Distributed systems:

The Byzantine Generals Problem

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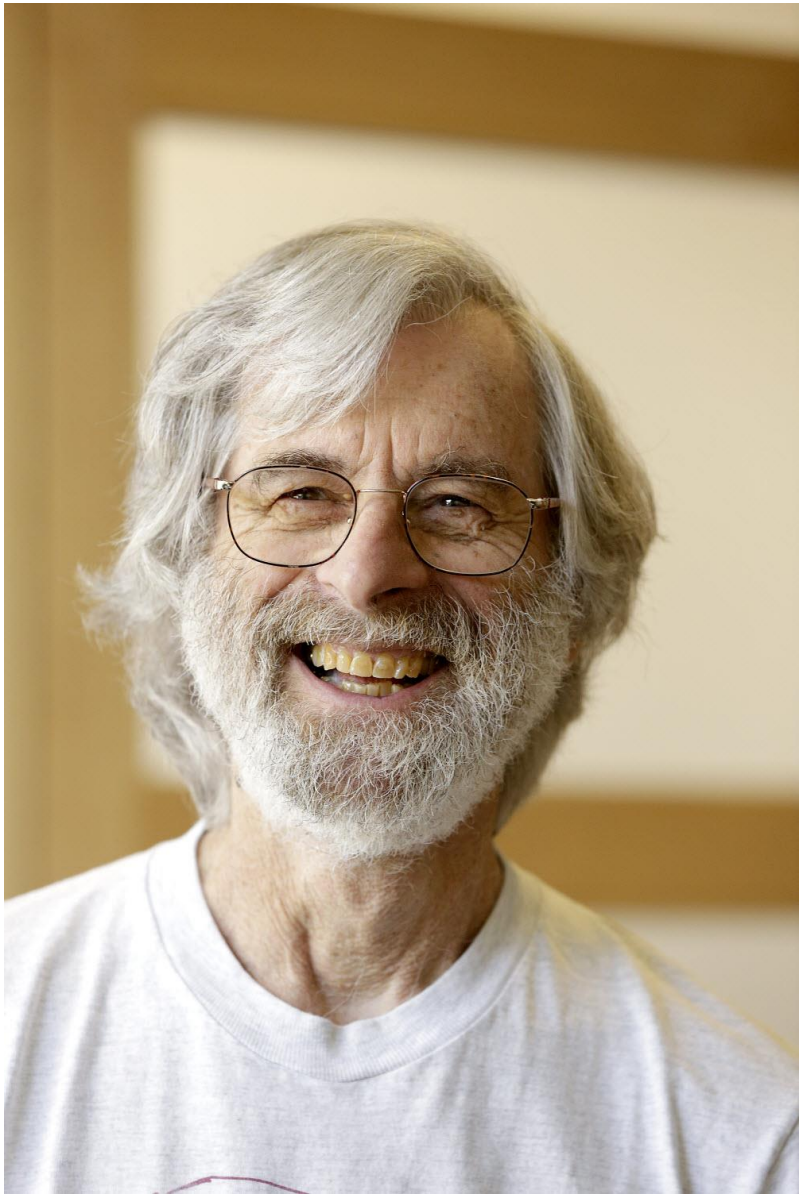
Distributed Programming Laboratory

System model so far

- *n* processes, message passing
- Process crashes
  - Algorithms become non-trivial
  - Additional assumptions required (P, correct majority..)
- What if processes could lie?



