Distributed Computing with Byzantine Players

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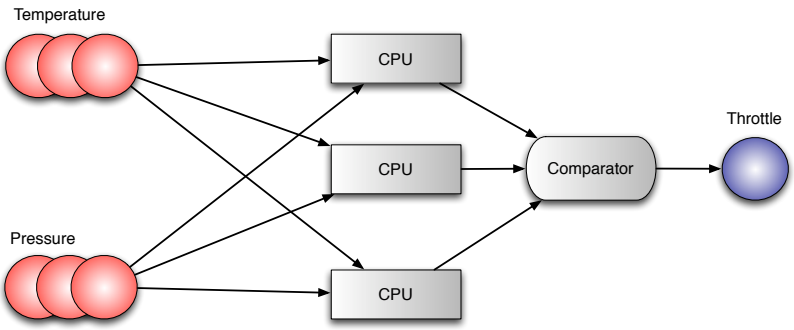
Motivation

Approach

- *Faults* and *attacks* occur in the network
- The network's user must *not* notice something wrong happened
- A *small* number of faulty components
- **Masking** approach to fault/attack tolerance

Principle



Problems

- Replicated input sensors may not give the same data
- Faulty input sensor or processor may not fail gracefully
- The system might not be tolerant to software bugs

Telling Truth from Lies

The Island of Liars and Truth-tellers

- An island is populated by two tribes
  - Members of one tribe **consistently lie**
  - Members of the other tribe **always tell the truth**
  - Tribe members can recognize one another, but an external observer can't

Puzzle I

- You run into a man and ask him if he is a truth-teller, but fail to hear the answer
- You inquire: "Did you say you are a truth-teller?"
- He responds: "No, I did not."
- To which tribe does the man belong ?

Puzzle II

- You meet a woman on the island.
- What single question can you ask her to determine whether she is a liar or a truth-teller?

Puzzle III

- You meet two people *A* and B on the island
- *A* says: "Both of us are from the liar tribe."
- Which tribe is *A* from ?
- What about *B* ?

Puzzle IV

- You meet two people, *C* and *D* on the island.
- *C* says: "Exactly one of us is from the liars tribe."
- Which tribe is *D* from ?

Puzzle V

- You meet two people *E* and *F* on the island
- *E* says: "It is not the case that both of us are from truth-tellers tribe."
- Which tribe is *E* from?
- What about *F*?

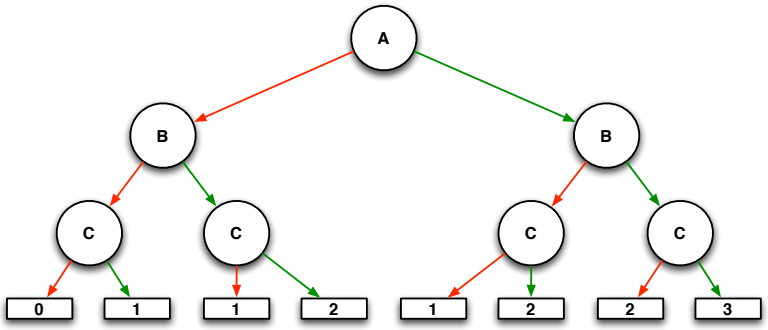
Puzzle VI

- You meet two people *G* and *H* on the island
- *G* says: "We are from different tribes."
- *H* says: "*G* is from the liars tribe."
- Which tribes are *G* and *H* from ?

Puzzle VII

- You meet three people *A*, *B*, and *C*
- You ask *A*: "how many among you are truth-tellers?", but don't hear the answer
- You ask *B*: "What did *A* say?", hear "one."
- *C* says: "*B* is a liar."
- Which tribes are *B* and *C* from?

Puzzle VII



The Island of Selective Liars

- Inhabitants lie consistently on Tuesdays, Thursdays, and Saturdays, and tell the through on the remaining days
- You ask: "What is today?" "Tomorrow?"
- Responses: "Saturday.", "Wednesday."
- What is the current day ?

The Island of Random Liars

- A new Island has three tribes
  - truth-tellers
  - consistent liars
  - randomly lie or tell the truth
- How to identify three representants of each tribe with only three yes/no questions?

Byzantine Generals

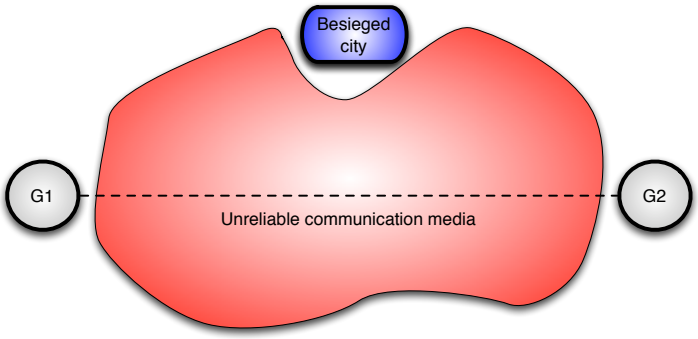
Settings

- Byzantine generals are camping outside an enemy city
- Generals can communicate by sending messengers
- Generals must decide upon common plan of action
- Some of the Generals can be traitors

Goal

- All loyal generals decide upon the same plan of action
- A small number of traitors cannot cause the loyal generals to adopt a bad plan

Two Generals Paradox



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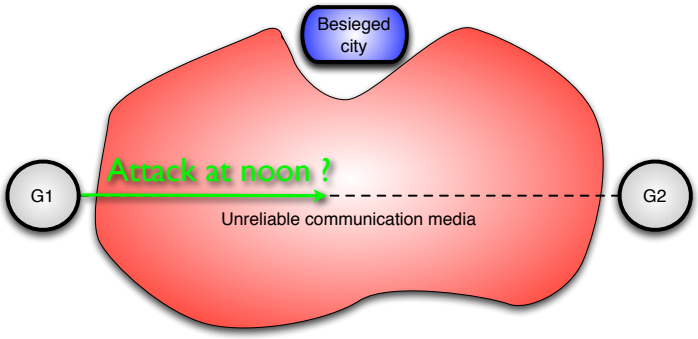

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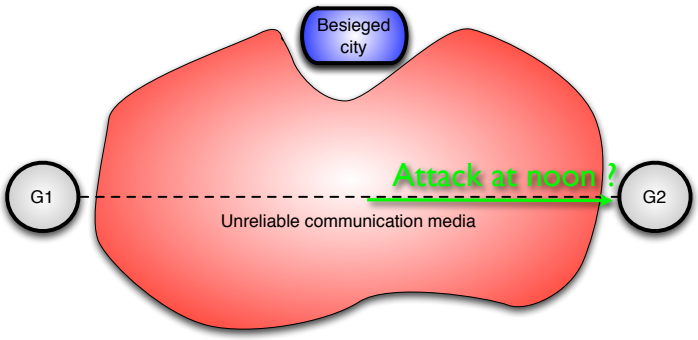

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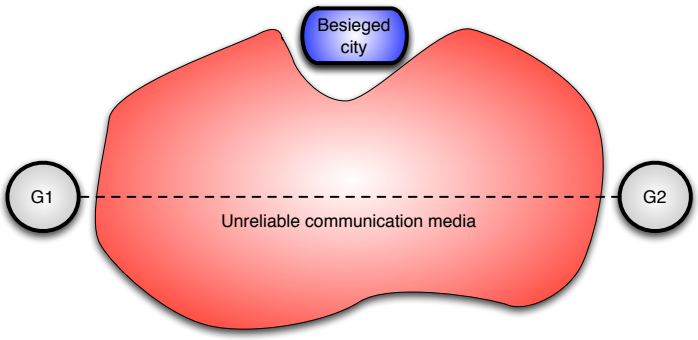

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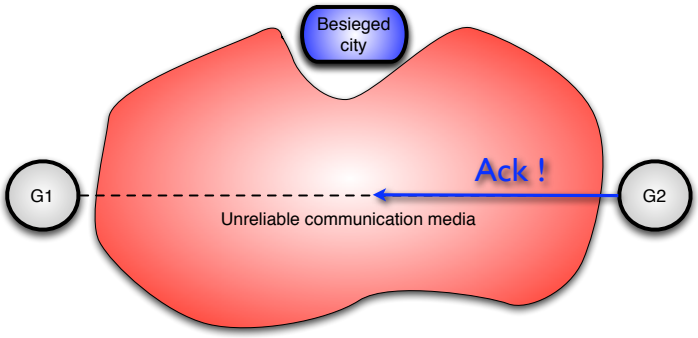

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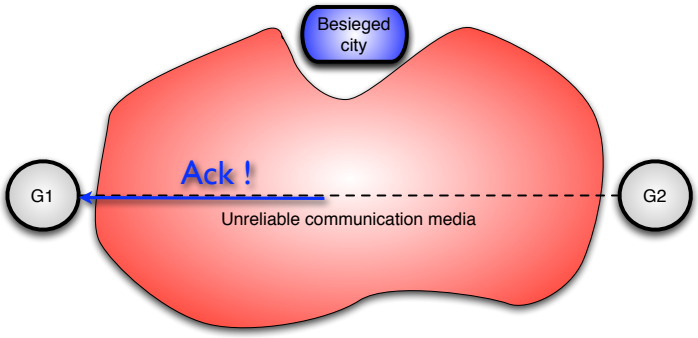

