The Byzantine Agreement — An Introduction

Radu Nicolescu
Department of Computer Science
University of Auckland

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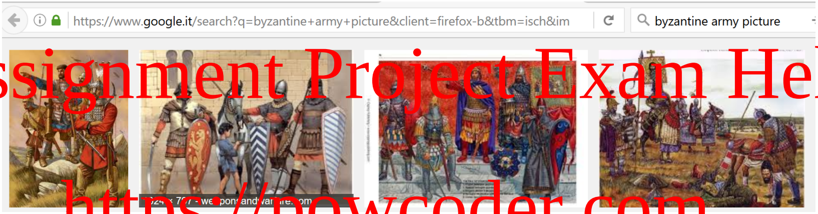
Byzantine agreement story

- Name is an allegory based on Byzantium's tumultuous history...

- http://en.wikipedia.org/wiki/Byzantium
- http://en.wikipedia.org/wiki/Byzantine_Empire

Byzantine agreement story

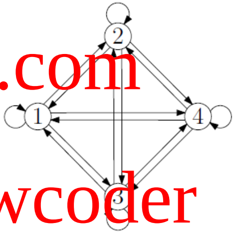


- $N = 4$ Byzantine armies, physically separated
- Generals start with their own initial decisions, 0 or 1
- They can communicate via $N(N-1)/2 = 6$ reliable channels
- They must reach a common decision
- Problem: among them there may be F Byzantine traitors, who may attempt to disrupt the agreement, by any means
- Deterministic agreement between loyal generals possible iff $N \geq 3F + 1$ and communications are synchronous

Byzantine agreement problem

- The N generals, basic story $N = 4$
- Complete graph K_N (loopbacks possible), with secure channels

- Generals' initial choices can be different: attack or withdraw (database: commit or rollback; binary: 1 or 0)



- Agreement required on one of their initial choices
- Generals should either all attack or all withdraw

Byzantine agreement problem

- However... among the N generals, there may be F traitors (faulty), thus only $N - F$ are loyal (non-faulty)
- Typically: $N = 4$, $F = 1$ (or, $N = 7$, $F = 2$)
- In fact, the problem can be deterministically solved iff $N \geq 3F + 1$ (we'll prove this later)
- We need two elves (loyals) for each orc plus one hobbit (loyal): $N \geq F + 2F + 1$ ☺
- Algorithms: Pease, Shostak, Lamport (1980); Lamport, Shostak, Pease (1982).
- Impossibility results: Fischer, Lynch, Paterson (1985) – FLP

Byzantine failures

- A traitor can:
- behave correctly (!)
- stop cooperating (stop sending messages)
- send confusing messages (different messages to different directions)
- briefly: anything that could disrupt the agreement!
- The algorithm must cope with such extremely malevolent adversaries
- The purpose is NOT to identify the traitors, but to ensure that the system continues to work properly (all loyal guys)

Byzantine agreement conditions

- Termination: all non-faulty processes eventually decide
- Agreement: no two non-faulty processes ever decide on different values

- Validity: if all non-faulty processes start with the same initial value $v \in V$, then v is the only one possible decision value [STRONG]

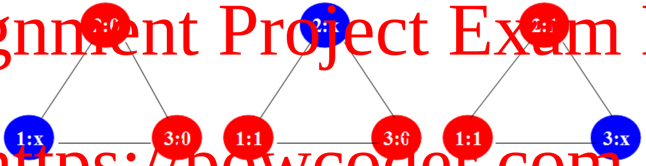
  - if the non-faulty processes start with different initial values, then the final decision could be any of these (as long as it is consistent)

Byzantine agreement scenarios ($N = 4$)

Initial	Final	Notes
0 0 0 0	0 0 0 0	required
0 0 0 1	0 0 0 0	majority rule? NO, required (why?)
0 0 1 1	v v v v	depending on a parameter v_0
0 1 1 1	1 1 1 1	majority rule? NO, required (why?)
1 1 1 1	1 1 1 1	required
0 0 0 *	0 0 0 *	required
0 0 1 *	0 0 0 * or 1 1 1 *	depending on parameter v_0 and the orc
0 1 1 *	0 0 0 * or 1 1 1 *	depending on parameter v_0 and the orc
1 1 1 *	1 1 1 *	required