Leslie Lamport: The Byzantine Generals Problem

Attack

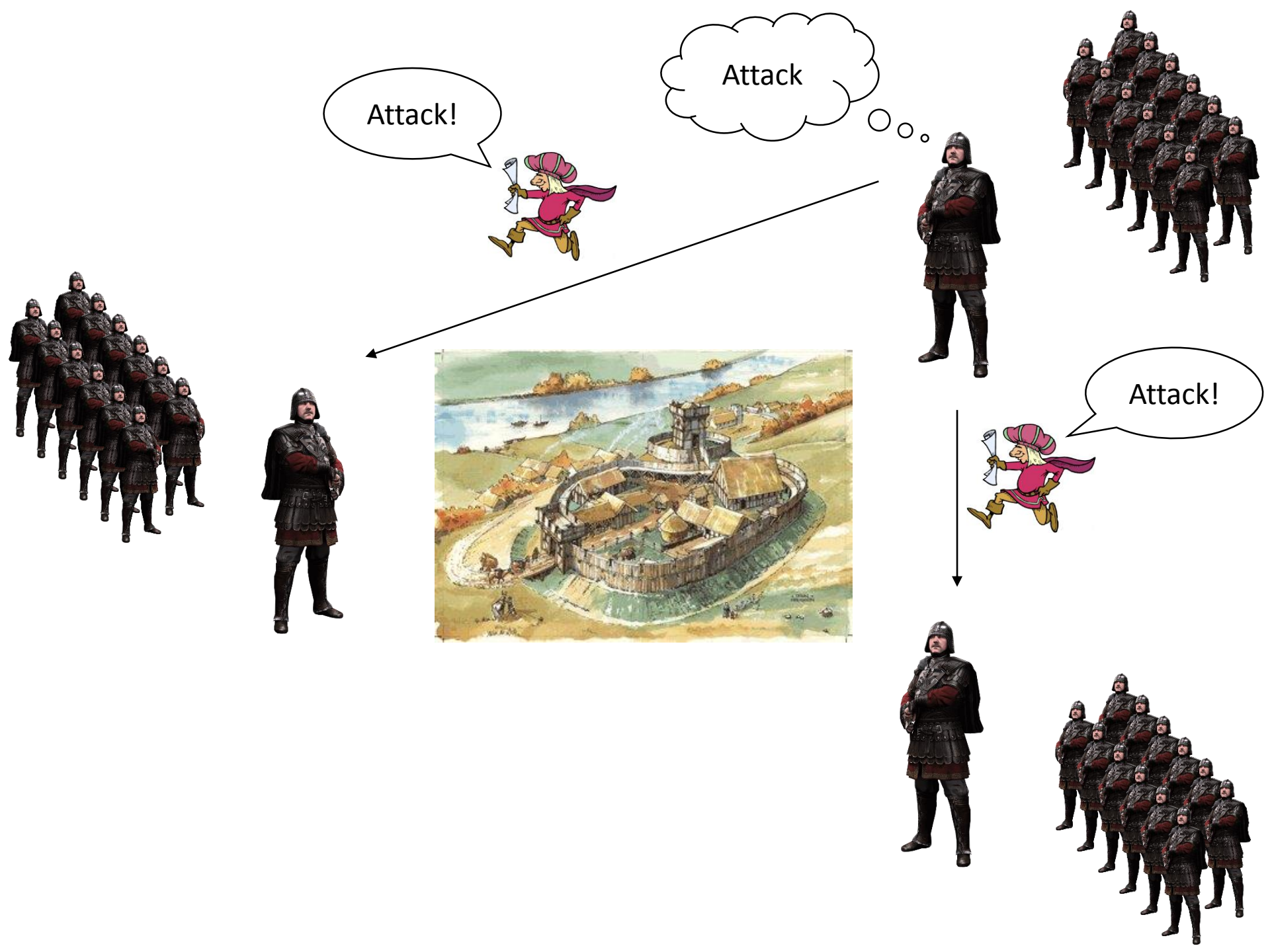
Retreat

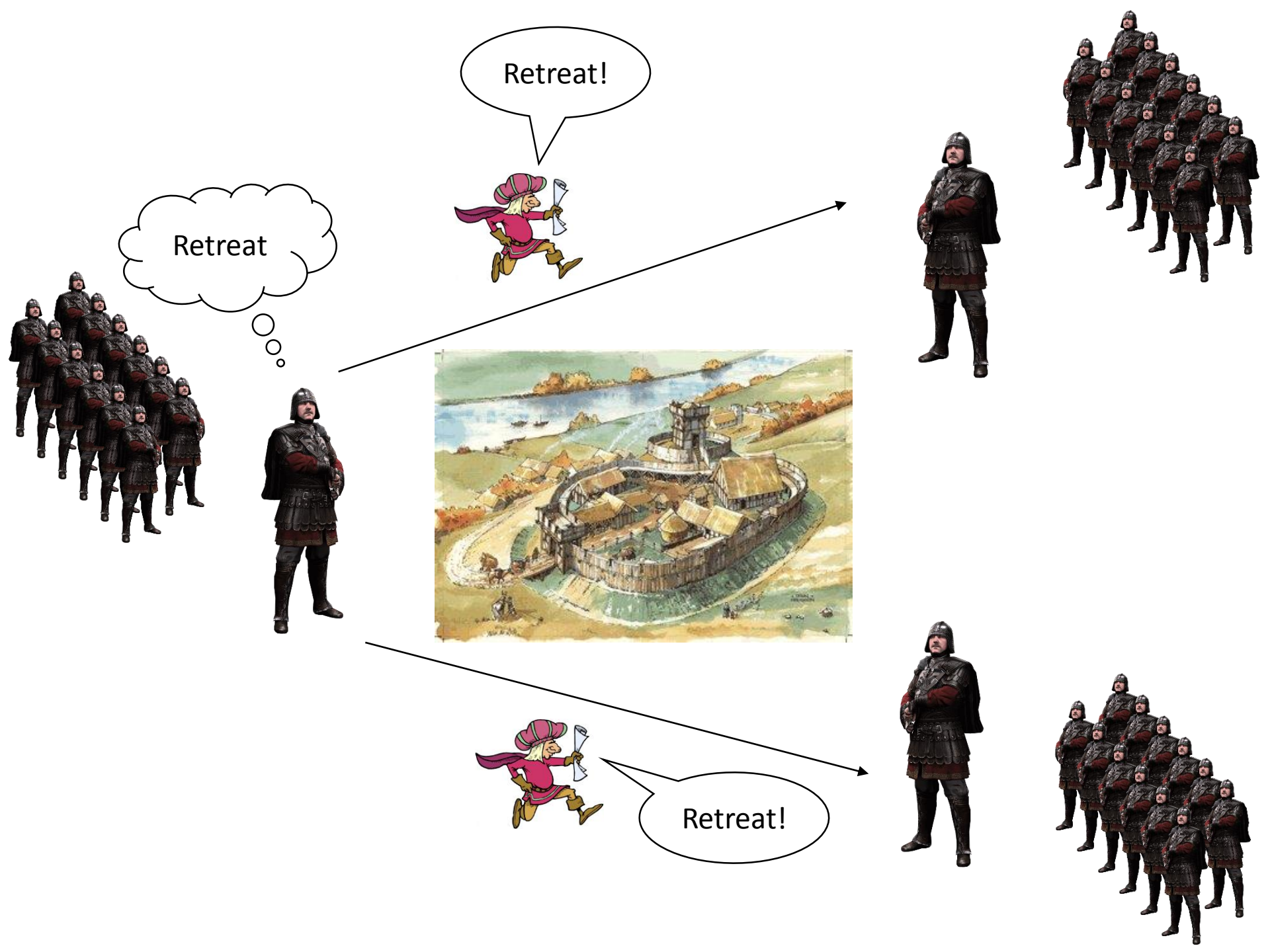
Retreat

Retreat!

Retreat

Retreat!


