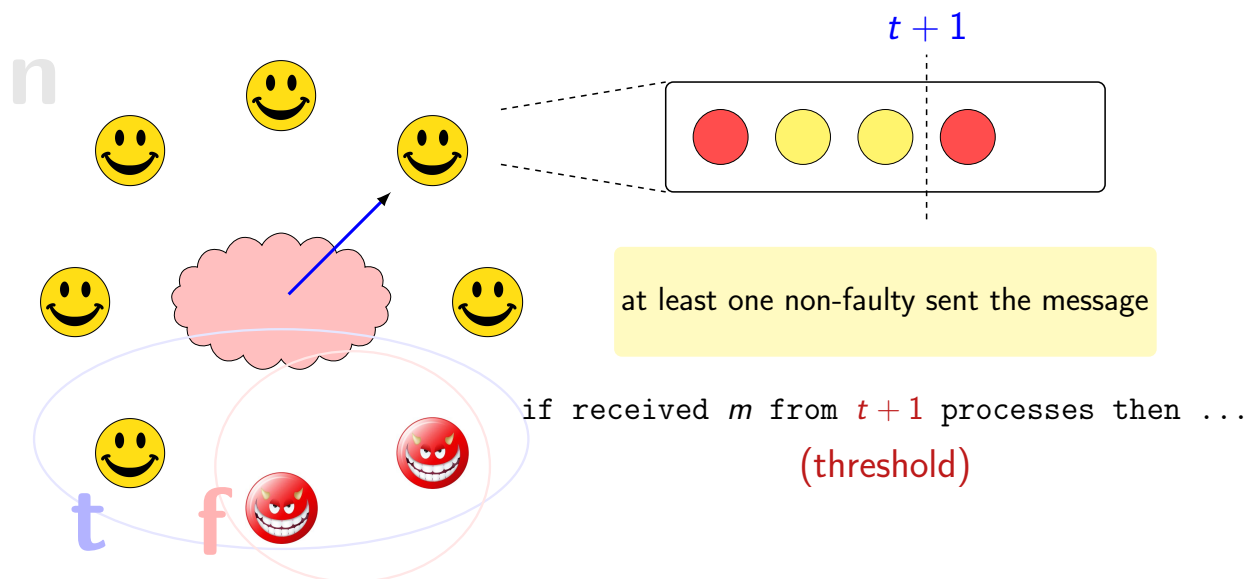
Correct processes count **distinct** incoming messages

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Classic correctness argument — hand-written proofs

Proof: Unforgeability

If $v_i = \text{FALSE}$ for all correct processes i , then for all correct processes j , accept_j remains FALSE forever.

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- contradiction to p being the first one.

Proof: Completeness

If $v_i = \text{TRUE}$ for all correct processes i , then there is a correct process j that eventually sets accept_j to TRUE.

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If a correct process i sets accept_i to TRUE, then eventually all correct processes j set accept_j to TRUE.

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Problems with hand-written proofs

- code inspection becomes confusing for larger algorithms

Bracha & Toueg's algorithm (JACM 1985)

```
msg_count: array of [types: 0..1] of integer
msg: record of type: (initial, echo, ready)
value: integer
while (there is no i such that
    msg_count(initial, i) ≥ 1 or
    msg_count(echo, i) > (n + k)/2 or
    msg_count(ready, i) ≥ k + 1)
    receive(msg)
    if it is the first message received from the sender
    with these values of msg.type, msg.from
    then msg_count(msg.type, msg.value) = msg_count(msg.type, msg.value) + 1
end
for all q, send(echo, i)
while (there is no i such that
    msg_count(echo, i) > (n + k)/2 or
    msg_count(ready, i) ≥ k + 1)
    receive(msg)
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    with these values of msg.type, msg.from
    then msg_count(msg.type, msg.value) = msg_count(msg.type, msg.value) + 1
end
for all q, send(ready, i)
while (there is no i such that
    msg_count(ready, i) ≥ 2k + 1)
    receive(msg)
    if it is the first message received from the sender
    with these values of msg.type, msg.from
    then msg_count(msg.type, msg.value) = msg_count(msg.type, msg.value) + 1
end
decide i
```

FIG. 3. An asynchronous Byzantine Agreement protocol.

Part II, Part V

Condition-based consensus (Mostéfaoui *et al.*, 2003)

```
Function Consensus( $v_i$ )
(1) foreach  $j \in [1..n]$  do  $V_i[j] \leftarrow \perp$  enddo; % Initialization%
    %-----Phase 1-----
(2)  $UR\_Broadcast$  PHASE1( $v_i, i$ );
(3) wait until (PHASE1( $-, -$ ) messages have been delivered from at least  $(n - f)$  processes);
(4) foreach  $j \in [1..n]$  do if (PHASE1( $v_j, j$ ) has been delivered) then  $V_i[j] \leftarrow v_j$  endif enddo;
(5)  $w_i \leftarrow S(V_i)$ ; % Estimate of the decision %
    %-----Phase 2-----
(6)  $UR\_Broadcast$  PHASE2( $v_i, w_i, i$ );
(7) repeat wait until (a new PHASE2( $v_j, w_j, j$ ) message has been delivered);
(8)     if ( $V_i[j] = \perp$ ) then  $V_i[j] \leftarrow v_j$  endif;
(9)     if (PHASE2( $-, w, -$ ) msgs with same  $w$  delivered from a majority of proc.)
(10)         then return( $w$ ) endif
(11) until (a PHASE2( $-, -, -$ ) message has been delivered from each process) endrepeat;
(12) return (a deterministically chosen value of  $V_i$ )
```

Figure 1. A Condition-Based Message Passing Consensus Protocol ($f < n/2$)

Part II, Part V

Problems with hand-written proofs

- code inspection becomes confusing for larger algorithms
- hidden assumptions
 - resilience condition
 - reliable communication (fairness)
 - non-masquerading
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Problems with hand-written proofs

- code inspection becomes confusing for larger algorithms
- hidden assumptions
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 - failure model
- re-using proofs if one of the ingredients changes?
- if I cannot prove it correct, that does not mean the algorithm is wrong
... how to come up with counterexamples?
- ultimate goal: verify the actual source code.
... it is not realistic that developers do mathematical proofs.

We have convinced a human, ...

... why should we convince a computer?

- it is easy to make mistakes in proofs

We have convinced a human, . . .

. . . why should we convince a computer?

- it is easy to make mistakes in proofs
- it is easier to overlook mistakes in proofs
 - distributed algorithms require “non-centralized thinking” (untypical for the human mind)
 - many issues to consider at the same time (interleaving of steps, faults, timing assumptions)

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 - distributed algorithms require “non-centralized thinking” (untypical for the human mind)
 - many issues to consider at the same time (interleaving of steps, faults, timing assumptions)
- people who tried to convince computers found bugs in published. . .
 - Byzantine agreement algorithm (Lincoln & Rushby, 1993)
 - clock synchronization algorithm (Malekpour & Siminiceanu, 2006)

End of Part I

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Model vs. reality: assumption coverage

Every assumption has a probability that it is satisfied in the actual system:

- $n > 3t$
less likely than $n > t$
- every message sent is received within bounded time
less likely than that it is eventually received
- processes fail by crashing
less likely than they deviate arbitrarily from the prescribed behavior
- non-masquerading
less likely than processes that can pretend to be someone else

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To use a distributed algorithm in practice:

- one must ensure that an assumption is suitable for a given system
- the probability that the system is working correctly is the probability that the assumptions hold
(given that the distributed algorithm actually is correct)