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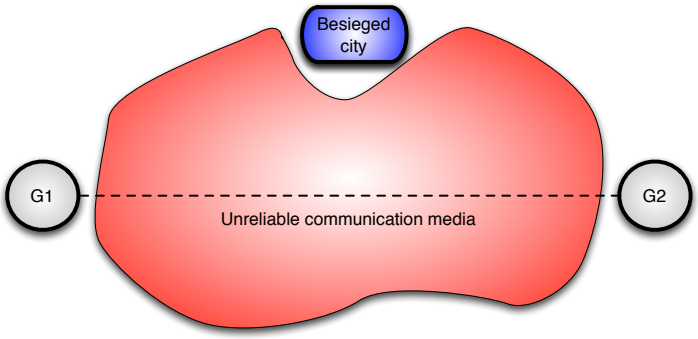
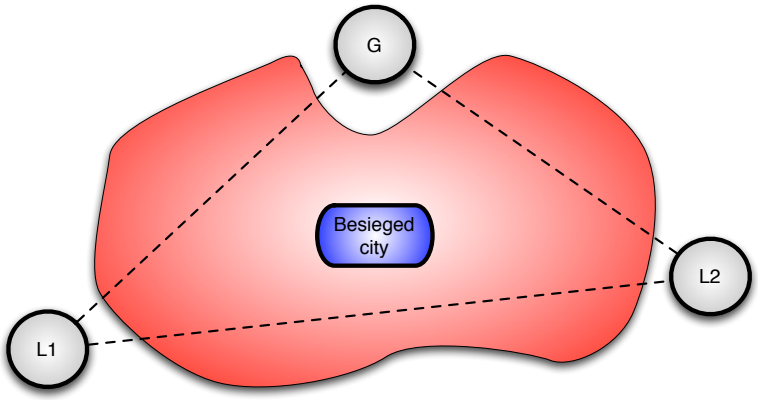


The Byzantine Generals Problem



The (simple) Byzantine Generals Problem

- Generals lead *n* divisions of the Byzantine army
- The divisions communicate via reliable messengers
- The generals must **agree** on a plan ("attack" or "retreat") even if some of them are **killed** by enemy spies

Oral Model

- **A1**: Every message that is sent is delivered correctly
- **A2**: The receiver of a message knows who sent it
- **A3**: The absence of a message can be detected

Solution?

plan: **array of** {A,R}; finalPlan: {A,R}

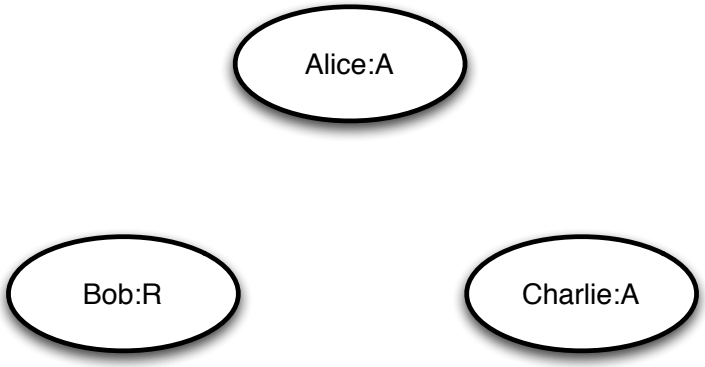
1: plan[myID] := *ChooseAorR*()

2: for all other G *send*(G, myID, plan[myID])

3: for all other G *receive*(G, plan[G])

4: finalPlan := *majority*(plan)

Reliable Networks



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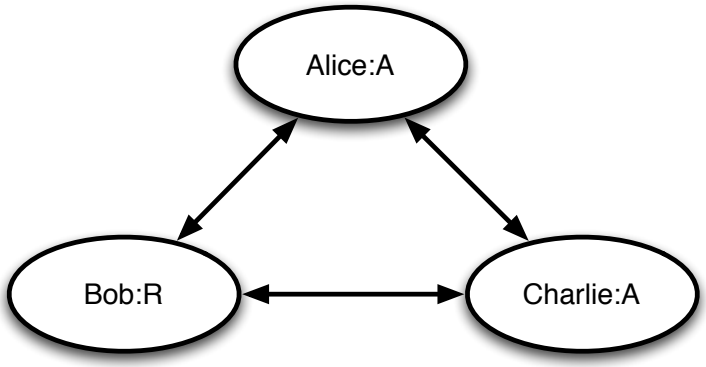

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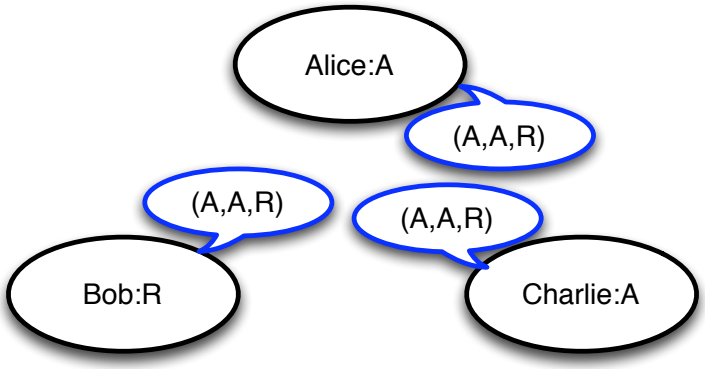

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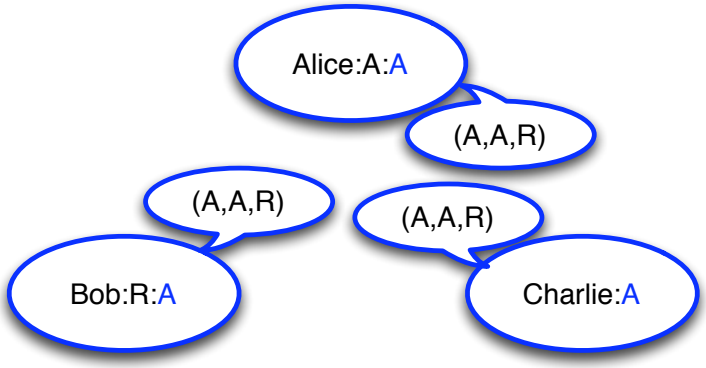
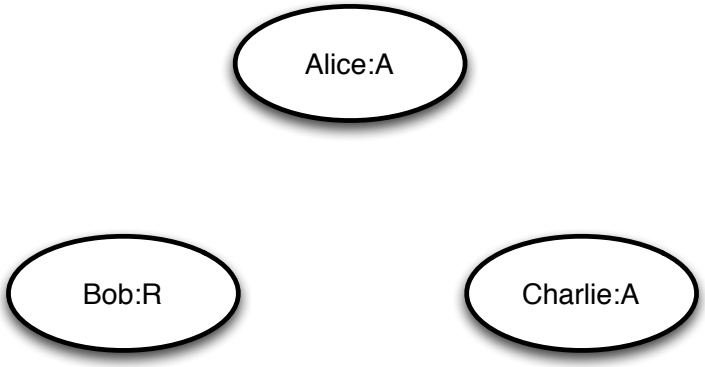


Crashing Networks



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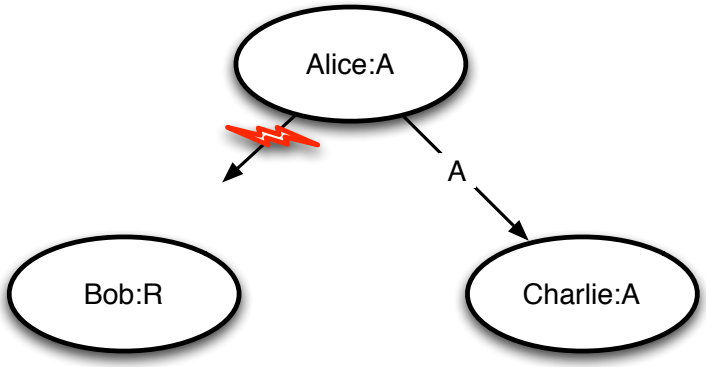

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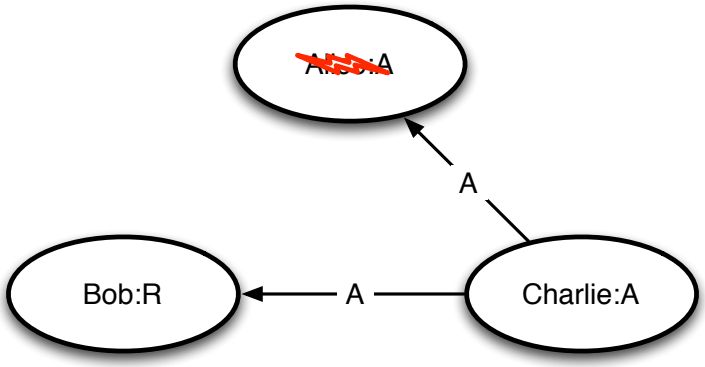

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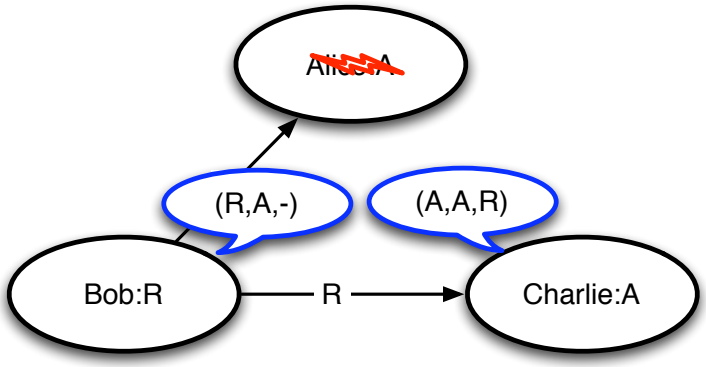

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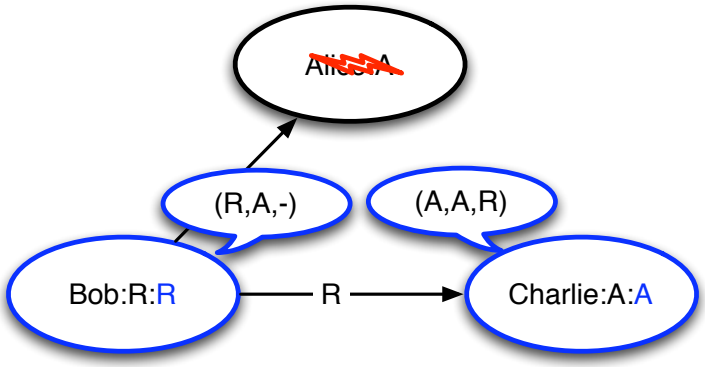


