Fault-Tolerant Computing

About This Presentation

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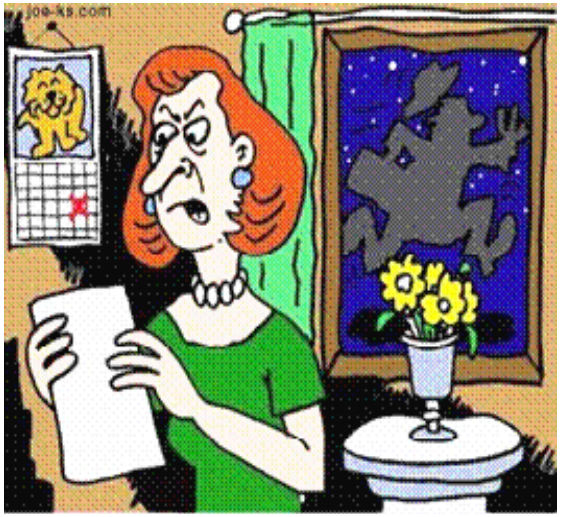
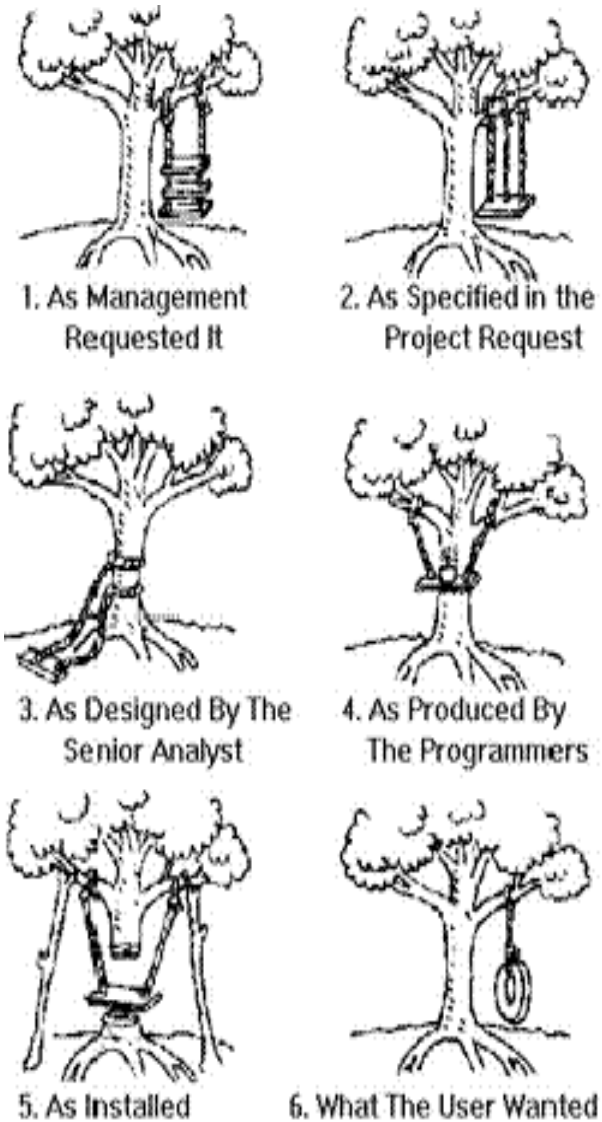
Agreement and Adjudication



Abe, I just noticed – our marriage license has an expiration date! And it's today! Do you know anything about this, Abe? . . . Abe? . . . Abe?