Attack!
Attack
Attack!


Retreat!
Retreat
Retreat!

Retreat
Attack
Retreat

Retreat
Attack
Retreat

Retreat!

Retreat
Attack
Retreat

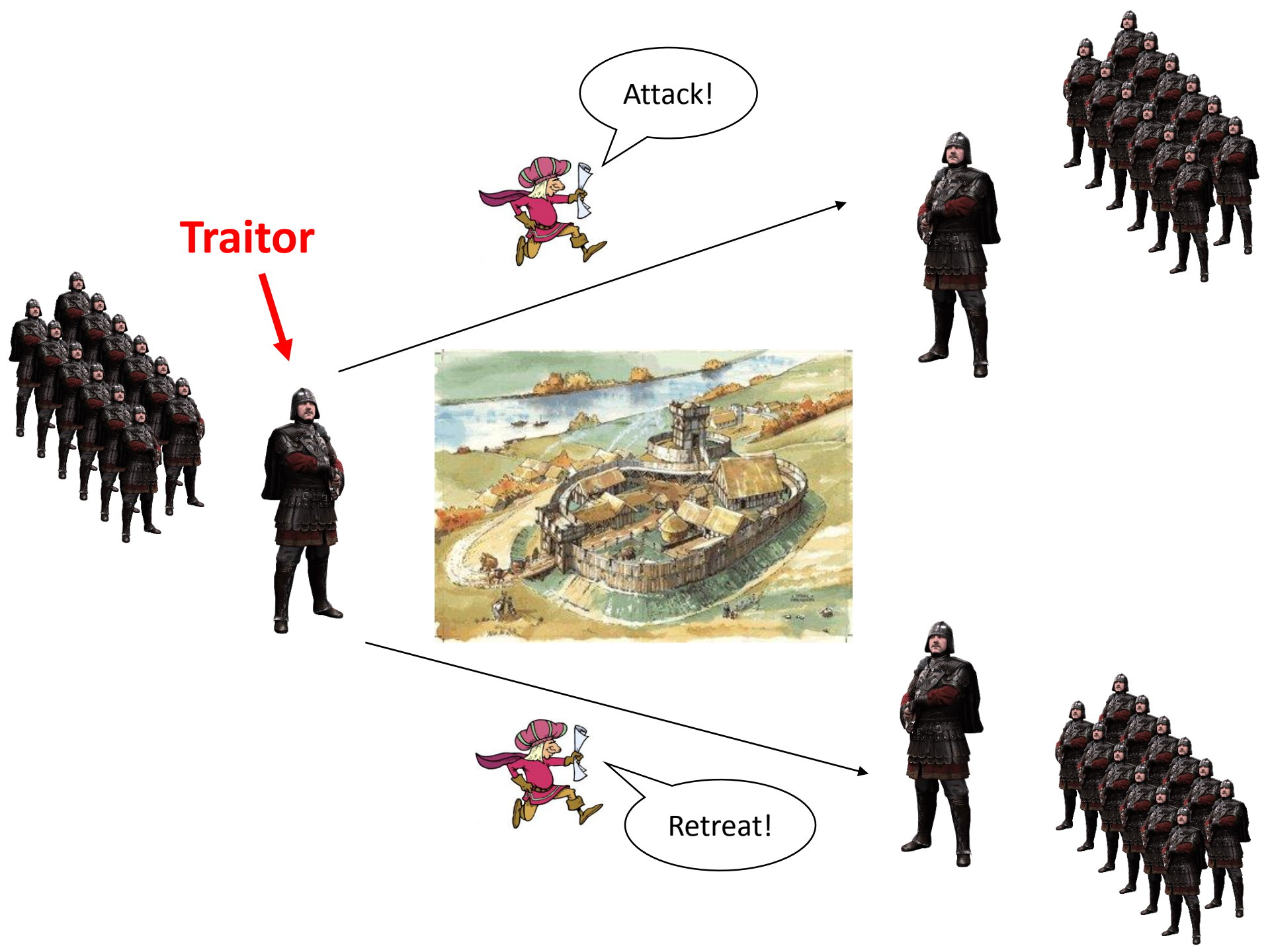
Retreat!