The Byzantine Generals Problem

- A general and *n-1* lieutenants lead n divisions of the Byzantine army
- The divisions communicate via messengers that can be captured or delayed
- The generals must **agree** on a plan ("attack" or "retreat") even if some of them are **traitors** that want to prevent agreement

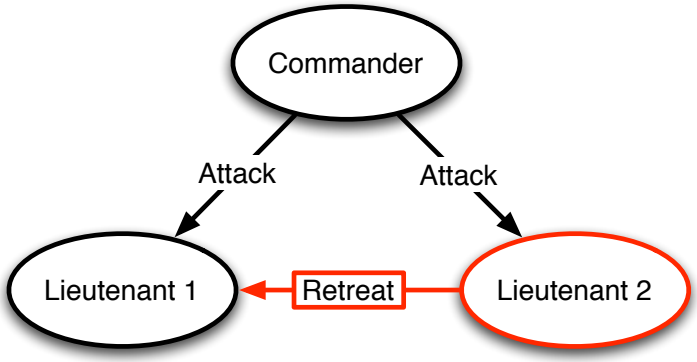
The Byzantine Generals Problem

- A commanding general must sent an order to his n-1 lieutenants generals such that
  - **IC1**: all loyal lieutenants obey the same order
  - **IC2**: if the commanding general is loyal, then every loyal lieutenant obeys the order he sends

Oral Model

- **A1**: Every message that is sent is delivered correctly
- **A2**: The receiver of a message knows who sent it
- **A3**: The absence of a message can be detected

3k+1 nodes are necessary (oral model)



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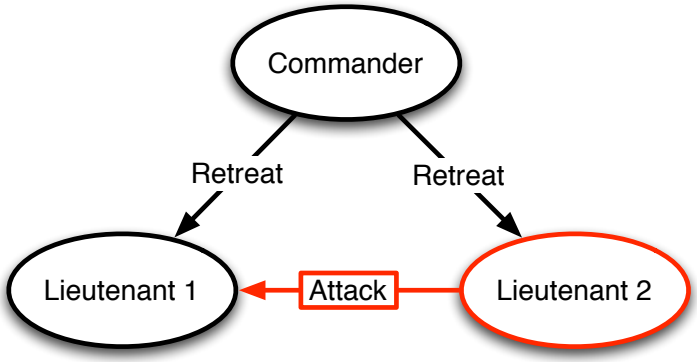

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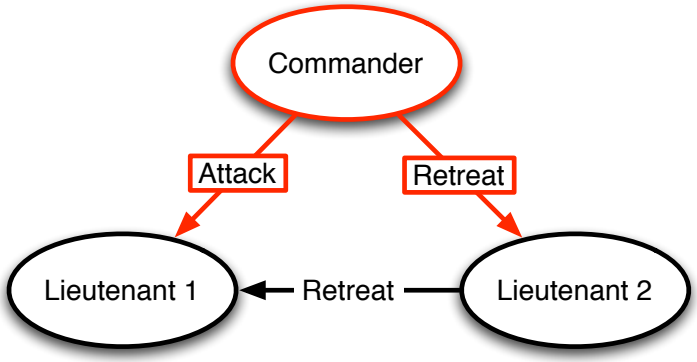

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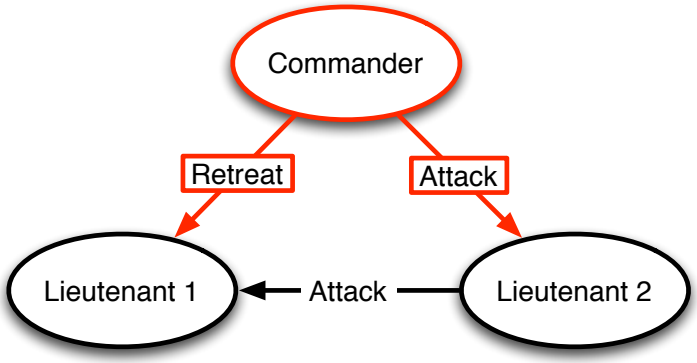

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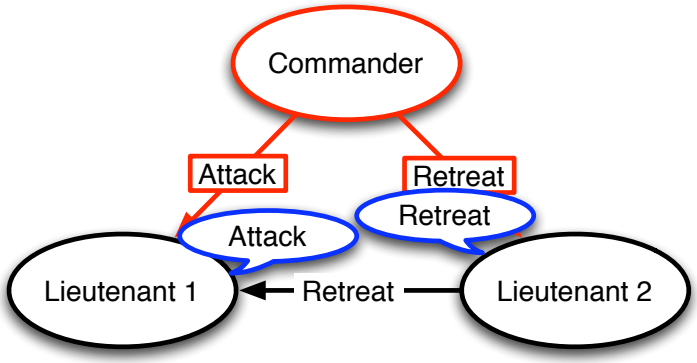

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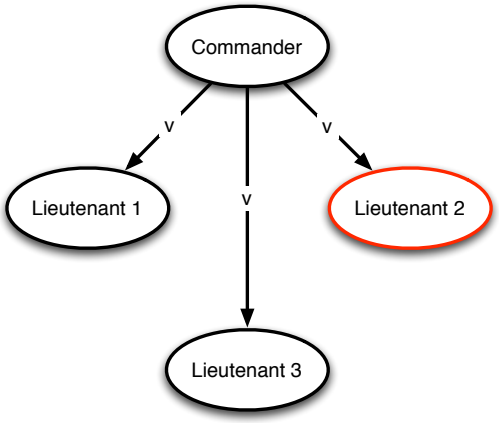

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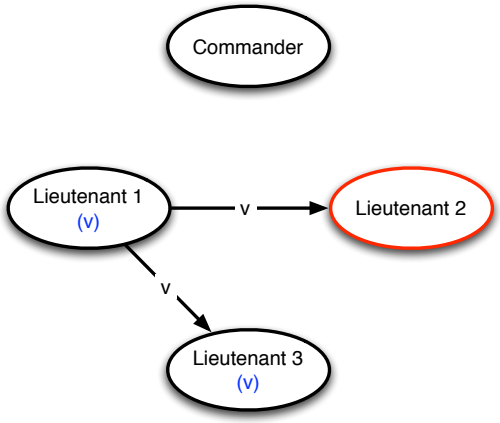

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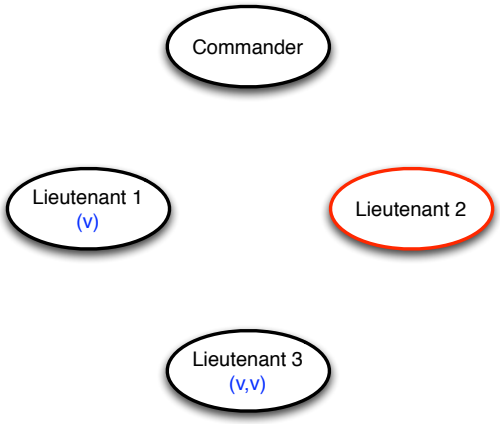

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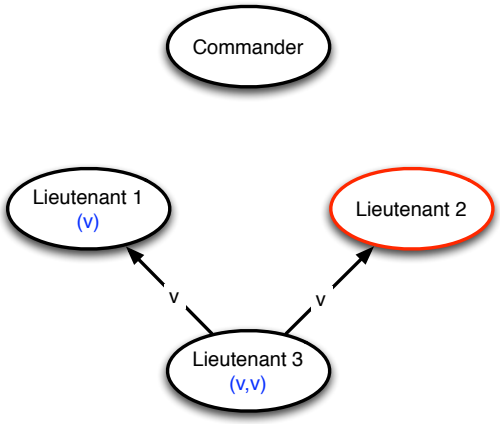

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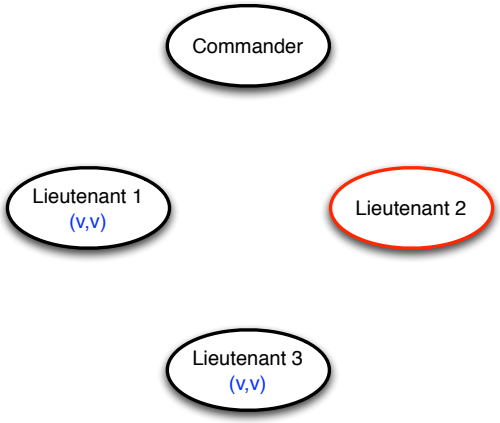

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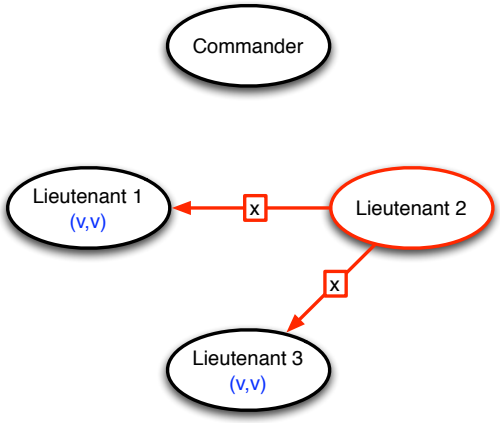

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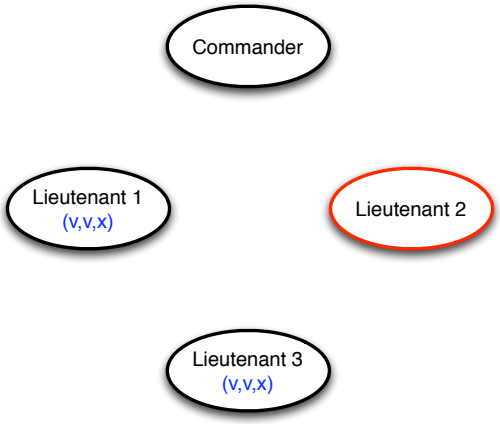