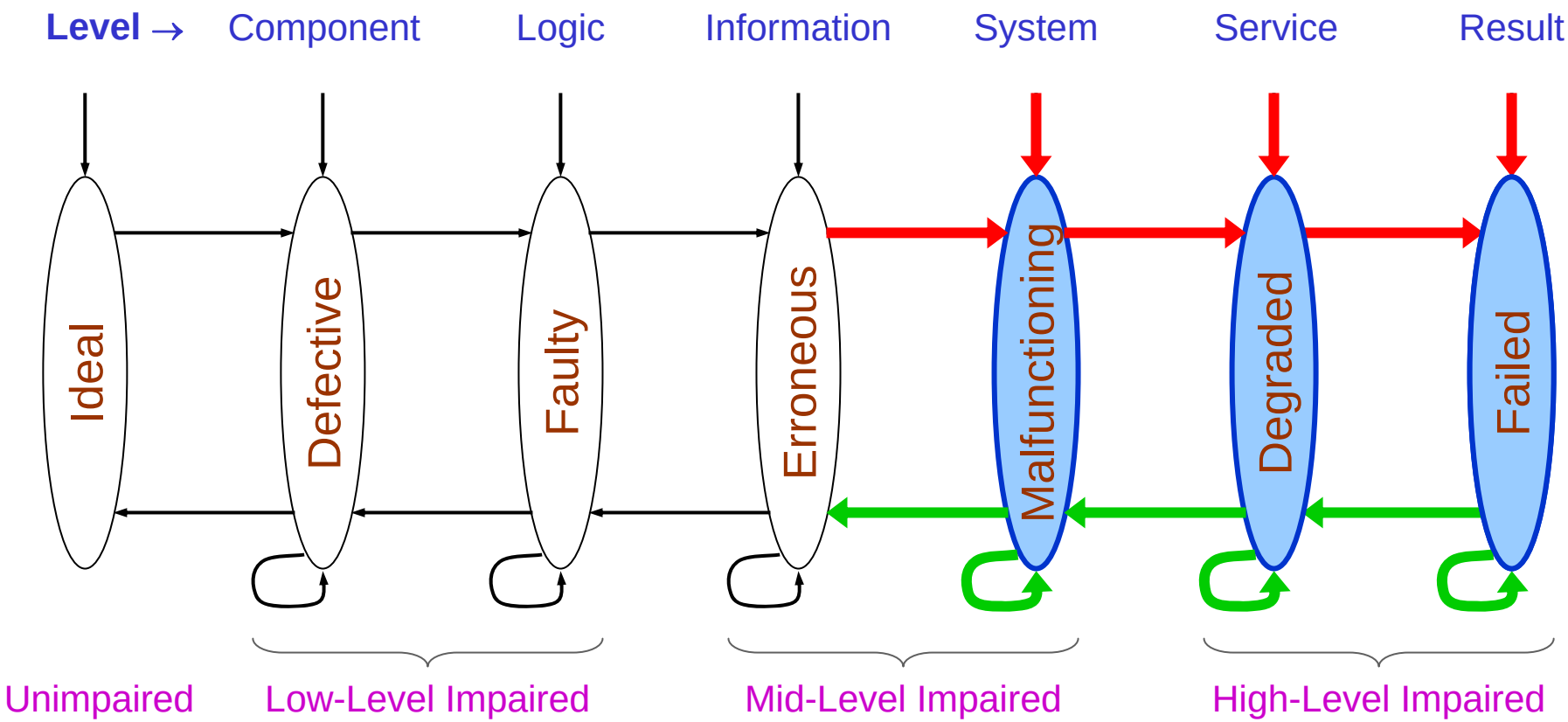
"Next case: the Internet economy versus millions of investors who should have known better."

Software Specification



"It was the only mission statement everyone could agree on."

Multilevel Model of Dependable Computing



Introduction to Voting

Voting schemes and associated terminology in dependable computing were originally derived from concepts in sociopolitical elections

With inputs drawn from a small set of integers, the similarity between the two domains is strong

Example: Radar image analysis used to classify approaching aircraft type as civilian (0), fighter (1), bomber (2).

If three independent units arrive at the conclusions ⟨1, 1, 2⟩, then the presence of a fighter plane may be assumed

Option or candidate 1 “wins” a majority of the vote

With a large or infinite input domain, voting takes on a new meaning

Example: There is no strict majority when distance of an approaching aircraft, in km, is indicated as ⟨12.5, 12.6, 14.0⟩, even though the good agreement between 12.5 and 12.6 could lead to a 12.55 km estimate

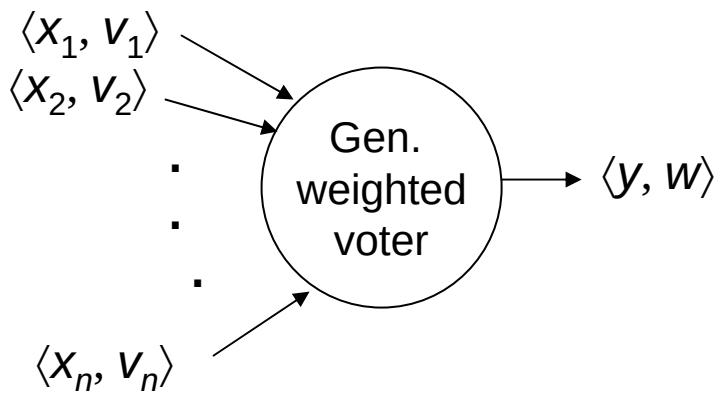
A General Framework for Voting

Virtually all voting schemes of practical interest can be formulated in terms of the generalized weighted voting model, as follows:

Given n input data objects $x_1, x_2, \ldots, x_n$ and associated nonnegative real votes $v_1, v_2, \ldots, v_n$, with $\Sigma v_i = V$, compute output y and its vote w such that y is "supported by" a set of input objects with votes totaling w, where w satisfies a condition associated with the voting subscheme

