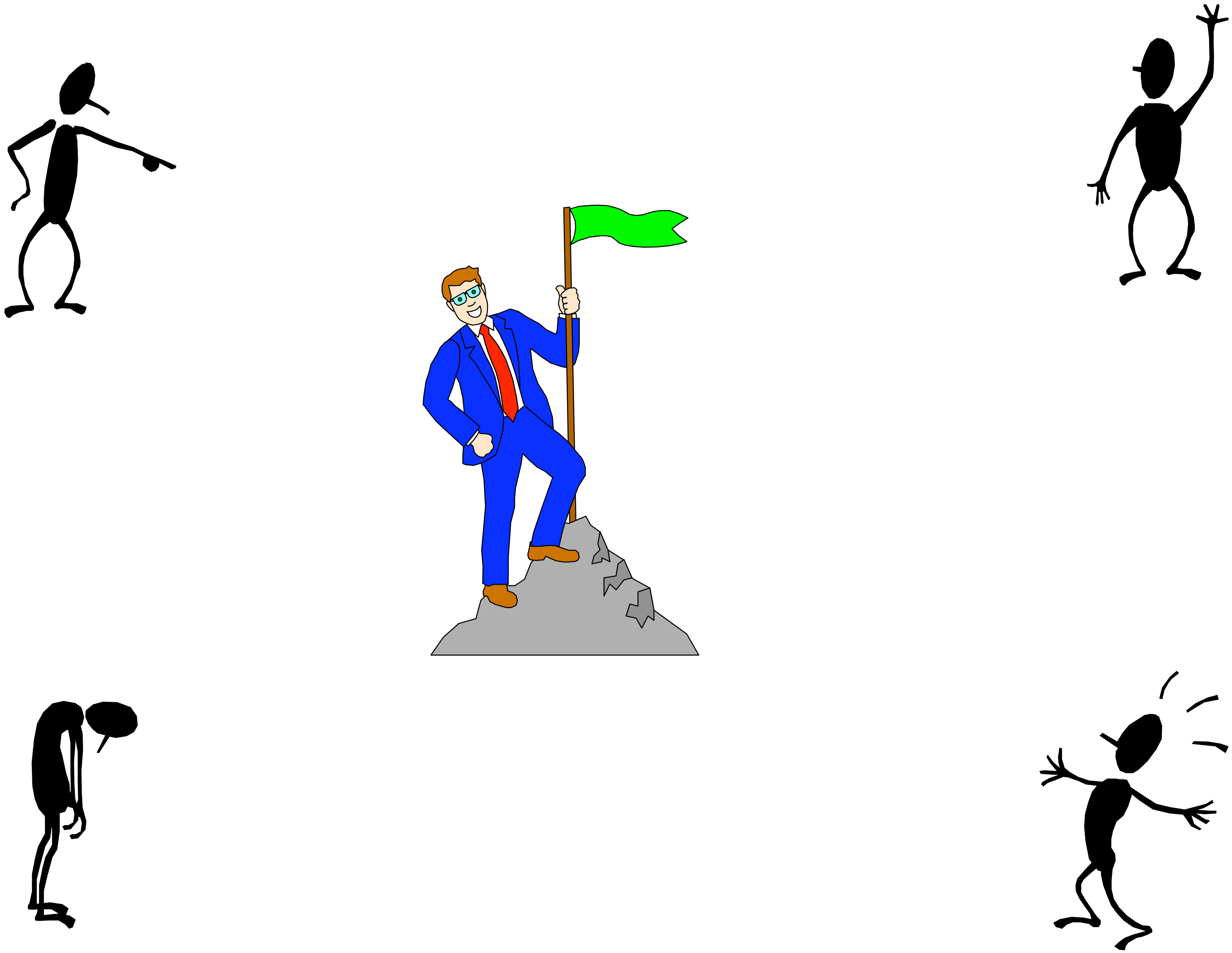
# *Introduction FT Agreement*

- We will discuss fault tolerant agreement algorithms during this class.
- We want to start out the discussion with the Byzantine General Problem
  - L. Lamport, R. Shostak, and M Pease, "The Byzantine Generals Problem"
- Variations of the problem will follow us throughout the rest of the semester.
- What started it all?
  - Clock synchronization problems in SIFT