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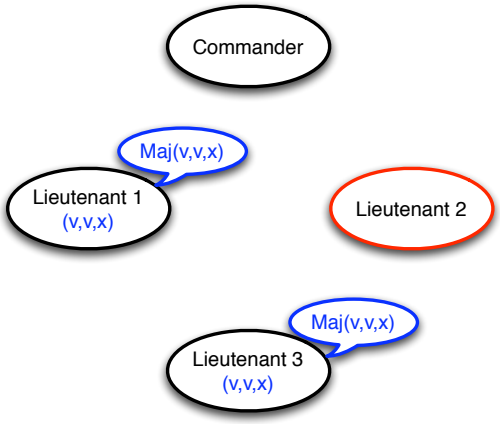

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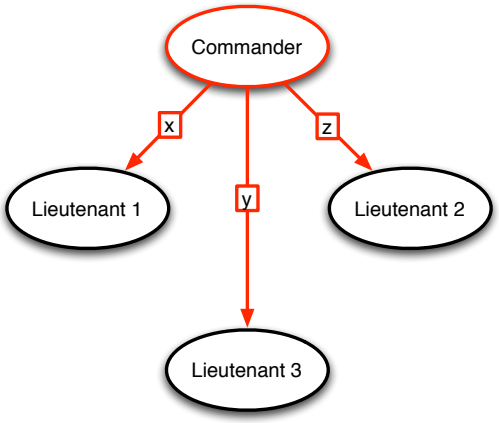

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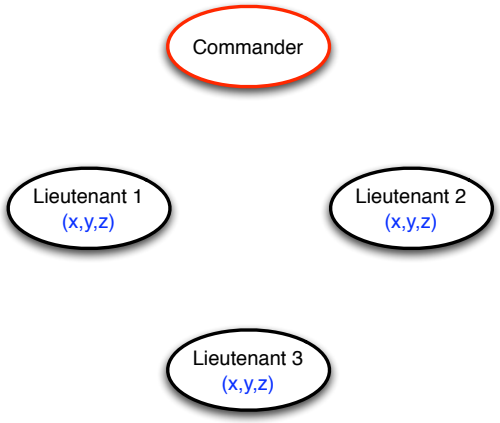

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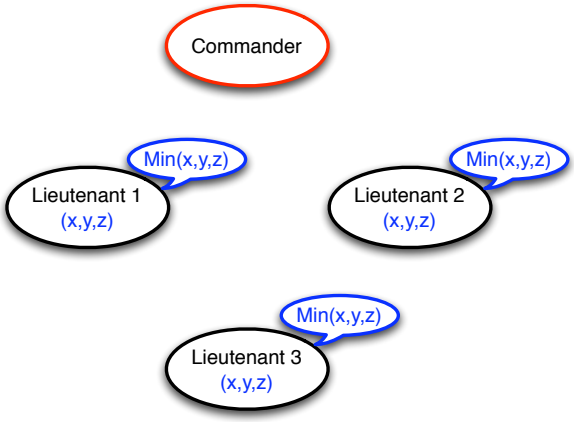
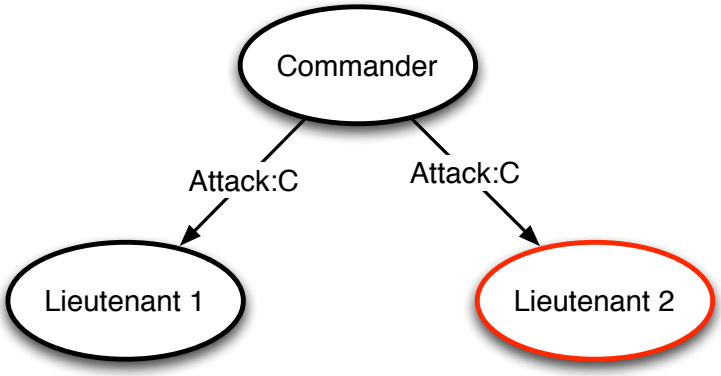


Written Model

- **A1-A3**: Same as before
- **A4**:
  - A loyal general's signature cannot be forged, and any alteration of the contents of his signed messages can be detected
  - Anyone can verify the authenticity of a general's signature

k+2 nodes are sufficient (written model)



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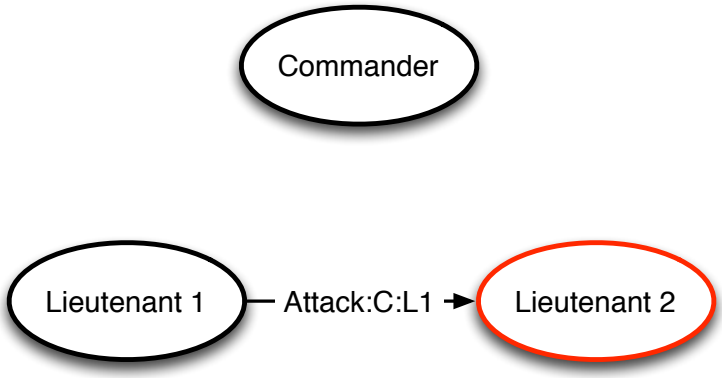

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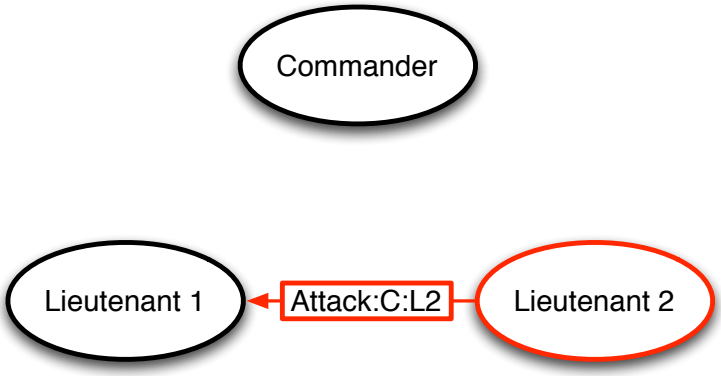

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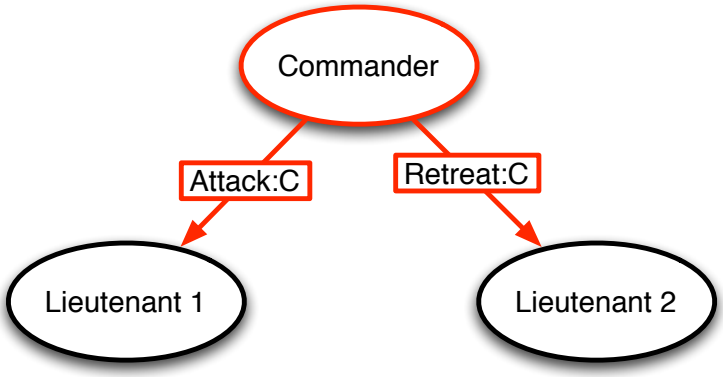

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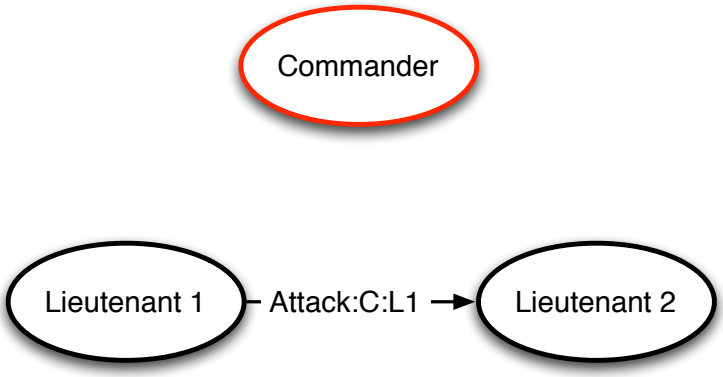

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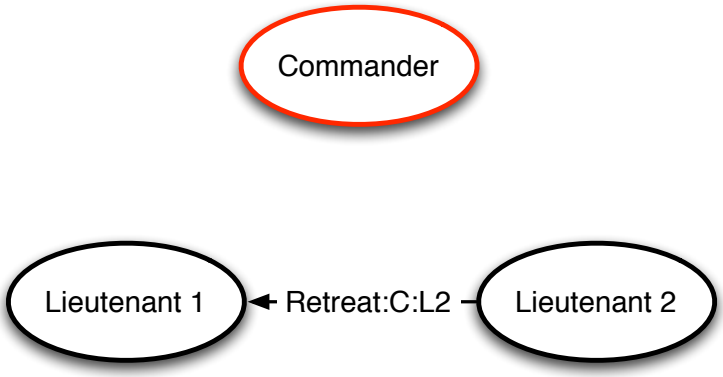

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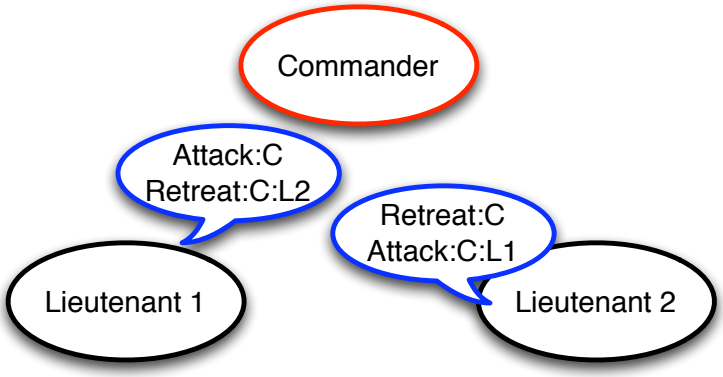