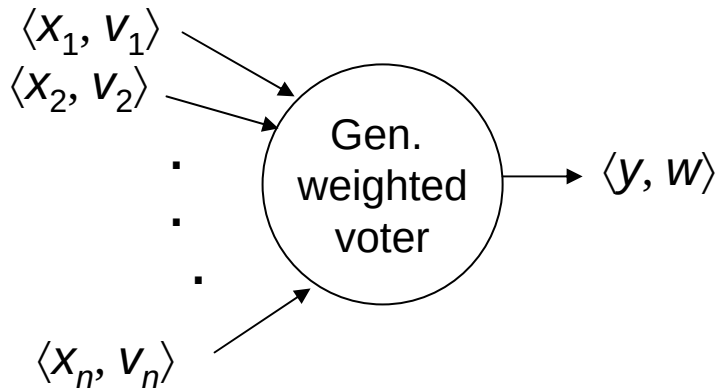
Possible voting subschemes:

Unanimity	$w = V$
Majority	$w > V/2$
Supermajority	$w \geq 2V/3$
Byzantine	$w > 2V/3$
Plurality	(w for y) $\geq$ (w for any $z \neq y$)
Threshold	$w >$ a preset lower bound



A Taxonomy of Voting Schemes

One can classify generalized weighted voting schemes into $2^4 = 16$ categories based on dichotomies associated with input data (the x_is), output data (y), input votes (the v_is), and output vote (w)



Input objects inflexible, or representing flexible "neighborhoods"

First entry in each box is the simpler of the two

	Input	Output
Data	Exact/ Inexact	Consensus/ Mediation
Vote	Oblivious/ Adaptive	Threshold/ Plurality

Total support from a subset of inputs (quorum), or shades of support from all inputs

Input weights set at design time, or allowed to change dynamically (adjustable/variable)

A term such as "threshold voting" stands for 8 different methods

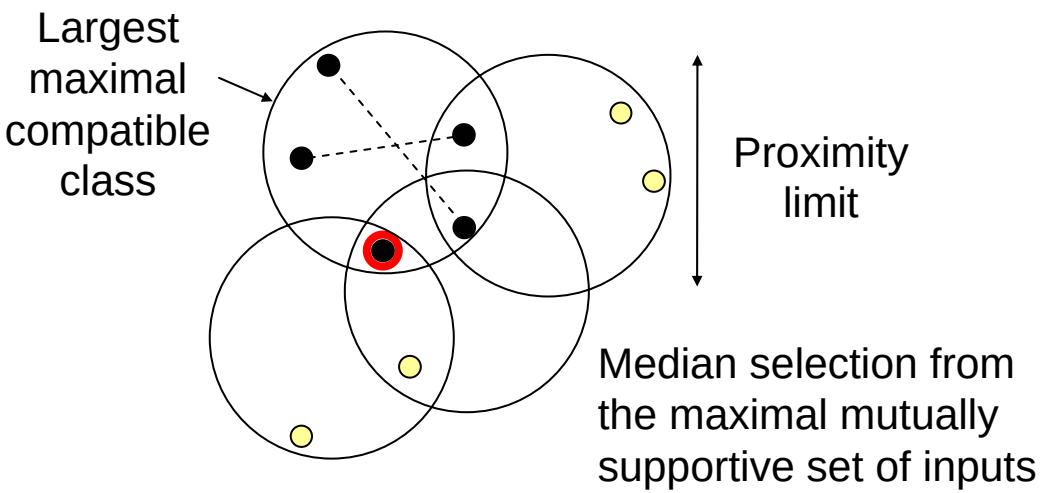
Support exceeds a lower bound, or is max over all possible outputs

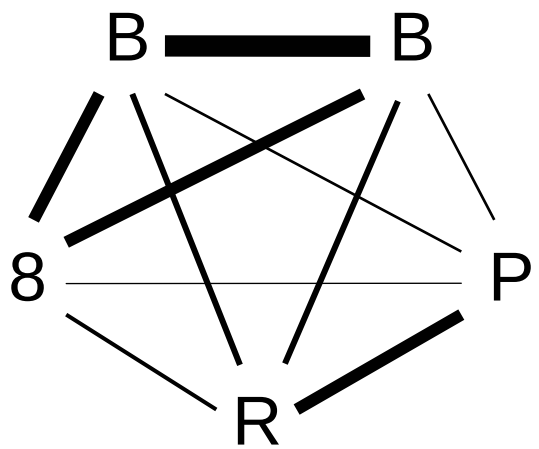
Approximate Voting

The notion of an input object "supporting" a particular output (akin to a hypothesis supporting an end result or conclusion) allows us to treat approximate and exact voting in the same way

Example 1: Input objects are points in the 2D space and the level of "support" between them is a function of their Euclidean distance