Retreat
Attack
Retreat

Retreat!

Retreat
Attack
Retreat

Traitor


Attack!
Traitor
Retreat!

Traitor

Attack
Attack
Retreat

Retreat
Attack
Retreat

Traitor

Retreat!

Attack!

Attack
Attack
Retreat

Retreat!

Retreat
Attack
Retreat

Requirements

- All *loyal* generals choose the same plan (Attack / Retreat)
- A few traitors cannot impose a bad plan on the loyal generals

Let’s formalize

v_1 = Retreat

1

v_2 = Attack

2

v_3 = Retreat

3

Let’s formalize

- n generals
- v_i = i-th general’s opinion (value: Attack / Retreat)
- generals only exchange oral messages

… 2 conditions …

Recall: Requirements

- **All *loyal* generals choose the same plan (Attack / Retreat)**
- A few traitors cannot impose a bad plan on the loyal generals

Let's formalize

- n generals
- v_i = i-th general's opinion (value: Attack / Retreat)
- generals only exchange oral messages

1) Every *loyal* general makes his decision based on the same information (d_1,…,d_n)

don't care

Traitor

1

d_1: Retreat
d_2: Attack
d_3: Retreat

2

d_1: Retreat
d_2: Attack
d_3: Retreat

3

Recall: Requirements

- All *loyal* generals choose the same plan (Attack / Retreat)
- **A few traitors cannot impose a bad plan on the loyal generals**

Traitor

don’t care

1

d_1: Attack
d_2: Attack
d_3: Attack

2

d_1: Attack
d_2: Attack
d_3: Attack

3

Traitor

don’t care

1

v_2 = Retreat

d_1: Attack
d_2: Attack
d_3: Attack

2

v_3 = Retreat

d_1: Attack
d_2: Attack
d_3: Attack

3

Let's formalize

- n generals
- v_i = i-th general's opinion (value: Attack / Retreat)
- generals only exchange oral messages

1) Every *loyal* general makes his decision based on the same information (d_1,…,d_n)

2) If i-th general is loyal, every *loyal* general must base his decision on $d_i = v_i$

Let's formalize

- n generals
- v_i = i-th general's opinion (value: Attack / Retreat)
- generals only exchange oral messages

1) Every *loyal* general makes his decision based on the same information (d_1,…,d_n)
   $\Leftrightarrow$ Every *loyal* general uses same value as d_i

2) If i-th general is loyal, every *loyal* general must base his decision on $d_i = v_i$

Commander and Lieutenants

- Solve once for each general *i*:
  - *1* commander (general *i*)
  - *n – 1* lieutenants (other generals)
  - commander *i* sends value v_i to lieutenants