Arbitrary Networks

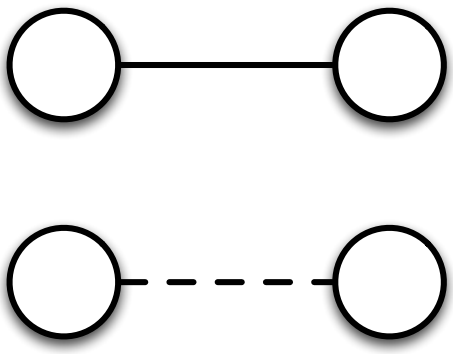
Topology Discovery

- **Given**
  - asynchronous network
  - up to *k* Byzantine nodes
  - each node knows its immediate neighbors identifiers
- **Goal**
  - each node must discover the complete network topology

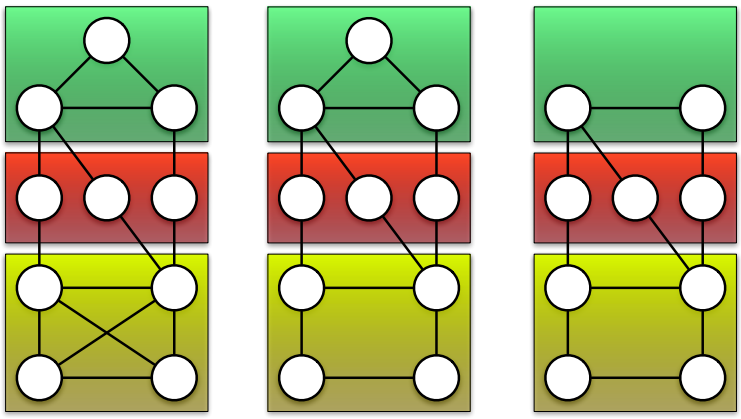
Weak Topology Discovery

- **Termination**
  - either all non-faulty processes determine the system topology or at least one detects fault
- **Safety**
  - for each non-faulty process, the determined topology is subset of actual
- **Validity**
  - fault detected only if it indeed exists

Weak Topology Discovery



Weak Topology Discovery



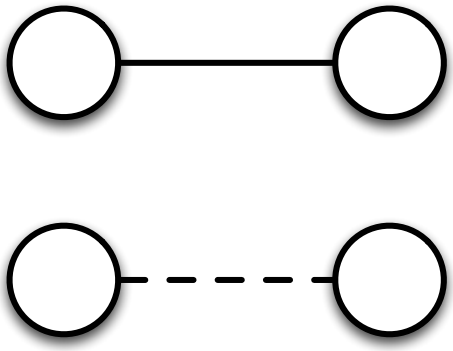
Weak Topology Discovery

- **Bounds**
  - cannot determine presence of edge if both adjacent nodes are faulty
  - cannot be solved if network is less than *k* +*1* connected

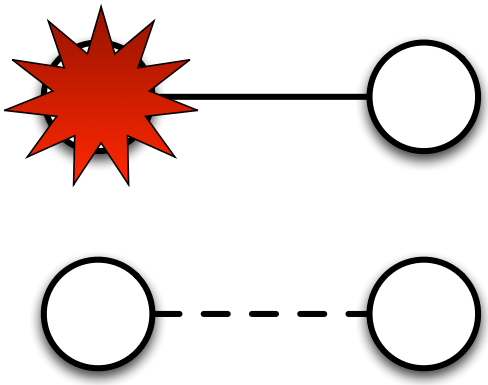
Strong Topology Discovery

- **Termination**
  - all non-faulty processes determine the system topology
- **Safety**
  - for each non-faulty process the determined topology is subset of actual

Strong Topology Discovery



Strong Topology Discovery



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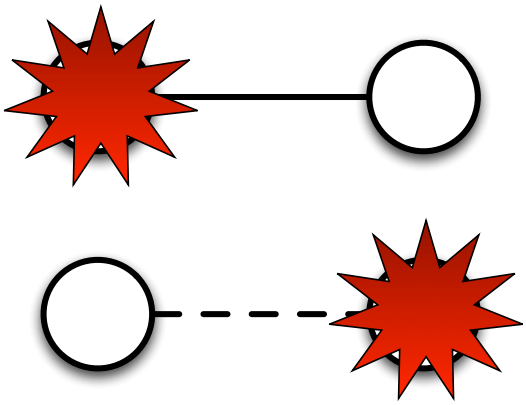
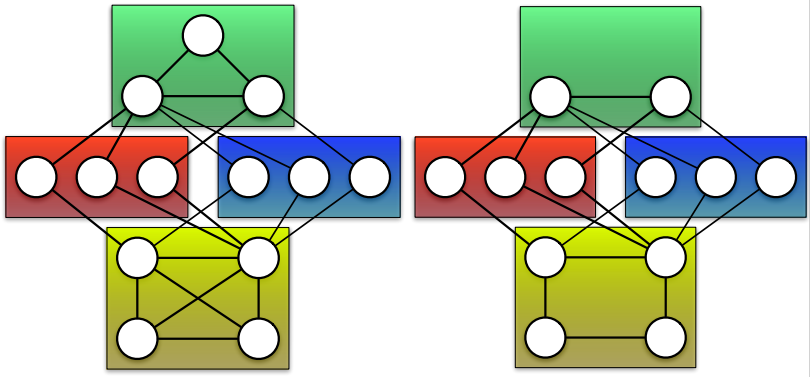
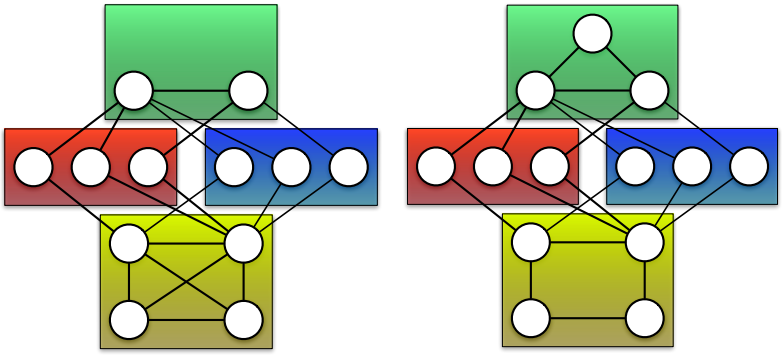


Strong Topology Discovery



Strong Topology Discovery



Strong Topology Discovery

- **Bounds**
  - cannot determine presence of edge if one neighbor is faulty
  - cannot be solved if network is less than $2k+1$ connected

Solutions Preliminaries

- **Main idea**
  - *Menger's theorem*: if a graph is k connected then for any two vertices there exists two internally node-disjoint paths connecting them
  - a single (non-source) node cannot compromise info if it travels over two node-disjoint paths

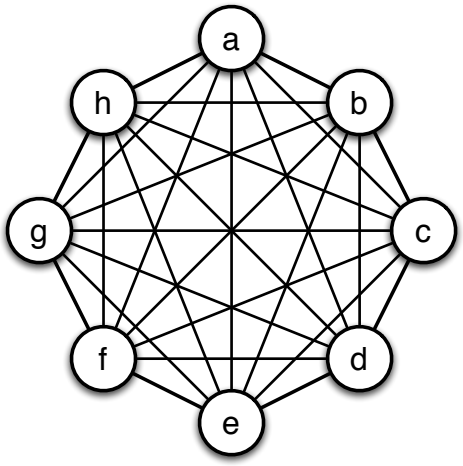
Solutions Preliminaries

- **Common Features**
  - every solution essentially involves flooding each node's neighbor info to the other nodes
  - solutions differ on how the nodes forward neighborhood info received from other nodes

A Naive Solution

- Store traveled path in message, forward message that contains simple path to all outgoing links
- Solves strong (and weak) topology discovery problems

A Naive Solution



A Naive Solution

- Store traveled path in message, forward message that contains simple path to all outgoing links
- Solves strong (and weak) topology discovery problems
- requires **exponential** number of messages

Detector

- **Basic design**
  - propagate neighbor info message for each process exactly once (*first time*)
    - if receive different info for same process, signal fault
    - since network is $k+1$ connected, info about non-faulty nodes reaches every node

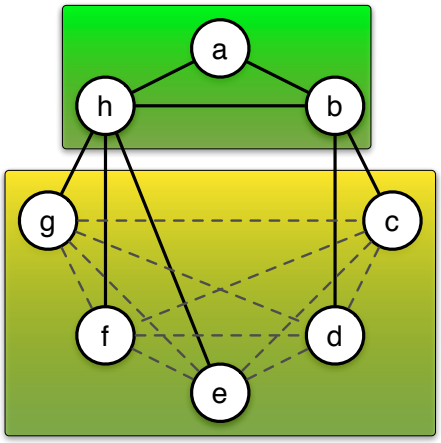
Detector

- **Handling fake nodes**
  - faulty process may send info about non-existent (fake) nodes thus compromising safety and termination
    - only faulty nodes can be connected to fake nodes ? (discovered network is less that $k+1$ connected)

Detector

- **Handling fake nodes**
  - faulty process may send info about non-existent (fake) nodes thus compromising safety and termination
    - when the network is not completely discovered yet, it may also be less than $k+1$ connected, problems with validity

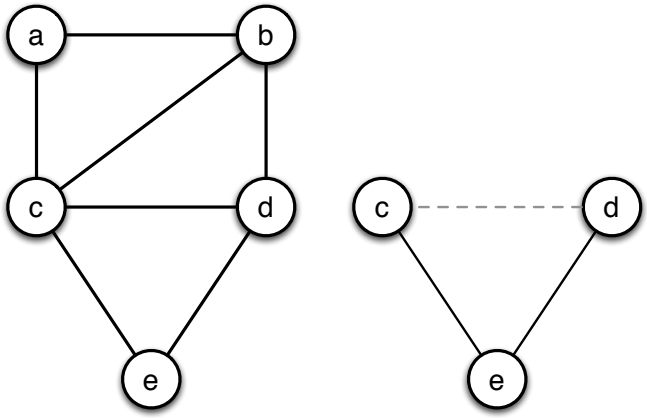
Detector



Detector

- **Neighborhood closure**
  - connect all nodes whose neighbor information is not received
    - the connectivity of this graph is no less than the actual topology
    - if the connectivity if this graph falls below $k+1$, signal fault