# *Byzantine General Problem*



# *Byzantine General Problem*

- Objective
  - A) All loyal generals must decide on the same plan of action
  - B) A "small" number of traitors cannot cause the loyal generals to adopt a "bad" plan.
- Types of agreement
  - exact agreement
  - approximate agreement
- Applications, e.g.
  - agreement in the presence of faults
  - event, clock synchronization

# *Byzantine General Problem*

- Key to disagreement
  - 1) Initial disagreement among loyal generals
  - 2) Ability of traitor to send conflicting messages
    - asymmetry
- Reduction of general problem to simplex problem with 1 General and n-1 Lieutenants
  - General gives order
  - Loyal Lieutenants must take single action

# *Byz. Gen. Prob. (Simplex)*

- Want

IC1: All loyal Lieutenants obey the same order

IC2: If the commanding General is loyal, the every loyal Lieutenant obeys the order he sends

  - IC1 & IC2 are called *Interactive Consistency Conditions*.
  - If the General is loyal, then IC1 follows from IC2.
  - However, the General need not be loyal.

- Any solution to the simplex problem will also work for multiple-source problems.
  - the $i^{th}$ General sends his value *v(i)* by using a solution to the BGP to send the order "use *v(i)* as my value", with the other Generals acting as the lieutenants.

# *BGP: Oral Message Solution*

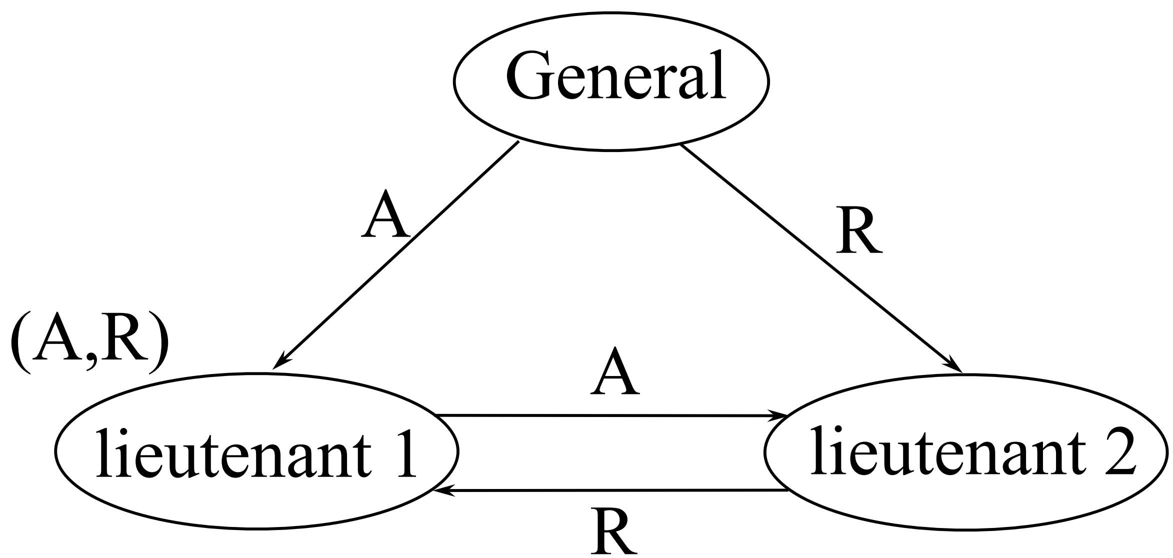
- Oral Message
  - message whose contents are under the control of the sender (possibly relays)
- Practical implication, sensor example
  - General = sensor
  - Lieutenants = processor redundantly reading sensor
  - Initial disagreement
    - time skew in reading,  bad link to sensor
    - analog - digital conversion error,  any threshold function
  - Asymmetry
    - communication problem, noise, V-level, bit timing