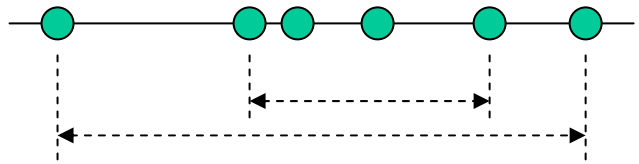
Example 2: Input objects are conclusions of character recognizers as to the identity of a character, with varying degrees of mutual support





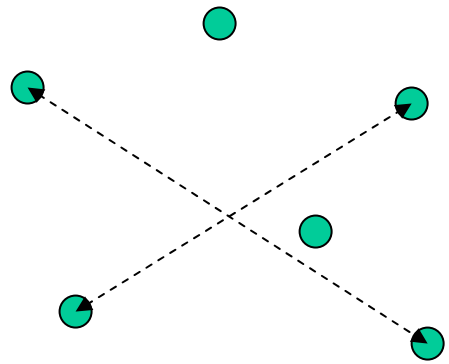
Generalized Median Voting

To find the median of a set of numbers, repeatedly remove largest and smallest numbers, until only one or two remain



If we replace "largest and smallest numbers" by "the two inputs that are furthest apart," we can use an arbitrary distance metric in our screening

A distance metric is any metric (mapping of pairs of inputs into real values) that satisfies the three conditions:



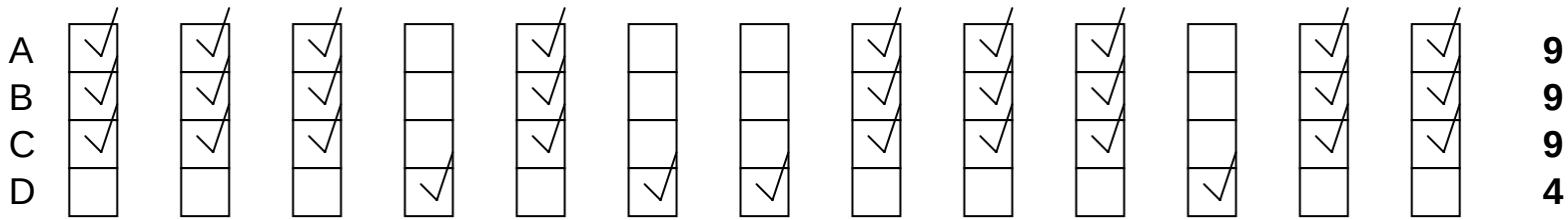
Isolation	$d(x, y) = 0$ iff $x = y$
Symmetry	$d(x, y) = d(y, x)$
Triangle inequality	$d(x, y) + d(y, z) \geq d(x, z)$

For example, the Hamming distance satisfies these conditions

Approval Voting

Approval voting was introduced to prevent the splitting of votes among several highly qualified candidates from leading to the election of a less qualified candidate in plurality voting

In approval voting, a voter divides the set of candidates into two subsets of “qualified” and “not qualified” and indicates approval of the first subset



In the context of computing, approval voting is useful when a question has multiple answers or when the solution process is imprecise or fuzzy

Example question: What is a safe setting for a particular parameter in a process control system?

When the set of approved values constitute a continuous interval of real values, we have “interval” inputs and “interval” voting