Byzantine Generals Problem

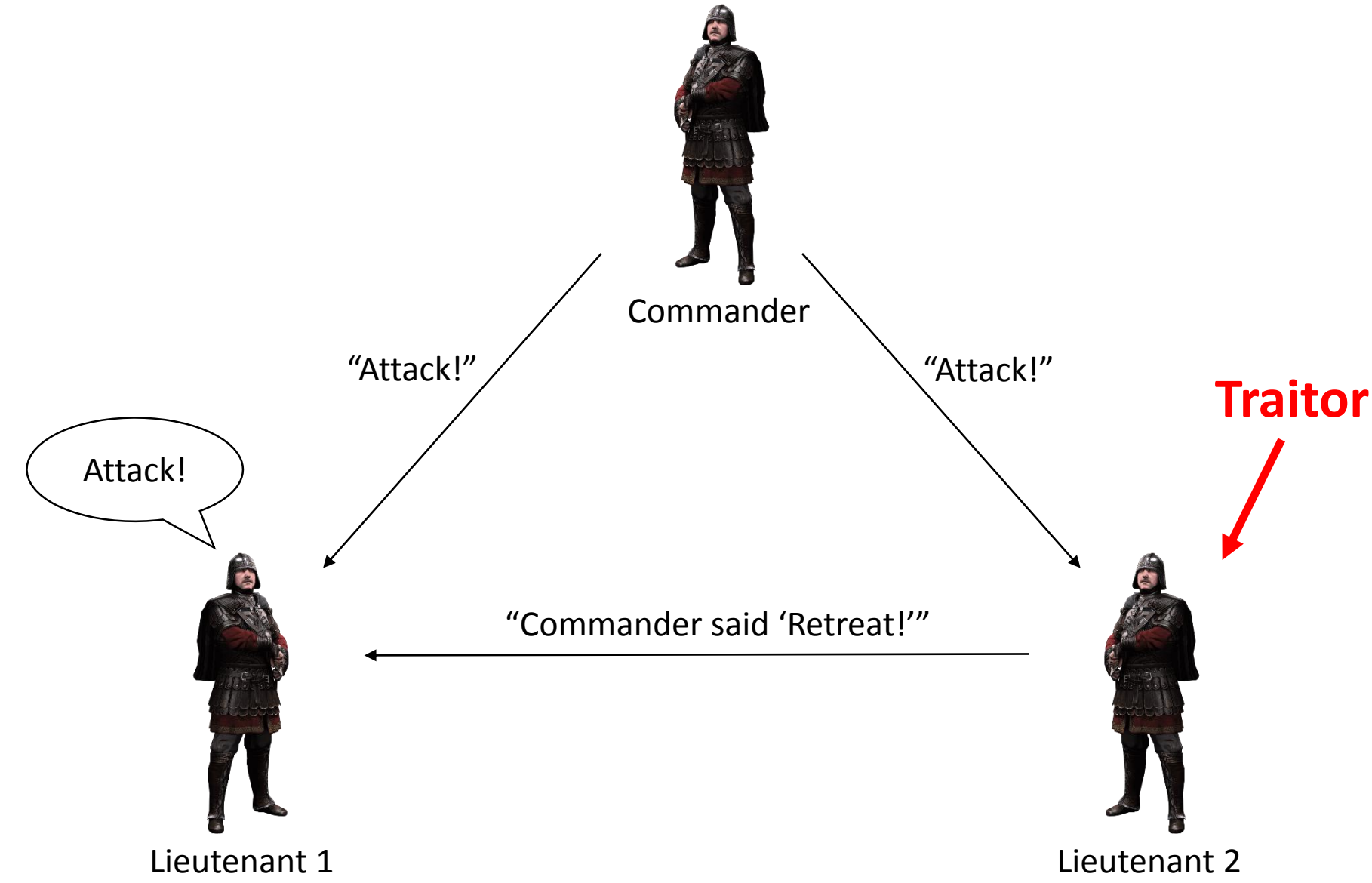
Commander must send an order to $n - 1$ lieutenants, such that:

BG1: All loyal lieutenants obey the same order

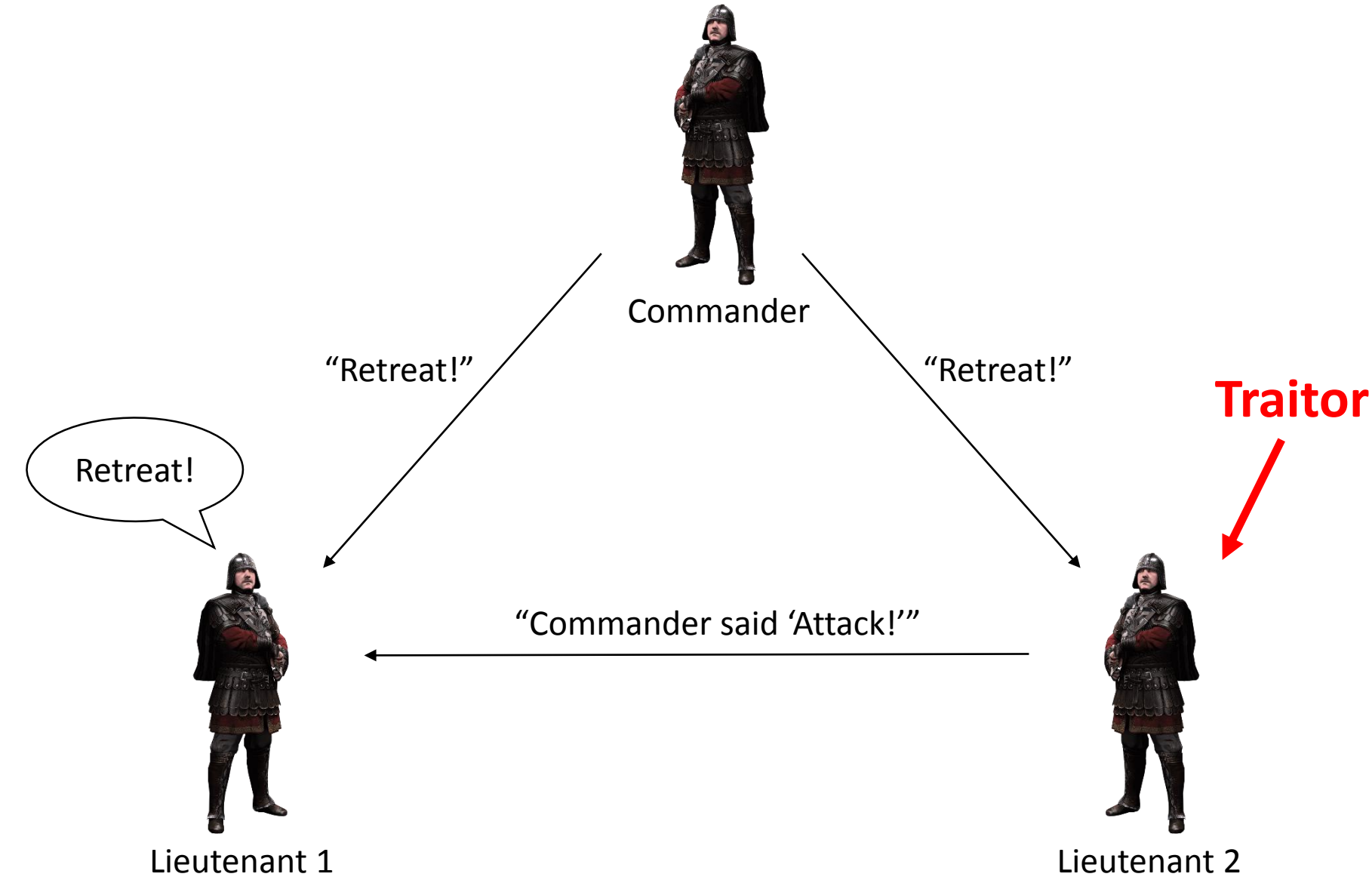
BG2: If commander is loyal, then every loyal lieutenant obeys commander's order