# *BGP: Oral Message Solution*

- The Byzantine Generals Problem seems deceptively simple, however
- no solution will work unless more than two-third of the generals are loyal.
- Thus, there exists no 3-General solutions to the single traitor problem using <u>oral messages</u>
- Assume the messages sent are
  - A = Attack
  - R = Retreat

# BGP: Oral Message Solution

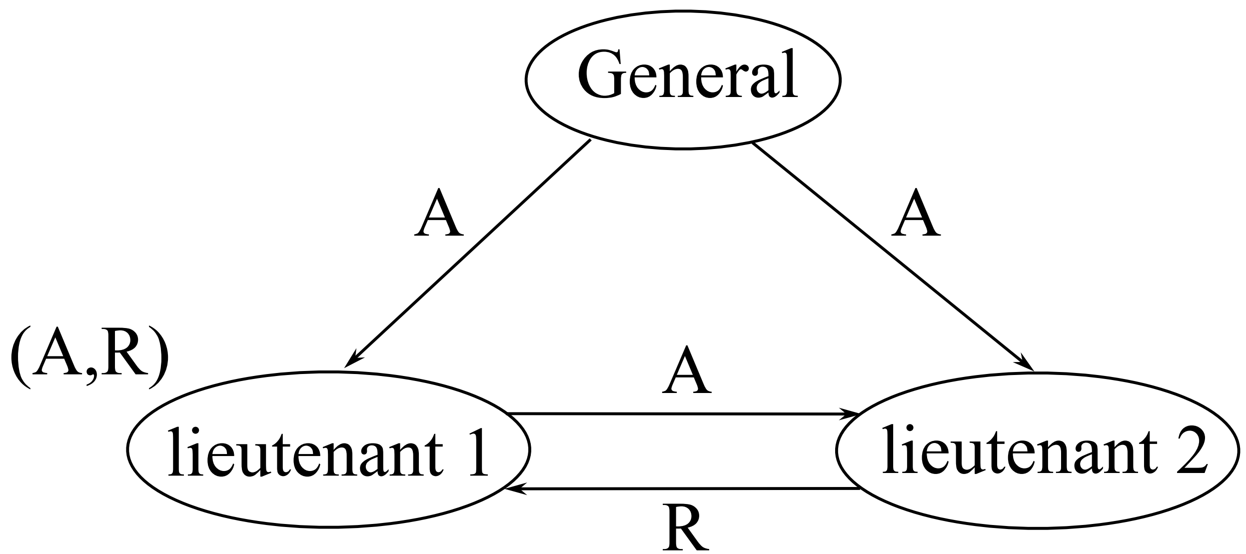
- Case 1: Commander is traitor:




  - commander is lying
  - who does lieutenant 1 believe
  - could pick default

# *BGP: Oral Message Solution*

- Case 2: Lieutenant 2 is traitor:



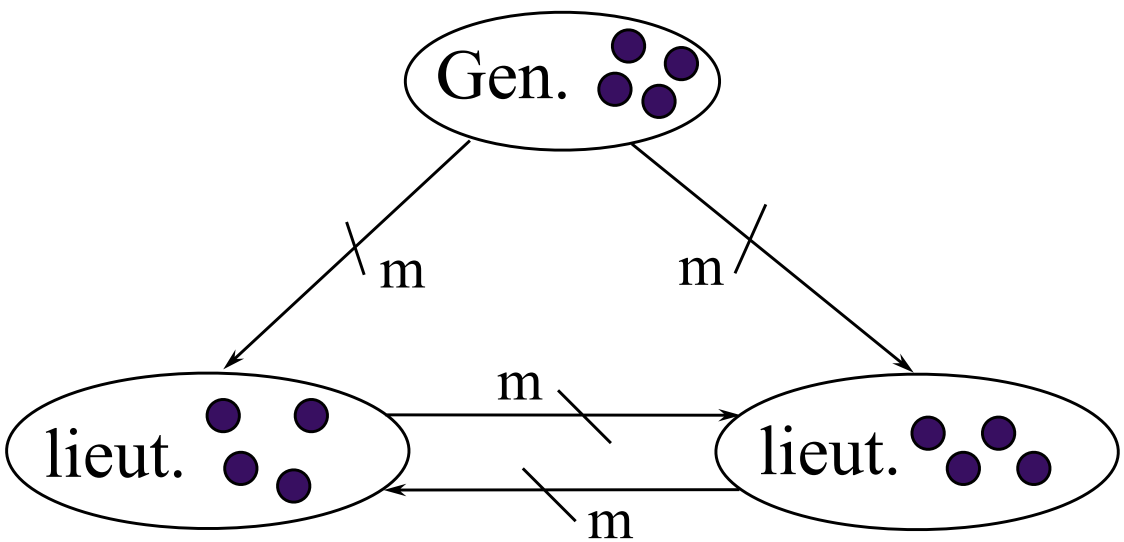

  - lieutenant 2 is lying
  - who does lieutenant 1 believe
  - could pick default, but what if it is R
    - then General has A and Lieutenant 1 has R !!!

# *BGP: Oral Message Solution*

- Given case 1 and case 2, lieutenant 1 cannot differentiate between both scenarios, i.e. the set of values lieutenant 1 has is (A,R).
- In general: Given m traitors, there exists no solution with less than 3m+1 generals for the <u>oral message</u> scenario.
- Assumptions about Oral Messages
  - every message that is sent is delivered correctly
  - the receiver of a message knows who send it
  - the absence of a message can be detected
  - how realistic are these assumptions?

# *BGP: Oral Message Solution*

- General case:
  - regroup generals
    - n Albanian generals
    - n/3 act as unit => 3 general Byzantine General Problem



# *BGP: Oral Message Solution*

## Algorithm OM(0)

1) The commander sends his value to every lieutenant

2) Each lieutenant uses the value he receives from the commander, or uses the value RETREAT if he receives no value

## Algorithm OM(m), m>0

1) The commander sends his value to every lieutenant.

2) For each *i*, let $v_i$ be the value lieutenant *i* receives from the commander, or else be RETREAT if he receives no value. Lieutenant *i* acts as the commander in Algorithm OM(m-1) to send the value $v_i$ to each of the *n*-2 other lieutenants.

3) For each *i*, and each $j \neq i$, let $v_j$ be the value lieutenant *i* received from lieutenant *j* in step 2) (using algorithm OM(m-1), or else RETREAT if he received no such value. Lieutenant *i* uses the value

$$majority(v_1, \ldots, v_{n-1})$$

# *BGP: Oral Message Solution*

OM(m) -- same thing, different wording

IF m = 0 THEN

a) commander sends his value to all other ($n$-1) lieutenants.

b) lieutenant uses value received or default (i.e. RETREAT if no value was received).

ELSE

a) each commander node sends value to all other ($n$-1) lieutenants

b) let $v_i$ = value received by lieut. $i$ (from commander OR default if there was no message)

Lieut. $i$ invokes OM($m$-1) as commander, sending $v_i$ to other ($n$-2) lieutenants.

c) let $v_{ji}$ = value received from lieutenant $j$ by lieutenant $i$.

Each lieutenant $i$ gets $v_i$ = maj(what everyone said $j$ said in prev.round, except $j$ himself)

trust myself more than what others say I said

# *example n=4 => one traitor*

- procedure OM(1)

IF {not valid since m=1}

ELSE

1) commander transmits to L1,L2,L3

2) values are received by L1,L2,L3

so lieuts call OM(0)

| procedure OM(0)<br>IF {m=0}<br>1) each lieut sends value to other 2 lieuts<br>ELSE {not valid} |
|---|

each lieut has received 3 values (use majority)