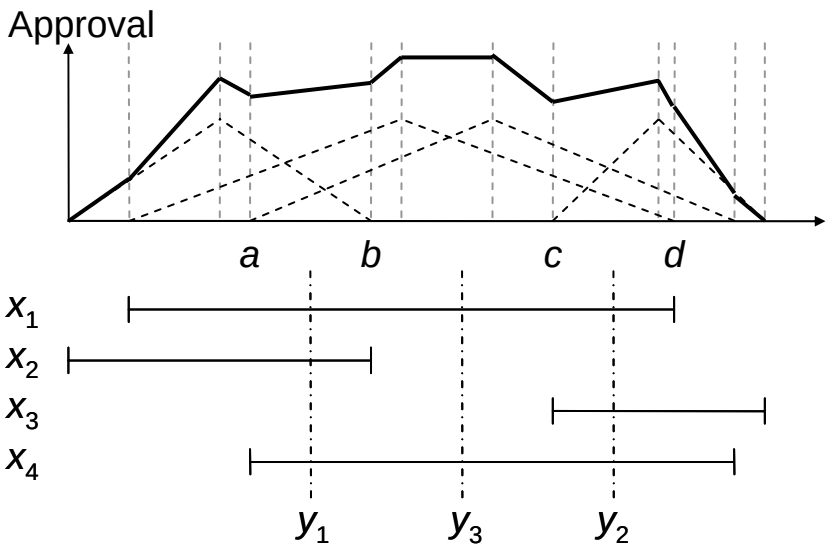
Interval Voting

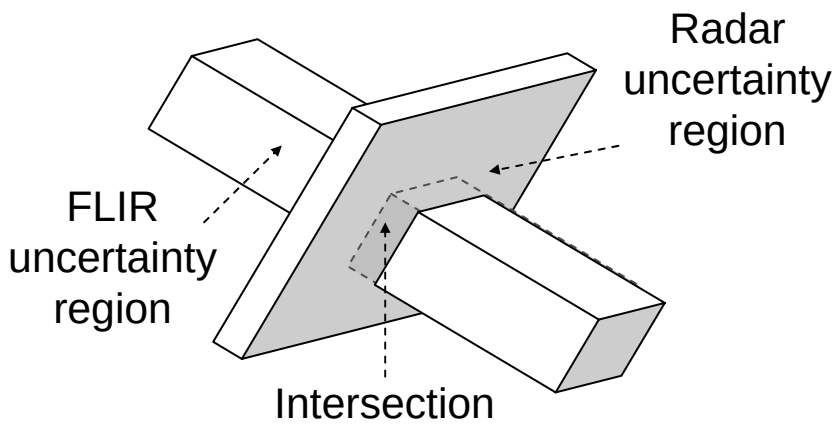
Inputs to the voting process are intervals, representing approved values

How should the voting result be derived from the input intervals?

Various combining rules can be envisaged
If there is overlap among all intervals, then the decision is simple

Depending on context, it may make sense to consider greater levels of approval near the middle of each interval or to associate negative approval levels outside the approved intervals





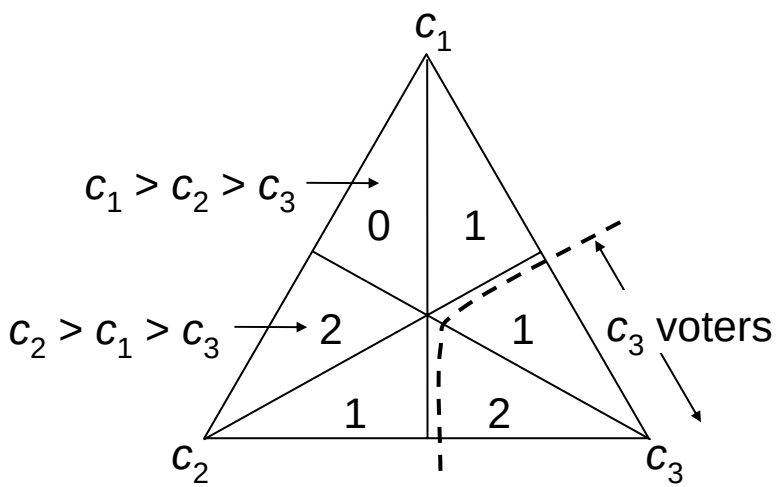
Combining two 3D intervals

The Impossibility of Perfect Voting

Properties of an ideal voting scheme:

1. No big brother
   (voters free to express preference)
2. Independence of irrelevant alternatives
   (preference for one candidate over another is independent of all others)
3. Involvement
   (every outcome is possible)
4. No dictatorship or antidictatorship
   (outcome not always conforming to, or opposite of, one voter's view)

Arrow's Theorem:
No voting scheme exists that satisfies all four conditions



True majority voting scheme:
Each voter orders all the candidates; no circular preference allowed
Choose a candidate who beats every other one in pairwise competitions
(both simple majority and plurality rules fail to choose a candidate)

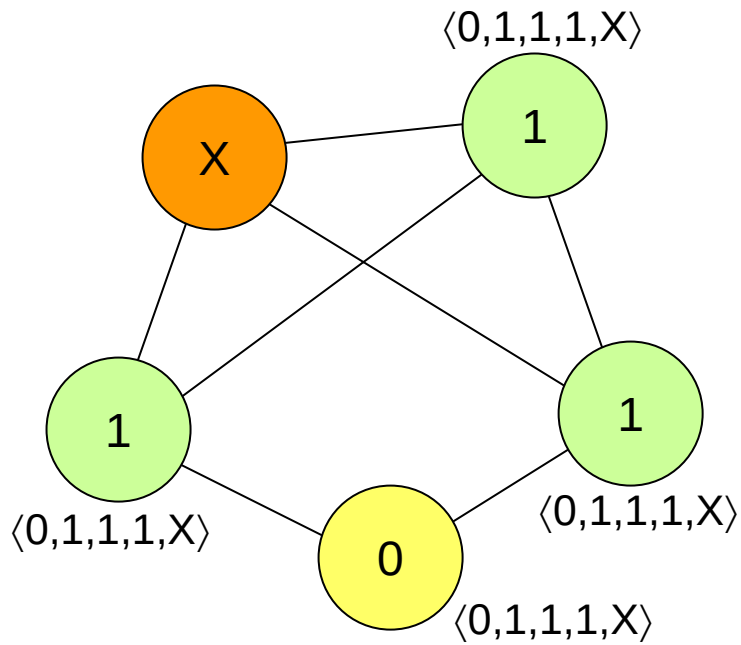
Distributed Voting: The Agreement Problem