In our case, command is "Use 'Attack' / 'Retreat' as d_i"

3 generals, 1 of them traitor



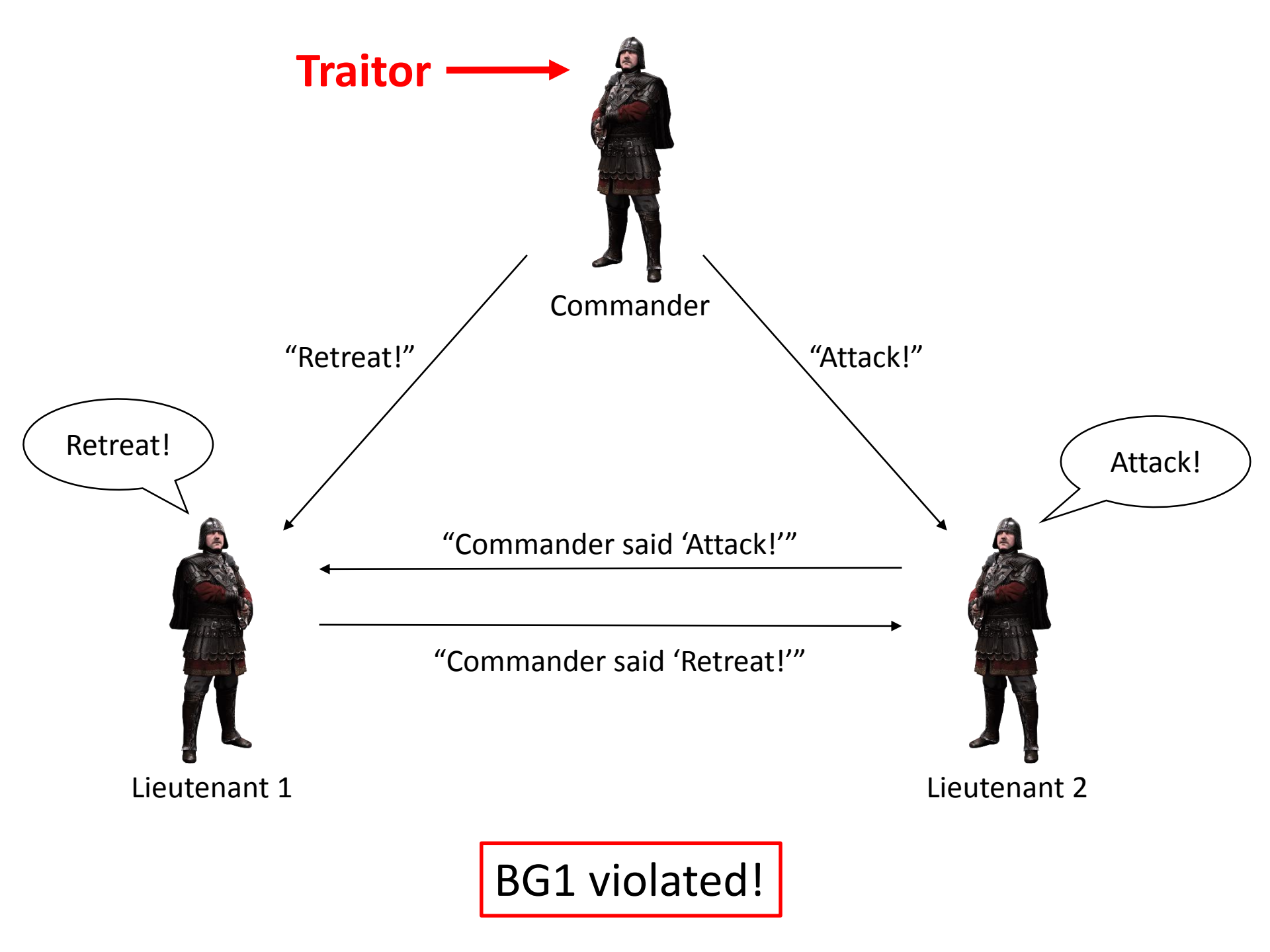
To satisfy BG2, Lieutenant 1 must obey “Attack!”.