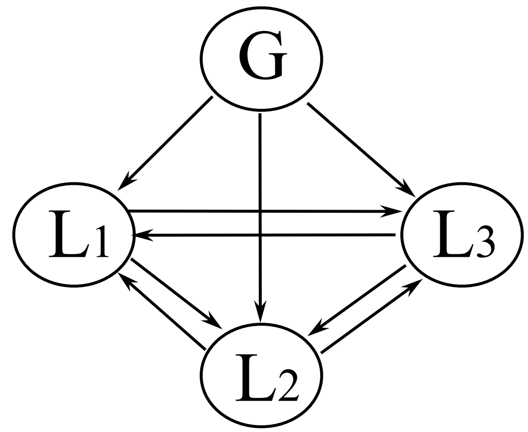
# *BGP example*

- case 1: L3 is traitor

v0 = 1

each loyal L has vector

110 or 111 => maj(1 1 0/1) = 1



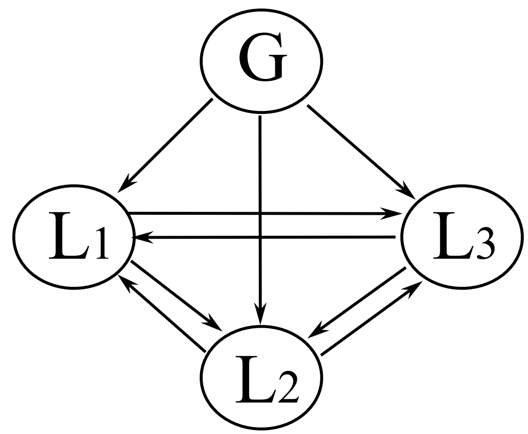

- case 2: G is traitor

v0 => L1=1 L2=1 L3=0

L1 has 110

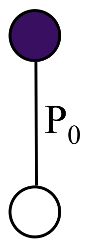
L2 has 110 maj() = 1