Problem: Derive a highly reliable value from multiple computation results or stored data replicas at multiple sites

Key challenge: Exchange data among nodes so that all healthy nodes end up with the same set of values; this guarantees that running the same decision process on the healthy nodes produces the same result

Errors are possible in both data values and in their transmission between sites

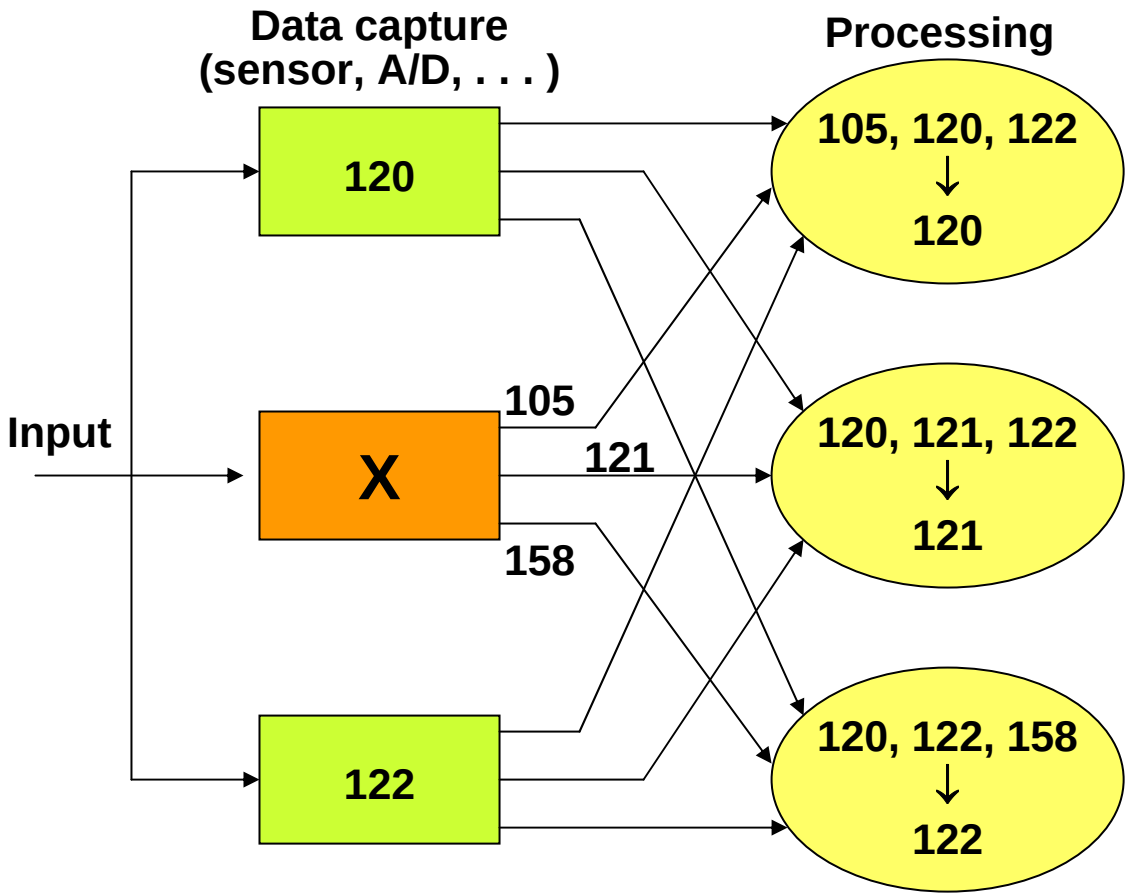
Agreement algorithms generally use multiple rounds of communication, with values held at each site compared and filtered, until the set of values held at all sites converge to the same set



Byzantine Failures in Distributed Voting

Three sites are to collect three versions of some parameter and arrive at consistent voting results

Assume median voting



The Interactive Consistency Algorithm

ICA(0) [no failure]

1. The transmitter sends its value to all other $n - 1$ nodes
2. Each node uses the value received from the transmitter, or a default value Φ if it received no value

ICA(f), $f > 0$ [f failures]