Detector



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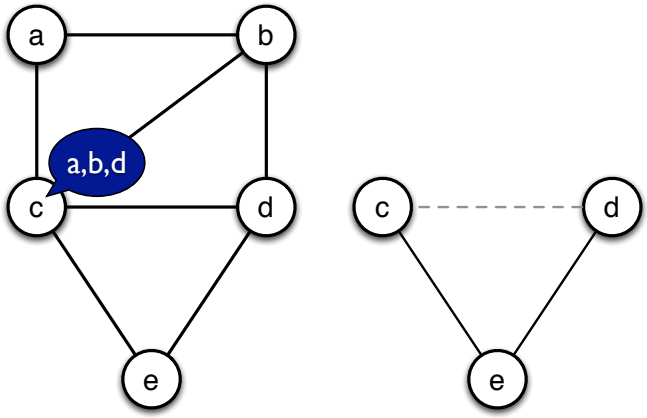

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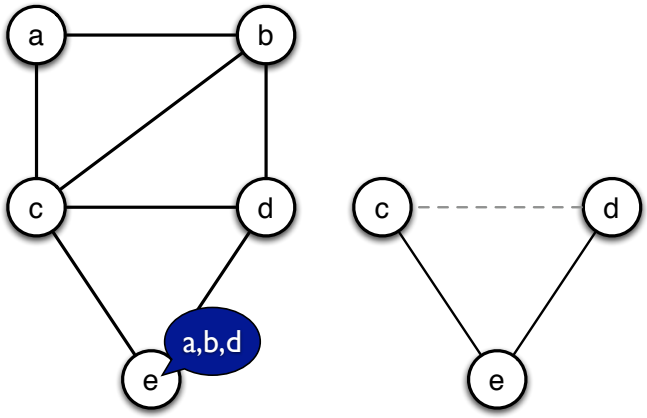

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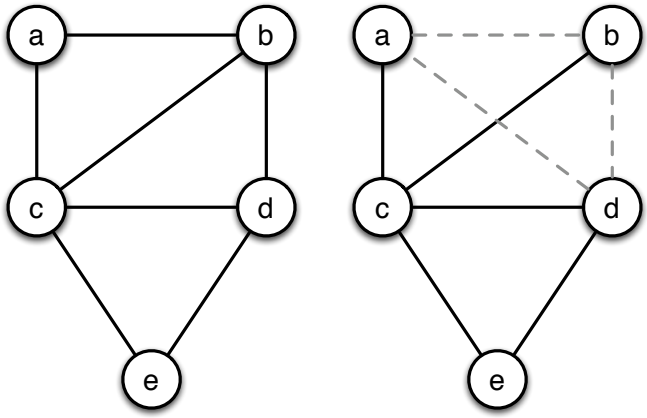

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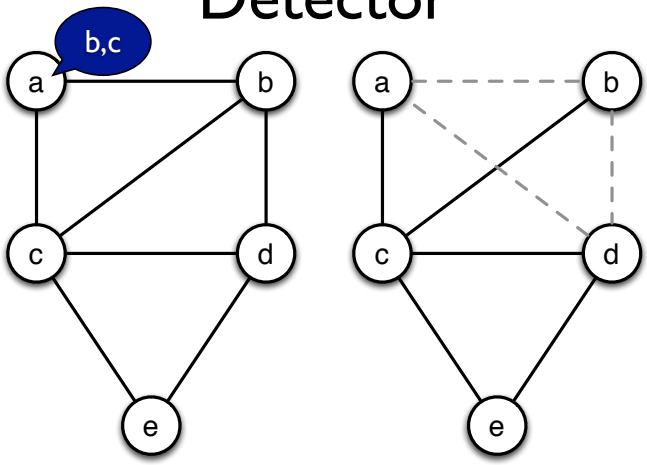

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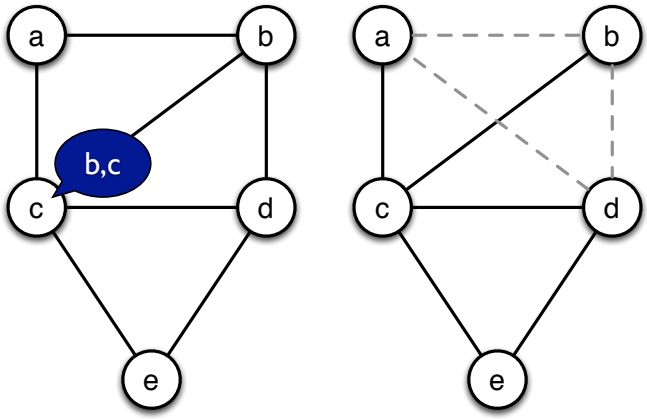

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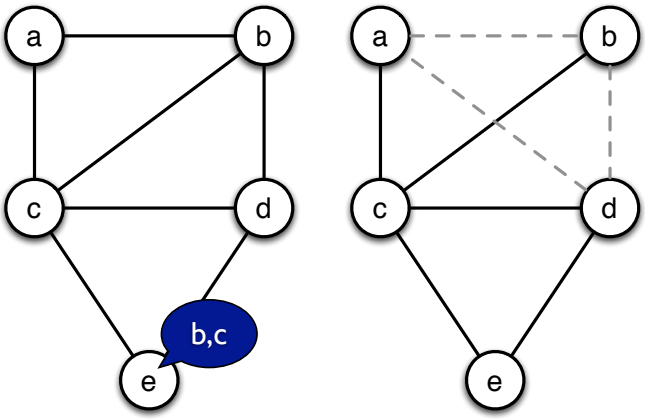

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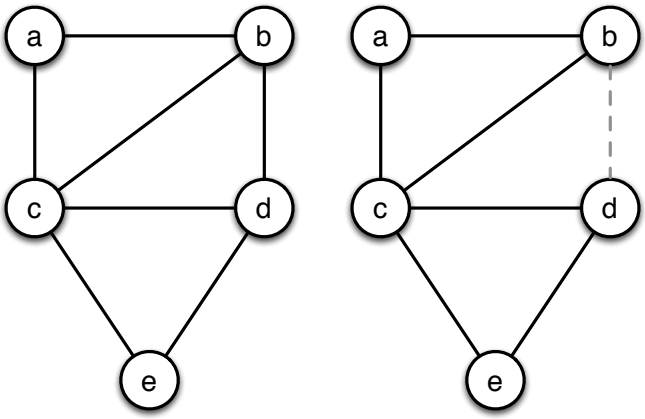

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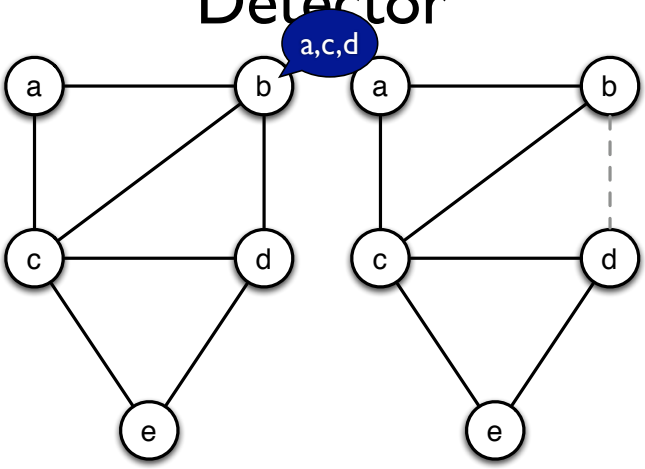

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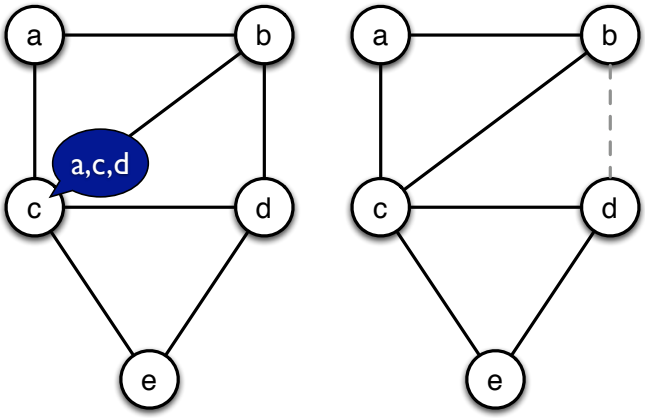

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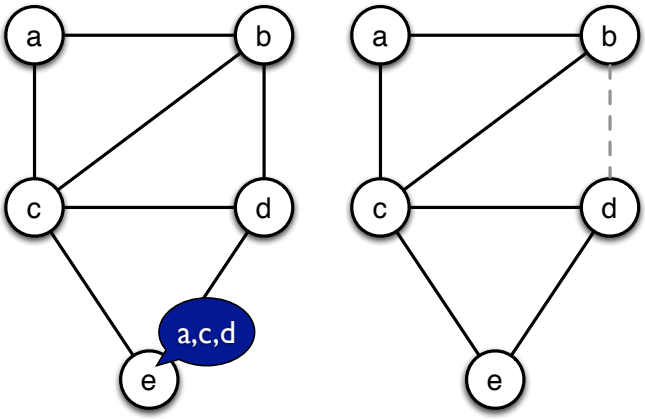