L3 has 011

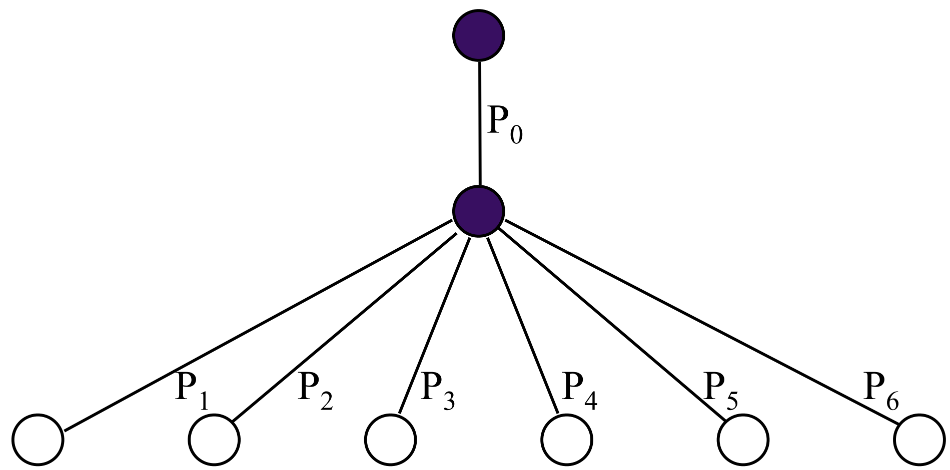


# *BGP with $N = 7$*

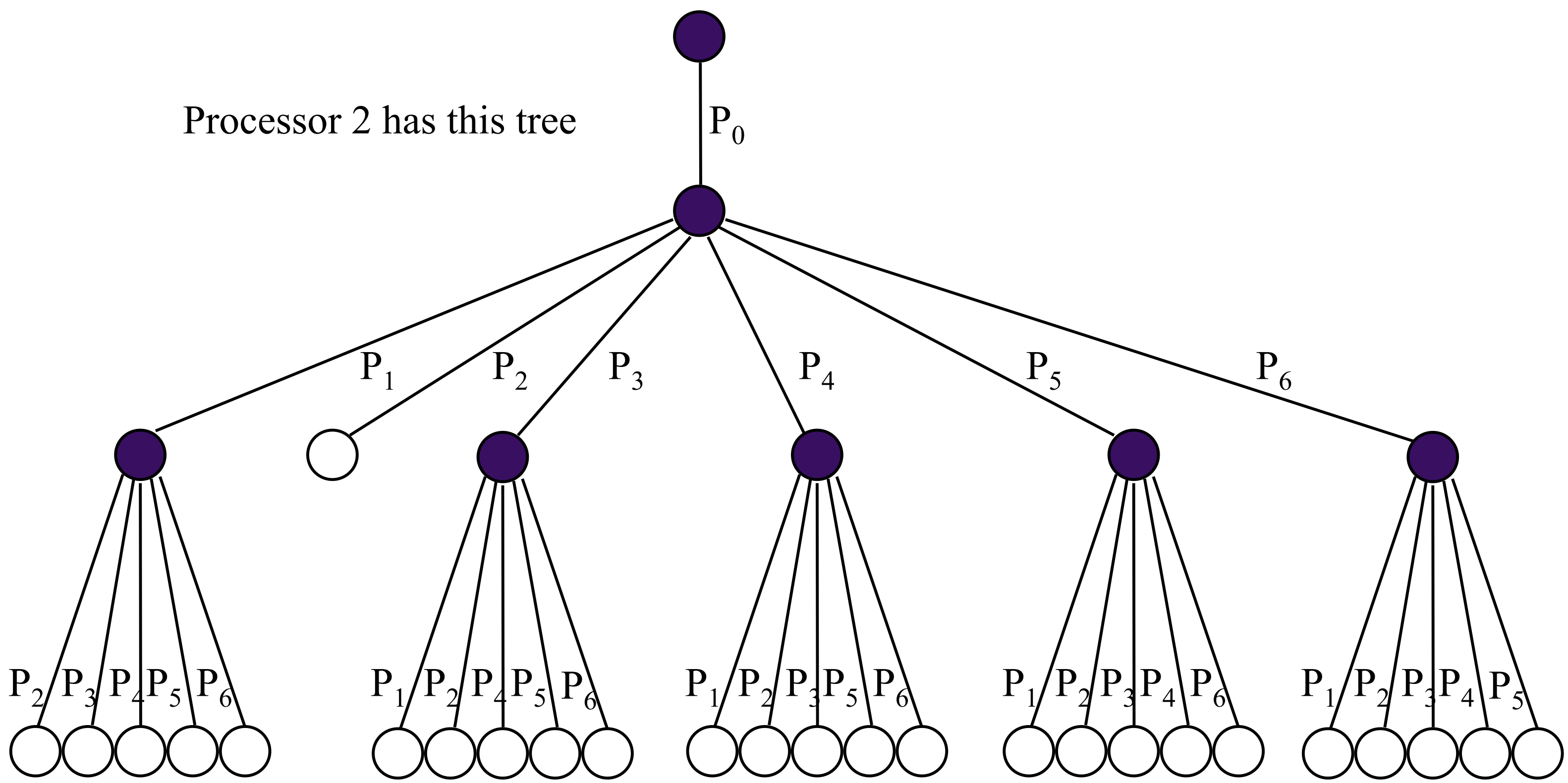
General sends message




After first rebroadcast



# *BGP with N =7*


Processor 2 has this tree
P0
P1
P2
P3
P4
P5
P6
P2 P3 P4 P5 P6
P1 P2 P4 P5 P6
P1 P2 P3 P5 P6
P1 P2 P3 P4 P6
P1 P2 P3 P4 P5