1. The transmitter sends its value to all other $n - 1$ nodes
2. Let v_i be the value received by node i from the transmitter, or a default value Φ if it received no value; node i then becomes the transmitter in its own version of ICA($f - 1$), sending its value to $n - 2$ nodes
3. For each node i, let $v_{i,j}$ be the value it received from node j, or a default value Φ if it received no value from node j. Node i then uses the value majority($v_{i,1}, v_{i,2}, \ldots, v_{i,i-1}, v_{i,i+1}, \ldots, v_{i,n}$)

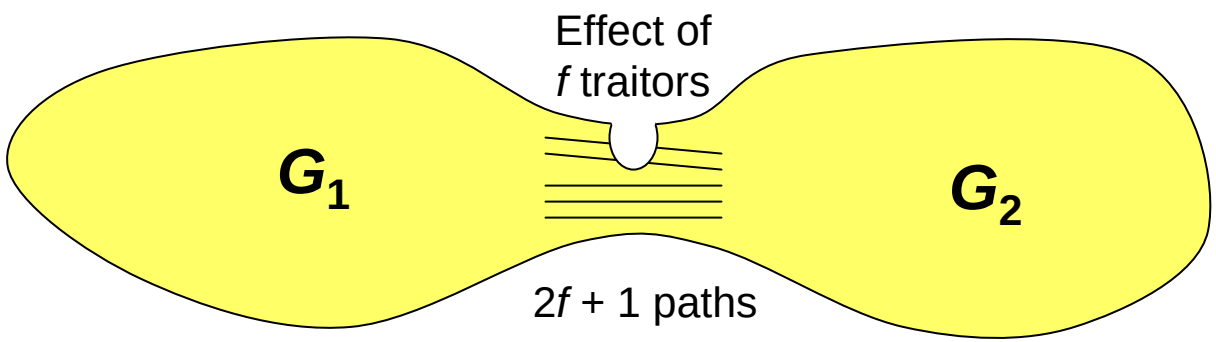
Correctness and Performance of ICA

Theorem 1: With ICA(f), all nonfailed nodes will agree on a common value, provided that $n \geq 3f + 1$ (proof is by induction on f)

ICA works correctly, but it needs an exponential number of messages:
$(n-1) + (n-1)(n-2) + (n-1)(n-2)(n-3) + \ldots + (n-1)(n-2) \ldots (n-m)$

More efficient agreement algorithms exist, but they are more difficult to describe or to prove correct; $f + 1$ rounds of message exchange is the least possible, so some algorithms trade off rounds for # of messages

Theorem 2: In a network G with f failed nodes, agreement is possible only if the connectivity is at least $2f + 1$



The Byzantine Generals Problem

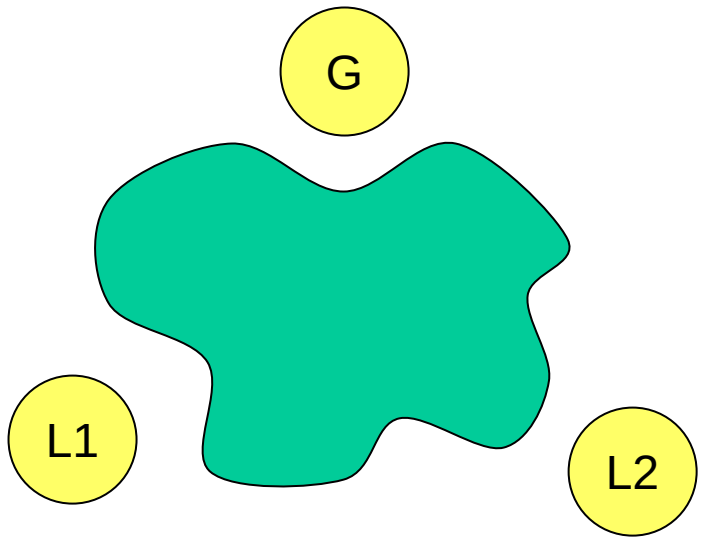
A general and *n* – 1 lieutenants lead *n* divisions of the Byzantine army camped on the outskirts of an enemy city

The *n* divisions can only communicate via messengers

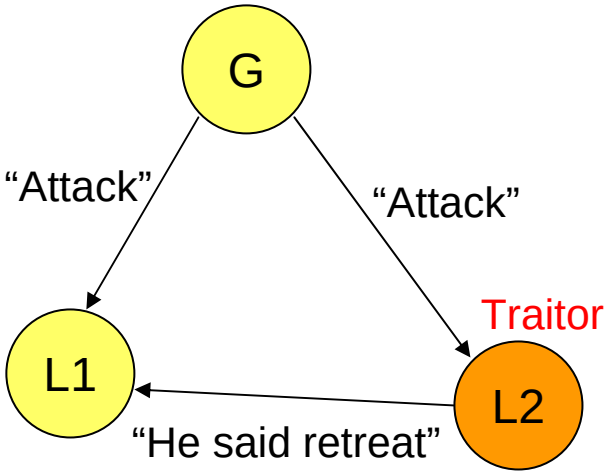
We need a scheme for the generals to agree on a common plan of action (attack or retreat), even if some of the generals are traitors who will do anything to prevent loyal generals from reaching agreement