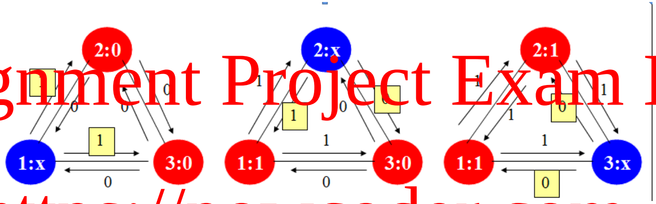
- The star (*) represents orc's arbitrary or malevolent choices
- The algorithm we study – EIG – uses an internal parameter, v_0, which (1) replaces missing or wrongly formatted messages, and (2) breaks ties

Informal example



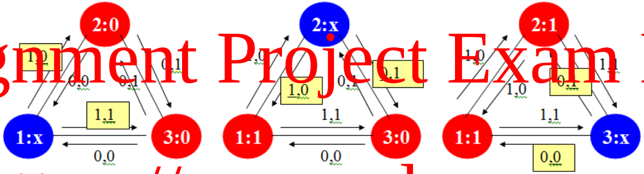
- The following agreement is required, between the elves:
  - Left: #2 and #3 should decide 0.
  - Right: #1 and #2 should decide 1.
  - Middle: #1 and #3 should reach a consistent decision.
- The orc processes have a perfect disrupting strategy (next)

Informal example



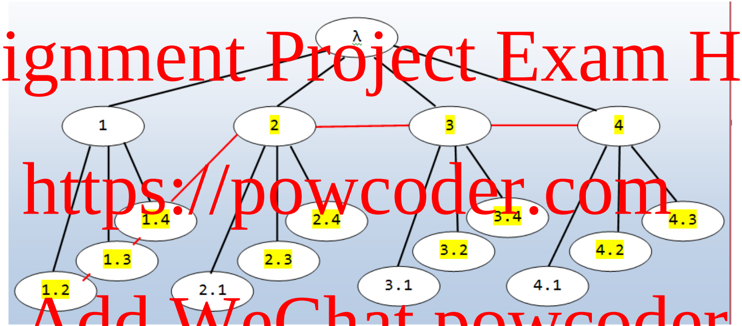
- Consider that they send to each other their initial values:
  - Process #3 cannot differentiate between the left and middle cases and should therefore take the same decision in both cases, i.e., 0.
  - Process #1 cannot differentiate between the right and middle cases and should therefore take the same decision in both cases, i.e., 1.
  - Thus, no common decision is possible for the middle case
- Conclusion: 1 round is not enough...

Informal example



- Consider that on the 2nd round the elves relay to each other the value received from the other process on the 1st round:
  - Process #3 still cannot differentiate between the left and middle cases...
  - Process #1 still cannot differentiate between the right and middle cases...
  - Thus, no common decision is possible for the middle case
- Conclusion: 2 rounds are not enough... arguments can continue for any number of rounds...

EIG tree

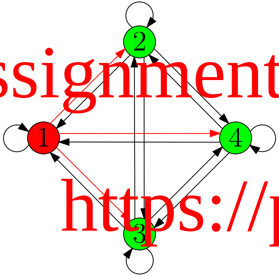


- EIG = Exponential Information Gathering
- Here, $F = 1$, $N = 3F + 1 = 4$, $L = F + 1 = 2$
- Description in Lynch's monograph

EIG tree

- Each non-faulty process maintains its own copy of the EIG tree
- The top-down val (α) attributes: first, the levels are filled top-down, according to received messages
- The bottom-up newval (β) attributes: next, the levels are recomputed bottom-up, without messaging, according to a local majority rule
- On each branch, there is at least one node with a label ending in the ID of a non-faulty node
- The first such nodes (top-down) are connected by a red cut
- The nodes on or above the red cut are common: they have the same newval values, in all non-faulty processes
- Thus the final decision is common, for all non-faulty processes
- Full description in Lynch's monograph – also our demo

Faulty process ι_1 sends out conflicting messages

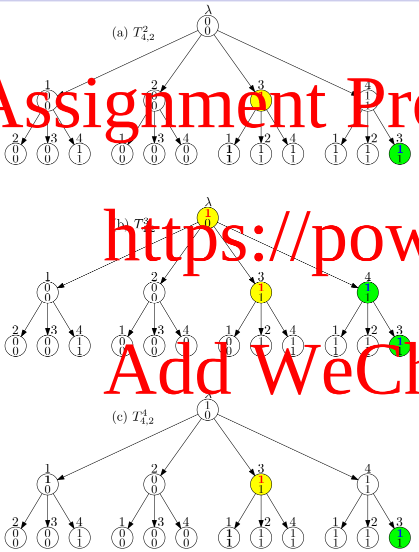


Process	ι_1	ι_2	ι_3	ι_4
Initial choice	?	0	1	1
Faulty	Yes	No	No	No
Round 1 messages	$(1, x)$	$(2, 0)$	$(3, 1)$	$(4, 1)$
Round 2 messages	$(2.1, 0)$ $(3.1, y)$ $(4.1, 1)$	$(1.2, 0)$ $(3.2, 1)$ $(4.2, 1)$	$(1.3, 0)$ $(2.3, 0)$ $(4.3, 1)$	$(1.4, 1)$ $(2.4, 0)$ $(3.4, 1)$
Final decision	?	0	0	0