# *BGP with $N = 3m+1$*

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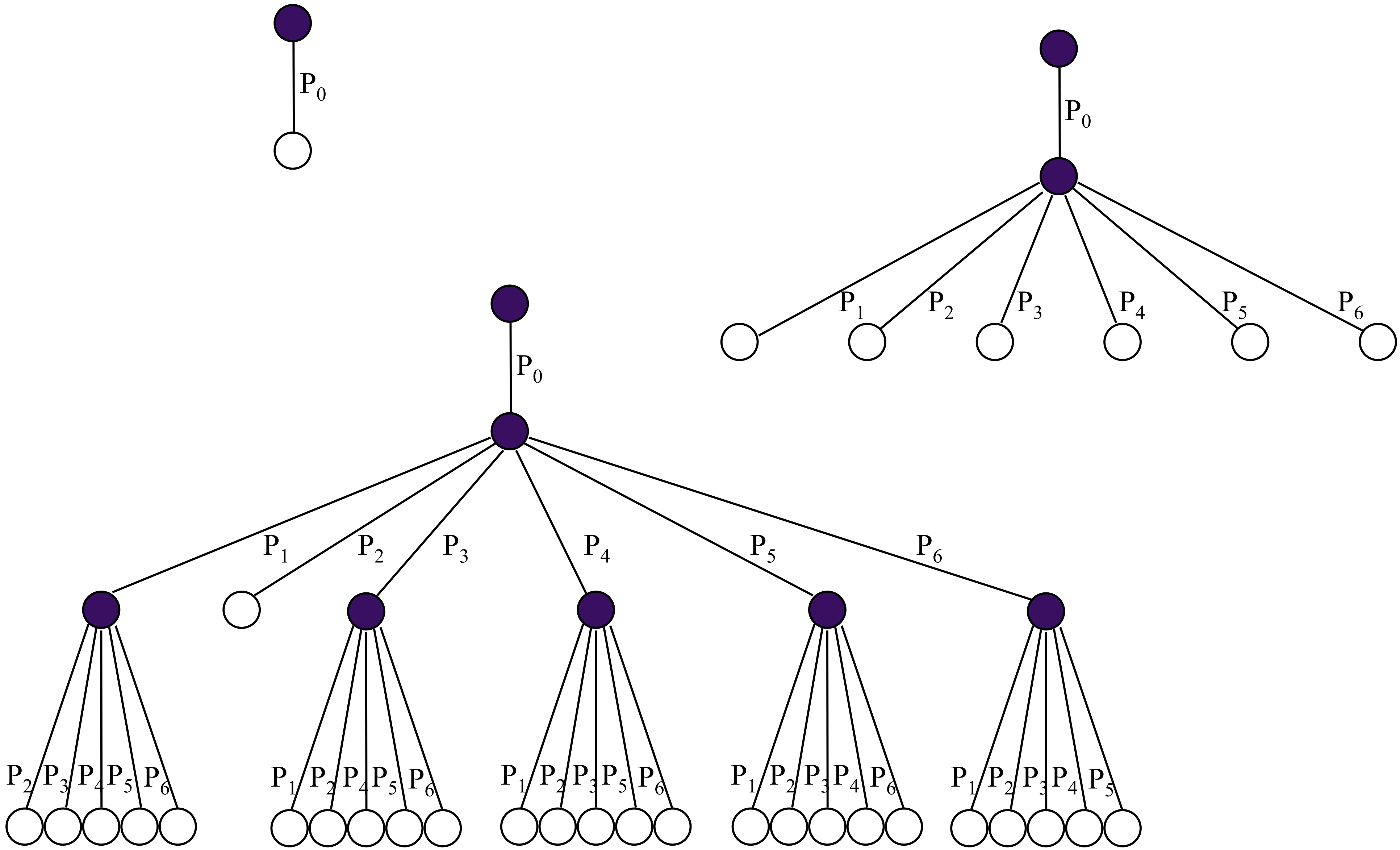
# *BGP with  N =7*


P0
P0
P1 P2 P3 P4 P5 P6
P0
P1 P2 P3 P4 P5 P6
P2 P3 P4 P5 P6
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P1 P2 P3 P5 P6
P1 P2 P3 P4 P6
P1 P2 P3 P4 P5