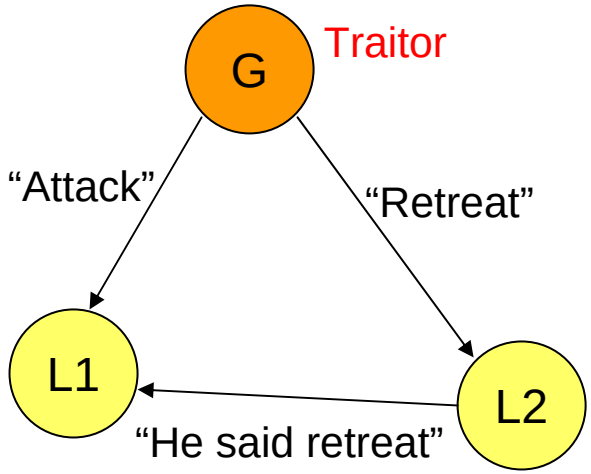
The problem is nontrivial even if messengers are totally reliable

With unreliable messengers, the problem is very complex

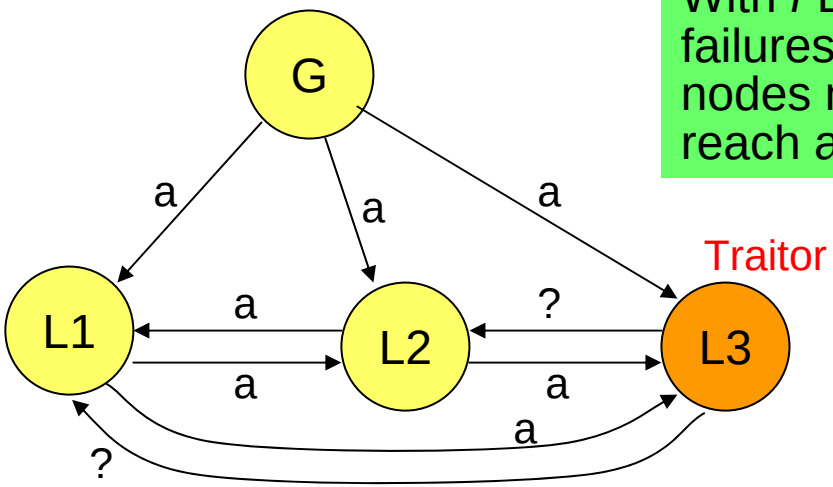


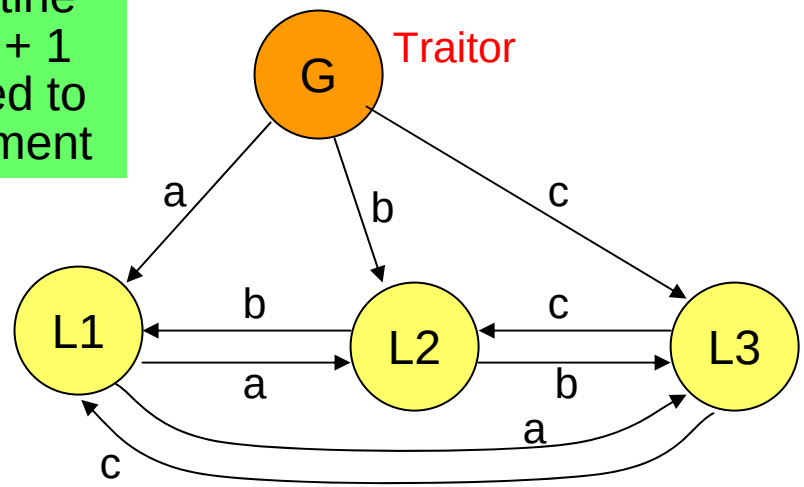
Byzantine Generals with Reliable Messengers





With *f* Byzantine failures, ≥ 3*f* + 1 nodes needed to reach agreement





Byzantine Resiliency

To tolerate *f* Byzantine failures:

We need 3*f* + 1 or more FCRs (fault containment regions)

FCRs must be interconnected via at least 2*f* + 1 disjoint paths

Inputs must be exchanged in at least *f* + 1 rounds

Corollary 1: Simple 3-way majority voting is not Byzantine resilient

Corollary 2: Because we need 2*f* + 1 good nodes out of a total of 3*f* + 1 nodes, at least a fraction (2*f* + 1)/(3*f* + 1) = 2/3 + 1/(9*f* + 3) of the nodes must be healthy

Anything greater than a supermajority (2/3) will do