To satisfy BG2, Lieutenant 1 must obey “Retreat!”.

3 generals, 1 of them traitor

To satisfy BG2, a loyal lieutenant must obey the order directly received from the commander.


Traitor
Commander
“Retreat!”
“Attack!”
Retreat!
Attack!
“Commander said ‘Attack!’”
“Commander said ‘Retreat!’”
Lieutenant 1
Lieutenant 2
BG1 violated!

3 generals, 1 of them traitor

To satisfy BG2, a loyal lieutenant must obey the order directly received from the commander.

$\Downarrow$

If commander is a traitor, BG1 is violated.

$\Downarrow$

No algorithm can satisfy BG1 and BG2 for 3 generals and 1 possible traitor.

Impossibility result

- No algorithm can solve the “Byzantine Generals Problem” for 3 generals, if one of them can be a traitor.

- Generalization: There is no algorithm for *3f* generals, if *f* or more of them can be traitors.
  (proof by reduction from 3 generals, 1 traitor)

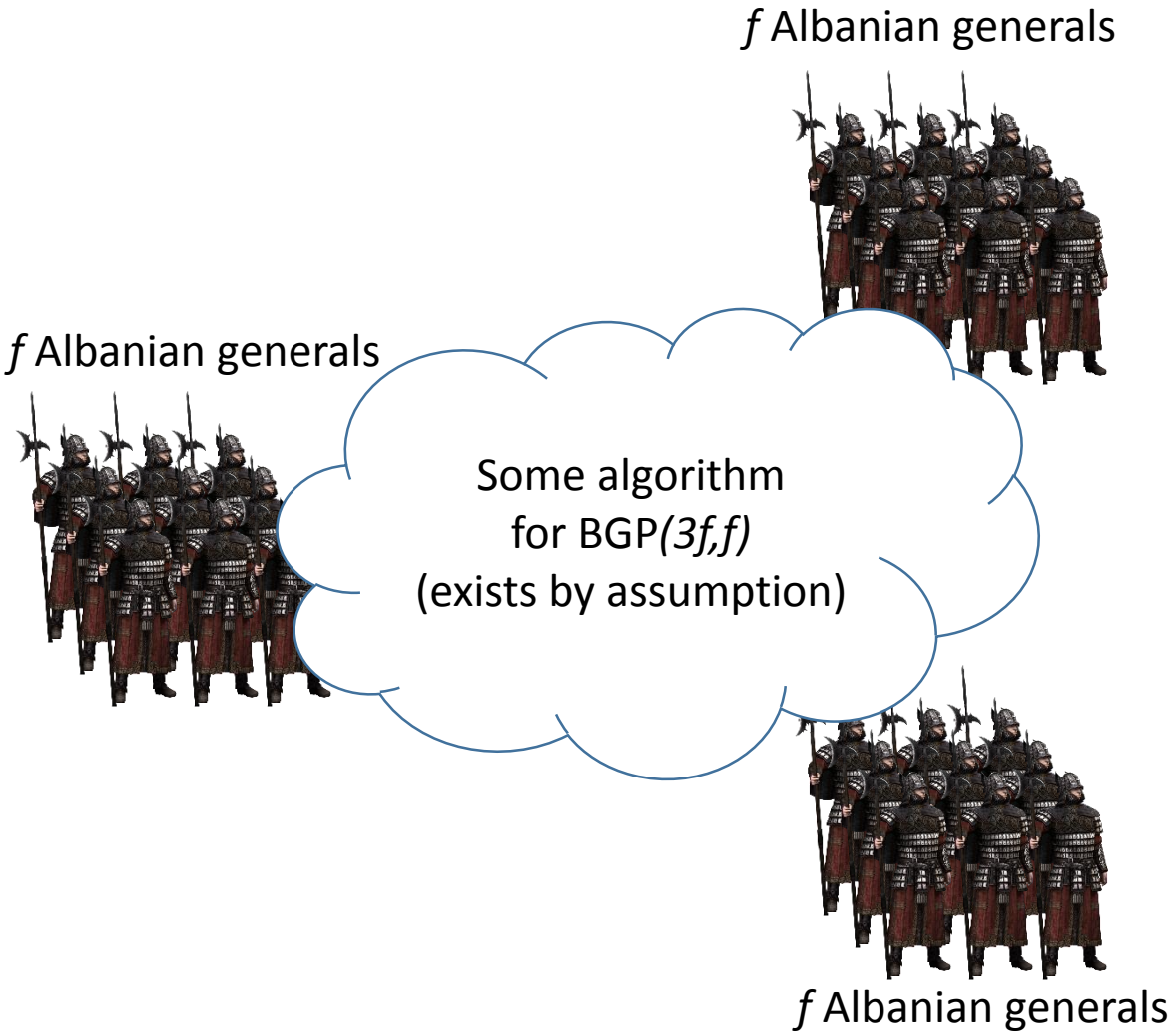
3f generals, *f* of them traitors

- Proof by contradiction:
  1. Assume a solution for BGP(*3f, f)* for some *f*
  2. Use it to solve BGP(*3,1*)