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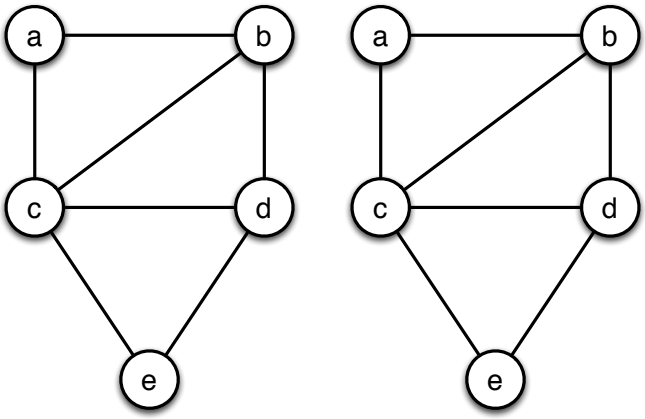
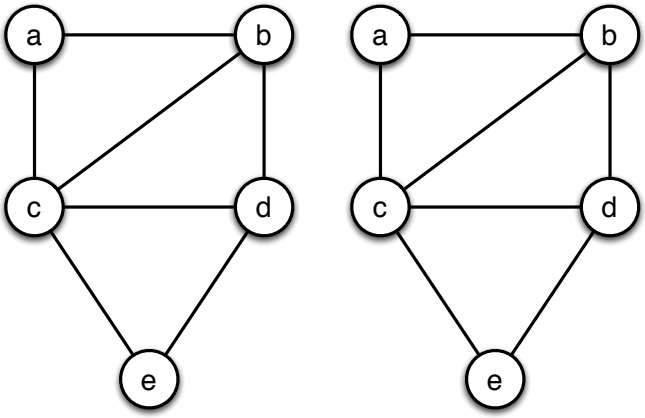
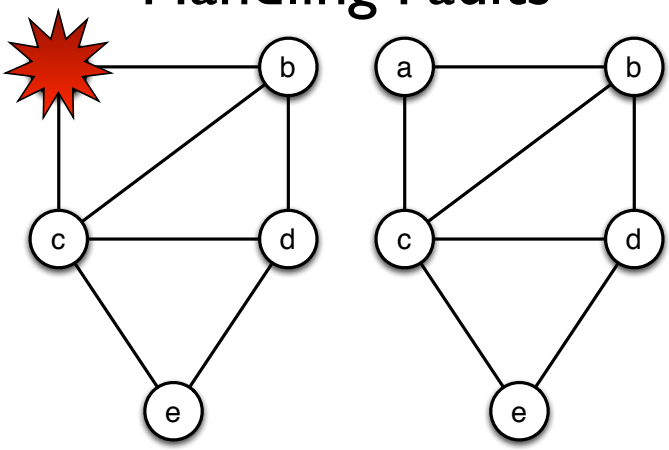


Handling Faults



Handling Faults



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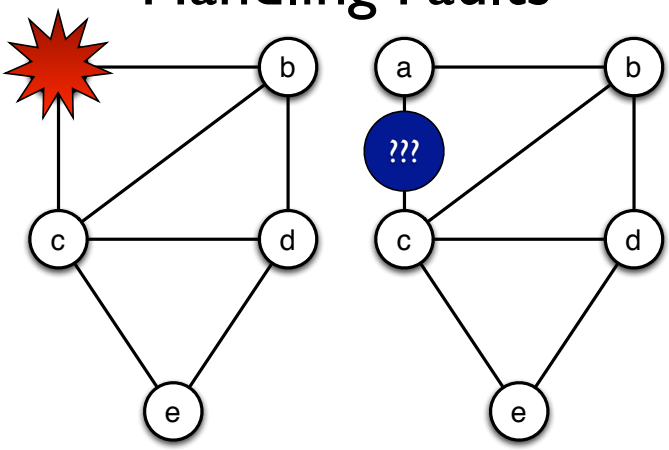

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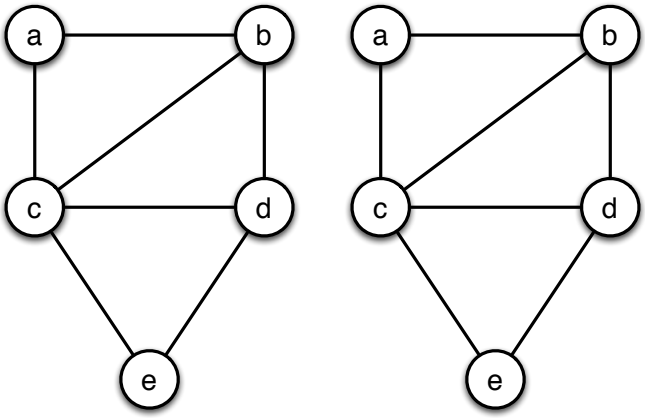

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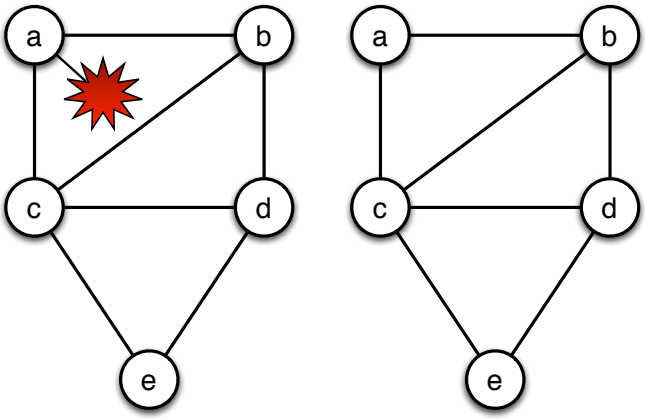

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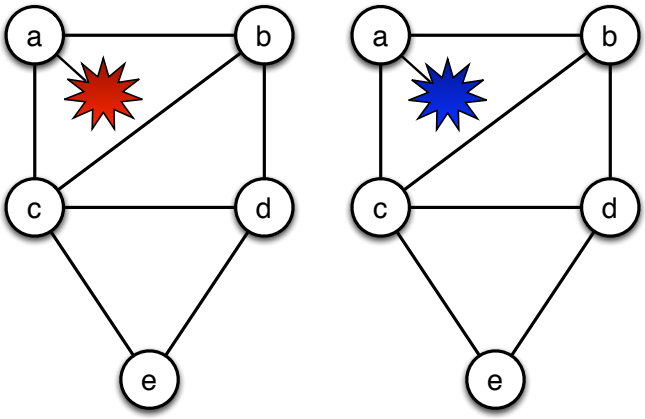

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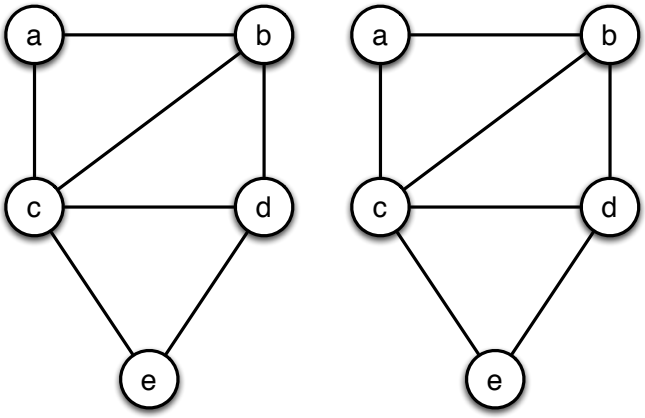

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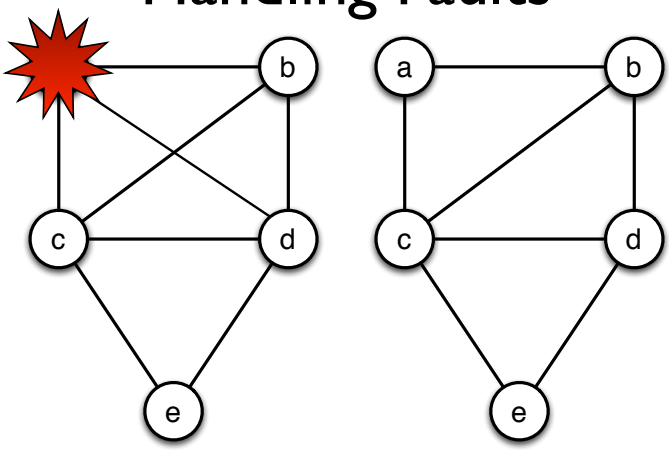

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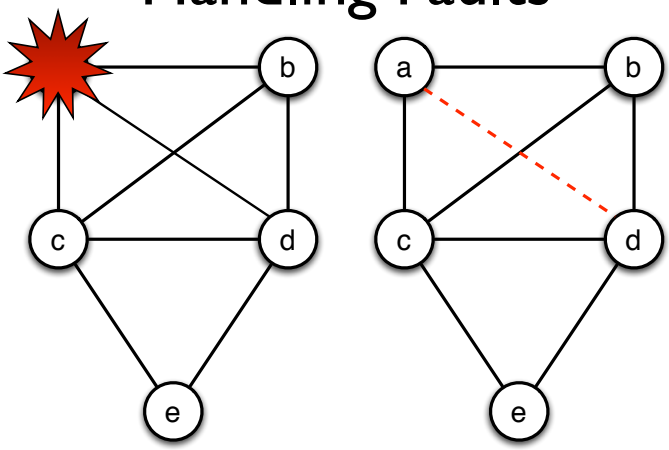


Detector

- **Definition**
  - Solution is *adjacent-edge complete* if non-faulty nodes discover all non-faulty nodes and their adjacent edges

Detector

- **Theorem**
  - *Detector* is an adjacent-edge complete solution to the *weak topology discovery* problem if the connectivity of the system exceeds the maximum number of faults

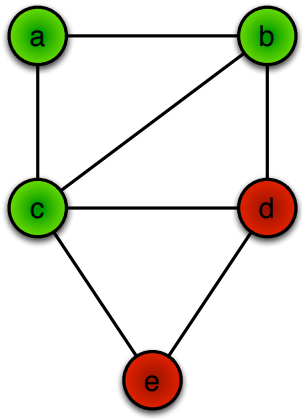
Explorer

- **Main idea**
  - collect node's neighbor information such that the info goes along more than twice as many node disjoint paths as max number of faulty nodes