- $x = 0, y = 1$ to process ι_2
- $x = 0, y = 0$ to process ι_3 – *try also* $x = 1, y = 0$
- $x = 1, y = 1$ to process ι_4

Non-faulty processes are always able to reach a common decision: *either* all 0, as here – *or* all 1

EIG trees for non-faulty processes



Process	ι_1	ι_2	ι_3	ι_4
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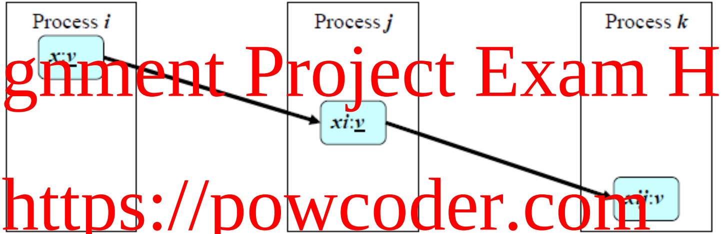
Round 1 messages	$(1, x)$	$(2, 0)$	$(3, 1)$	$(4, 1)$
Round 2 messages	$(2.1, 0)$ $(3.1, y)$ $(4.1, 1)$	$(1.2, 0)$ $(3.2, 1)$ $(4.2, 1)$	$(1.3, 0)$ $(2.3, 0)$ $(4.3, 1)$	$(1.4, 1)$ $(2.4, 0)$ $(3.4, 1)$
... Final decision	?	0	0	0

- α by top-down messaging
- L_1: (initial) $\iota_3 \xrightarrow{(3,1)} \iota_2, \iota_3, \iota_4$
- L_2: (relay) $\iota_3 \xrightarrow{(4.3,1)} \iota_2, \iota_3, \iota_4$
- β by bottom-up local voting
- common final decision

The top-down val() attribute



How val() are filled (example):

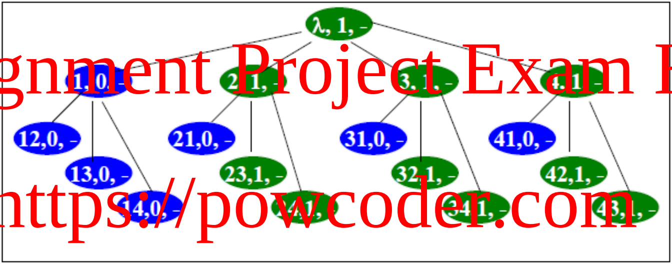
- val(2...) is about what #2 said
- val(2) is what #2 directly said
- val(21) is what #1 said that #2 said
- If #1 is lying about #2 in val(21), then #3 & #4 will "mask" this by val(23) & val(24)
- invalid or missing messages are assumed to be v_0

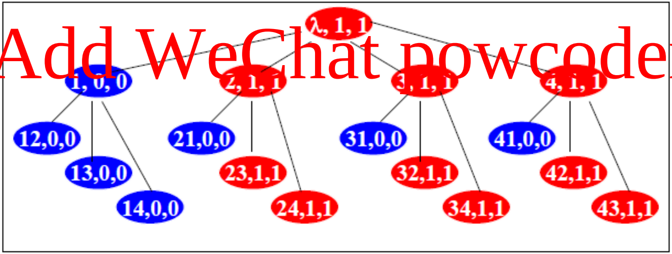
The bottom-up newval() attribute

newval()