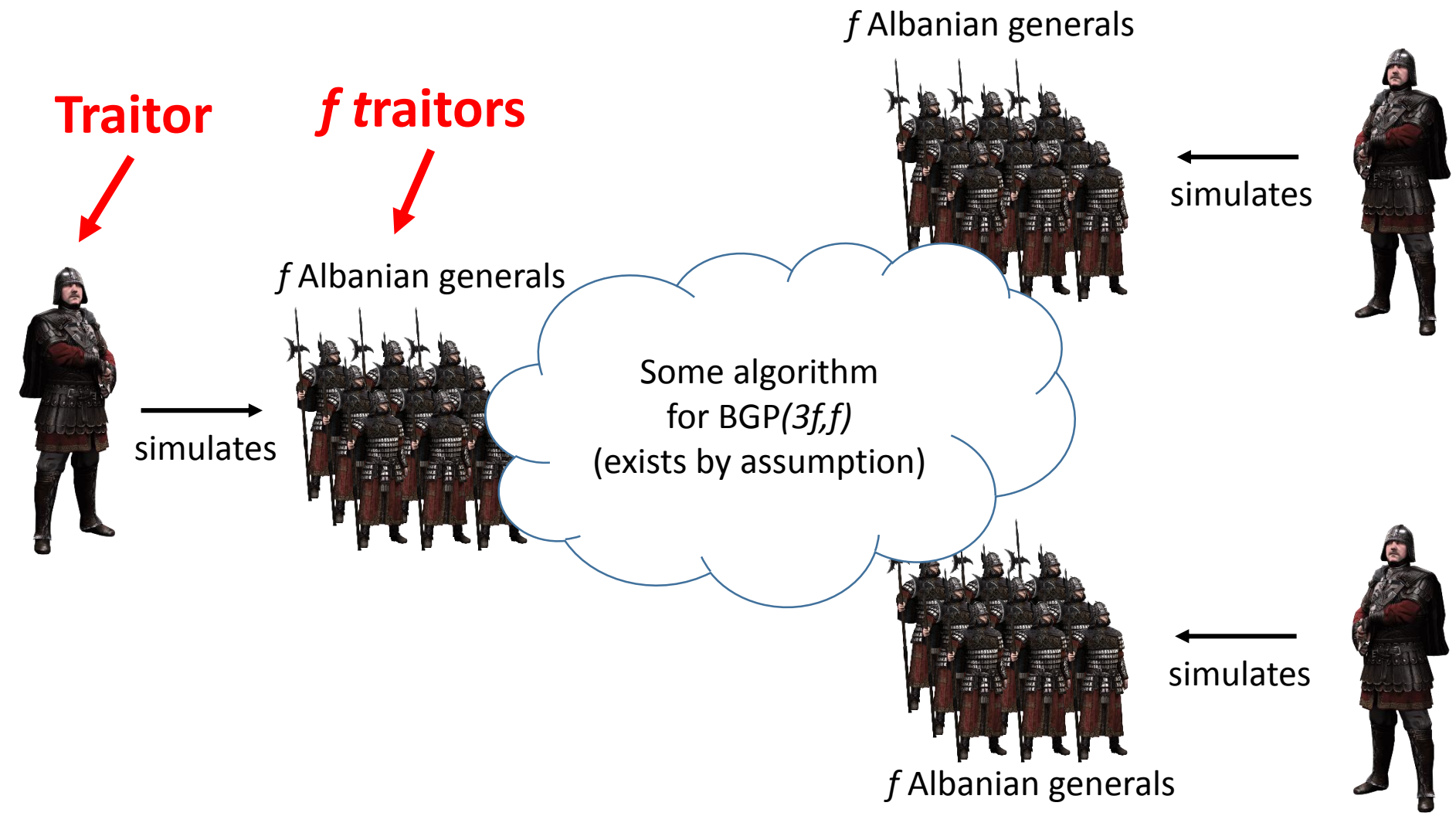
$\Downarrow$

Contradiction with "there is no solution to BGP*(3,1)*"

Albanian generals



Albanian generals



Unsolvability for BGP(*3f,f*)

If algorithm for BGP(*3f,f*) existed

⇓

Could use it to solve BGP(*3,1*)

⇓

Contradiction to unsolvability of BGP(*3,1*)

⇓

Conclusion: No alg. for BGP(*3f,f*) exists.

Conclusion

- If faulty processes can lie (not only crash)
  - Correct **majority** is **not enough**!
  - Even **two thirds** are **not enough**!
  - True for any synchrony assumptions

- What can we do? (next lecture)
  - Stronger assumption: > 2/3 are correct
  - Use signed messages