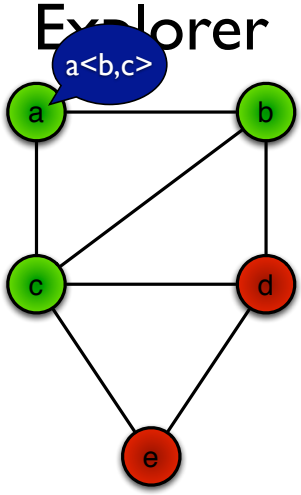
Explorer

- **Confirmed neighbor information**
  - *k+1* disjoint paths from source
  - non-intersecting paths from *k+1* confirmed neighbors

Explorer



Explorer



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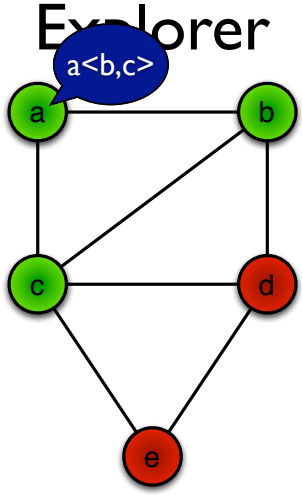

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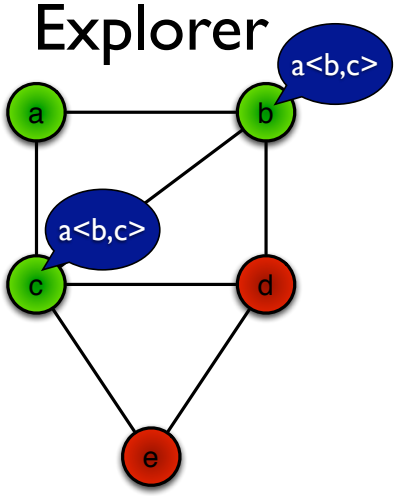

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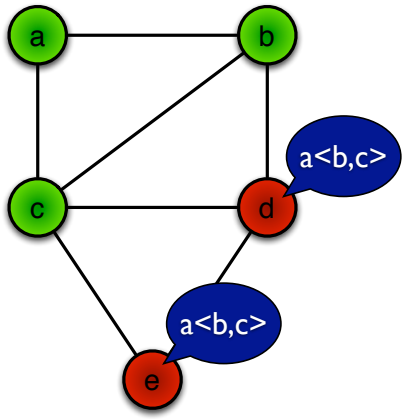

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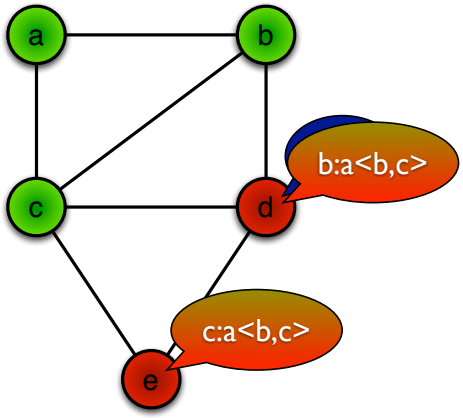

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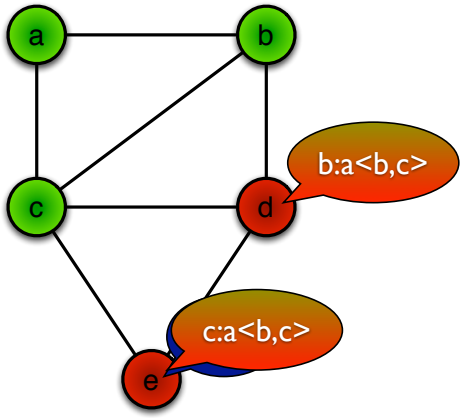

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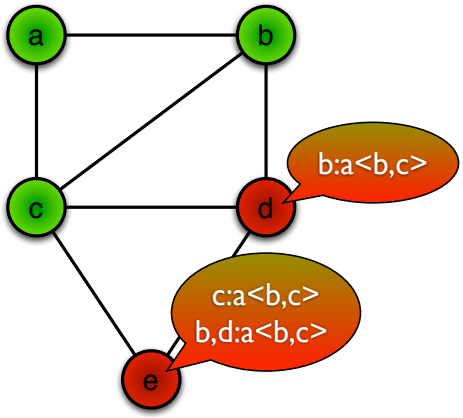

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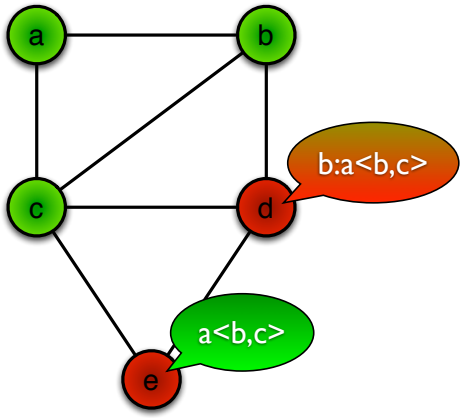

Explorer

- **Definition**
  - Solution is *two-adjacent edge complete* if non-faulty nodes discover all non-faulty nodes and edges adjacent to two non-faulty nodes

Explorer

- **Theorem**
  - (generalized) *Explorer* is a two-adjacent-edge complete solution to the *strong topology discovery problem* in case the graph connectivity is more than twice the number of faults

Composing Detector and Explorer

- **Observation**
  - *Detector* uses less messages when there are no faults
- **Idea**
  - run *Detector*, if a node discovers fault, invoke *Explorer*
  - requires *2k+1* connected topologies

Malice in Online Video Games

Online Games

- First Person Shooter (FPS)
- Real-time Strategy (RTS)
- Role playing Game (RPG)
- Massively Multiplayer Online Game (MMOG)
- Sports, puzzles

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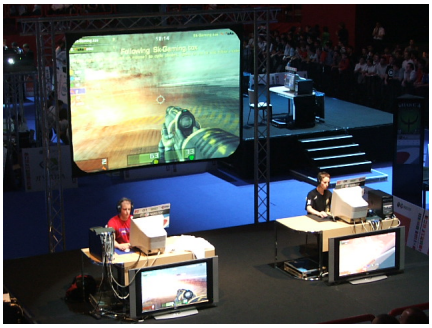
E-sport

- International competitions (ESWC, WCG, WSVG)
- Prizes over $1 million
- Professional leagues
- Professional players with sponsors, coachs ...
- In some countries, e-players are really famous



Online Cheat

- **First major online cheat**: Diablo 1997
- **FPS**: aim bot, aim proxy (Quake, Counter strike)
- **RTS**: maphack (Warcraft, Age of Empires)
- **1999-2000**: awareness of industry
- **recently**: gaming bots in MMOG (World of Warcraft)

Architectures

- **Client Server**
  - safer, server is trustable
  - "easy" to design
  - "centralized"
  - expensive, not scalable, faults ?
- **Peer-to-peer**
  - scalable
  - cheap
  - autonomous
  - difficult to design, cheating is easier

Binaries Protection

- **Avoid client-side modifications**
  - avoid unauthorized behaviors
  - ensure clients follow the same protocol
- [Munch06] proposes to execute dynamic verifications named mobile agents

Detection Mechanisms

- **Sometimes it is not possible to prevent cheating**
  - Keep log and verify afterwards [Kabus05]
  - Runtime verification of rules [Delap04]
- **Detection against Prevention**
  - Latency constraint are very high, prevention needs many message exchanges impacting this latency

Protocols

- **Enforcing fairness in spite of various latencies**
  - [Aggarwal05] on dead-reckoning
  - [Guo03] removing unfair advantage of low delay
- **Synchronisation protocols**
  - [Baughman01] lockstep protocol
  - [GD04] lockstep with improvements

Example: Synchronization

- Each round, every client sends its timestamped update
- Timestamps are needed to balance latency
- The server updates the world simulation using timestamps
- The server broadcasts the new game view
- If a message is late, the server modifies the view

Example: Synchronization

- **Problem**
  - Because latency may vary, timestamps are not verified
  - Malicious clients may ``know'' the future.

Example: Lockstep Protocol

- Each client sends to every other a commit of its update
- When every client has received every other update, they send the clear update
- The game view is updated and broadcast
- Performance issue: a late message freezes all messages

Defeating Maphack

- **In RTS, maphack is to be avoided**
  - Game clients are not trustable
  - Any information that leaked may be revealed
  - *Zero-Knowledge* Protocols

Defeating Maphack

- Consider two players such that:
  - Player *1* has value *A*
  - Player *2* has value *B*
- **Question**: How to know whether *A=B* without revealing *A* or *B* if *A!=B*
- **Bad solution**: exchange *hash(A)* and *hash(B)* and then compare

Defeating Maphack

- Let *f* and *g* be two commutative cryptographic functions respectively known only to *P1* and *P2*
  - *f(g(A)) = g(f(A))* for any *A*

Defeating Maphack

- *P1* computes *f(A)*
- *P1* sends *f(A)* to *P2*
- *P1* computes *f(g(B))*
- *P1* sends *f(g(B))* to *P2*
- if *f(g(B))=g(f(A))* then *A=B*

- *P2* computes *g(B)*
- *P2* sends *g(B)* to *P1*
- *P2* computes *g(f(A))*
- *P2* sends *g(f(A))* to *P1*
- if *f(g(B))=g(f(A))* then *A=B*

Roadmap

- Currently designing a P2P version of World of Warcraft server, that will be later used as a basis for experimenting malice-resilient protocols on a ``real'' platform.
- Malice-proof protocol design and implementation

Conclusion

Conclusion

- **Goal**: mask faults and attacks to the user
- **Basic principle**: redundancy and majority
  - not necessary to identify who misbehaves
  - most people must be reliable
  - protocols are much easier with cryptography (but how is crypto set up?)

Pros

- Masks the faults and attacks to the user
- Natural way to cope with failures
- Many protocols are available
  - Consensus, Atomic commit, Reliable Broadcast, Renaming,...

Cons

- Network must be properly initialized
- Global knowledge is assumed
  - size, names, maximum number of faults,...
- Global communication is used
- Global synchrony is assumed