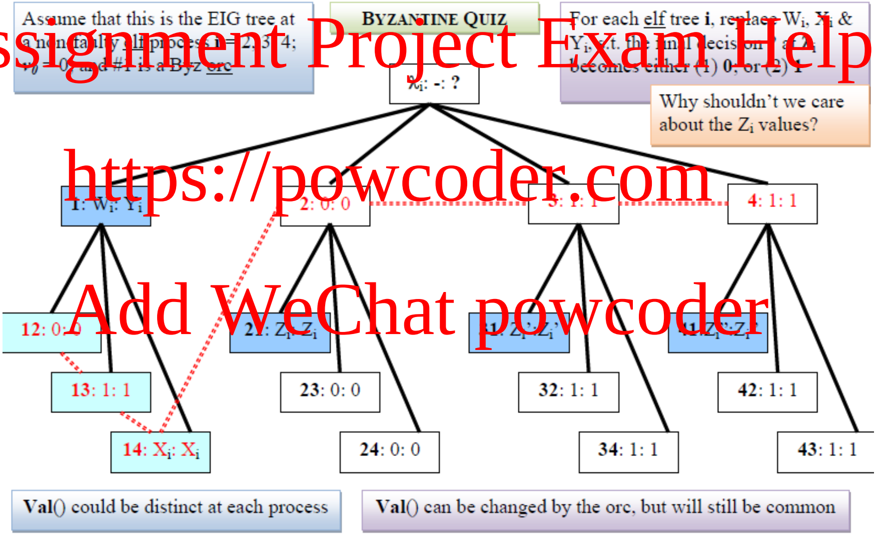
- computed new value
- no messaging anymore
- decision taken by a local majority voting procedure
  - or v_0 if there is no majority
- this “masks” failures
  - if any – within the accepted limits $(n \geq 3f + 1)$

The bottom-up newval() attribute

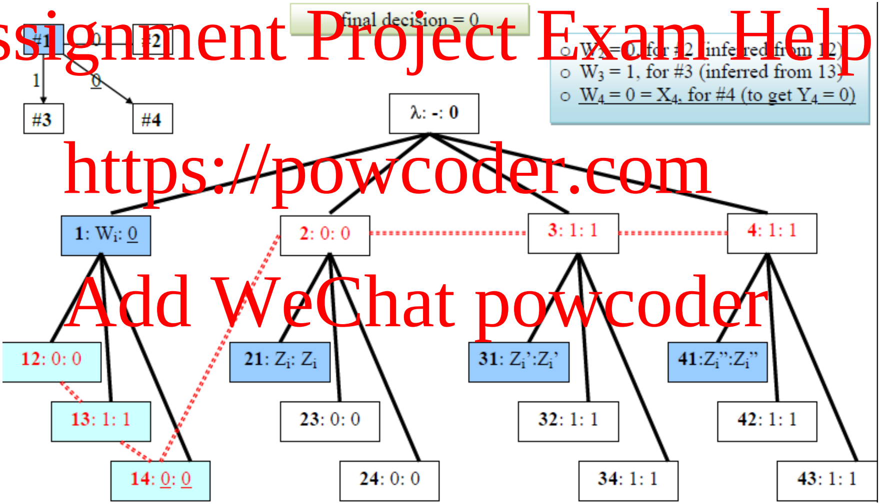




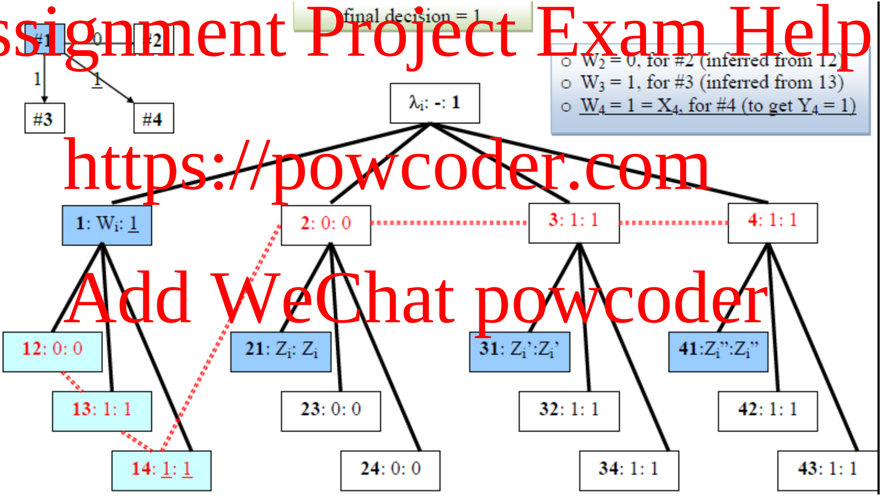
Byzantine quiz



Byzantine quiz: decision 0



Byzantine quiz: decision 1



Byz vs Triple modular redundancy (TMR)

BYZANTINE AGREEMENT VS TMR (more in text).