CS 60002: Distributed Systems

T2: Models of Distributed Systems

Department of Computer Science and Engineering

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Communication Abstraction

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- The underlying network can be much more complex
  - Heterogeneous network technologies
  - Complex message queueing (RED, WRED, …)
  - Heterogeneous network protocols (Connection-oriented or Connection-less, lossy or lossless)
  - Network performance counters may vary widely (low BDP low loss, low BDP high loss, high BDP low loss, high BDP high loss)

Latency vs Bandwidth

- **Latency**:
  - In the same datacenter ~1 ms
  - Two datacenters over same continent ~10ms
  - Geo-distributed datacenters over different continent ~100ms

- **Bandwidth**:
  - 4G Cellular data ~30Mbps
  - 5G Cellular data ~1 Gbps
  - Home broadband ~100Mbps
  - Inter-DC network ~10Gbps

AWS Snowball

- Use physical storage devices to transfer large amount of data between Amazon S3 and Local Datacenter Storage

- Faster-than-Internet !

- **High Latency High Bandwidth**
  - Latency ~1 Day
  - Bandwidth ~50 TB

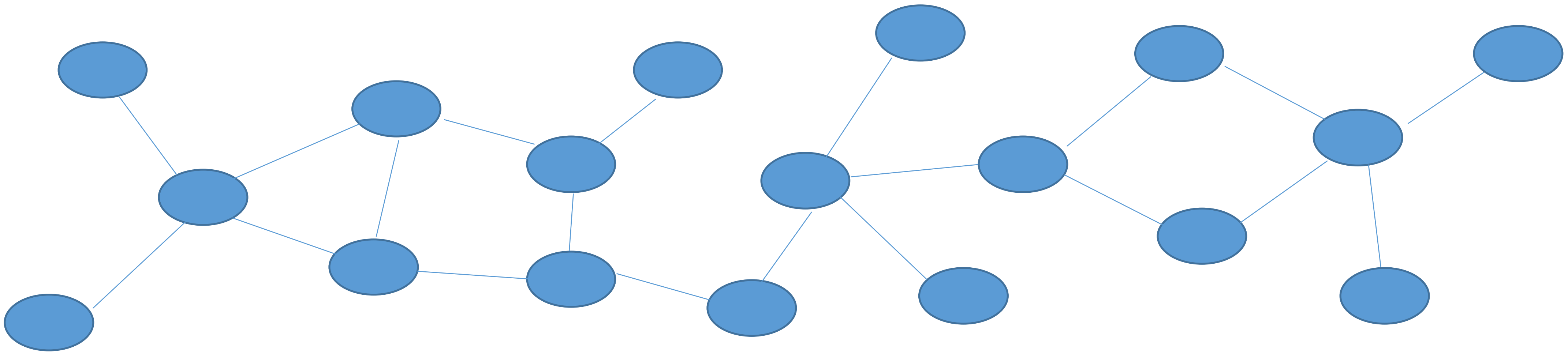
Architecture of the Communication Network

- The underlying physical network is like the Internet; you have switches, routers, gateways – but we are not concerned about them.

- We are more concerned of the application-level logical network; often termed as the **overlay network.**
  - **May be a Peer-to-Peer (P2P) overlay network**

- **Example:** BitTorrent network
  - Your BitTorrent client is connected to few other peers from where you download part of the files
  - The peers are directly connected to you over the overlay network
  - However, there might be multiple other physical network nodes in-between

Overlay Network



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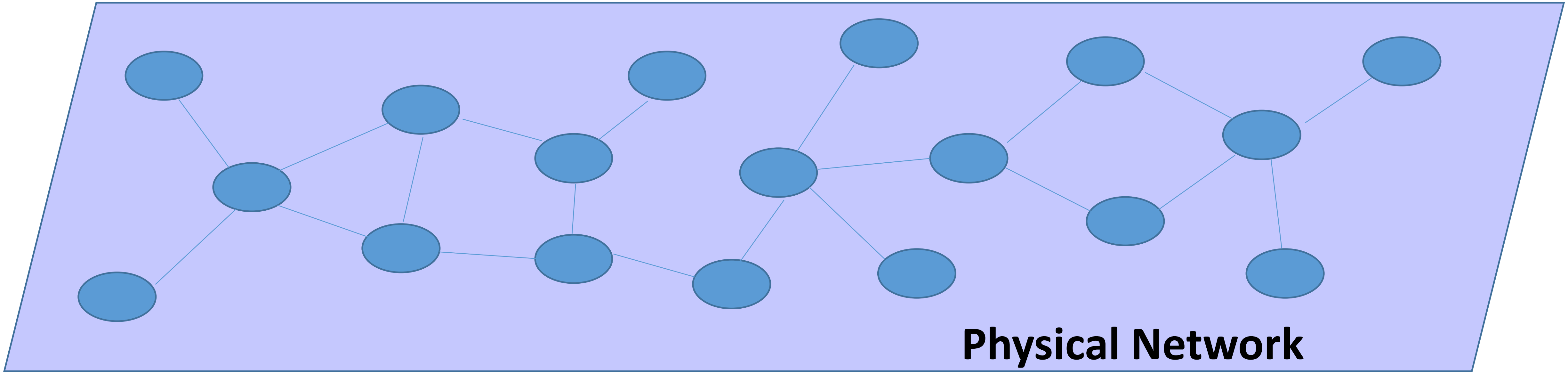

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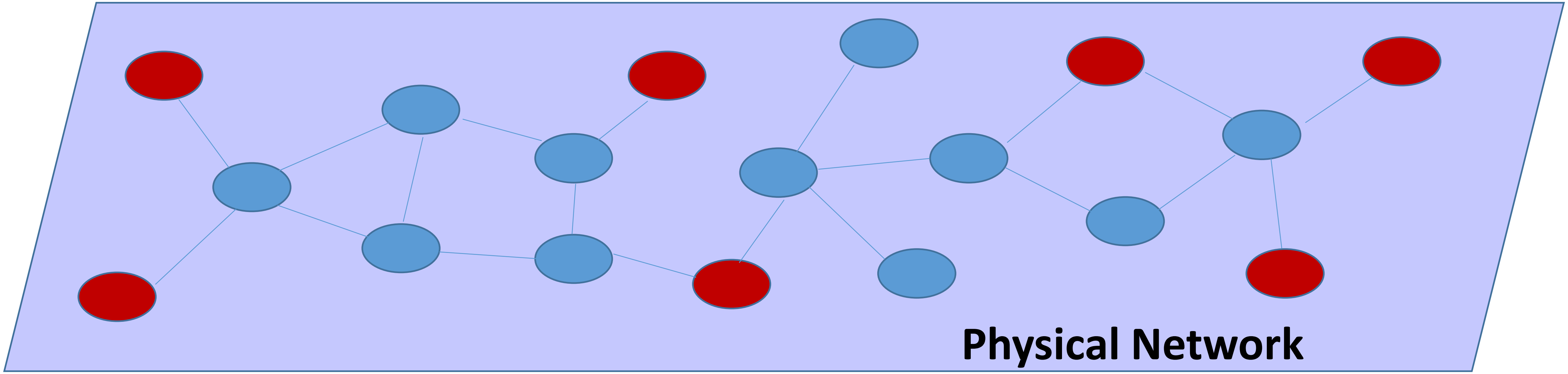

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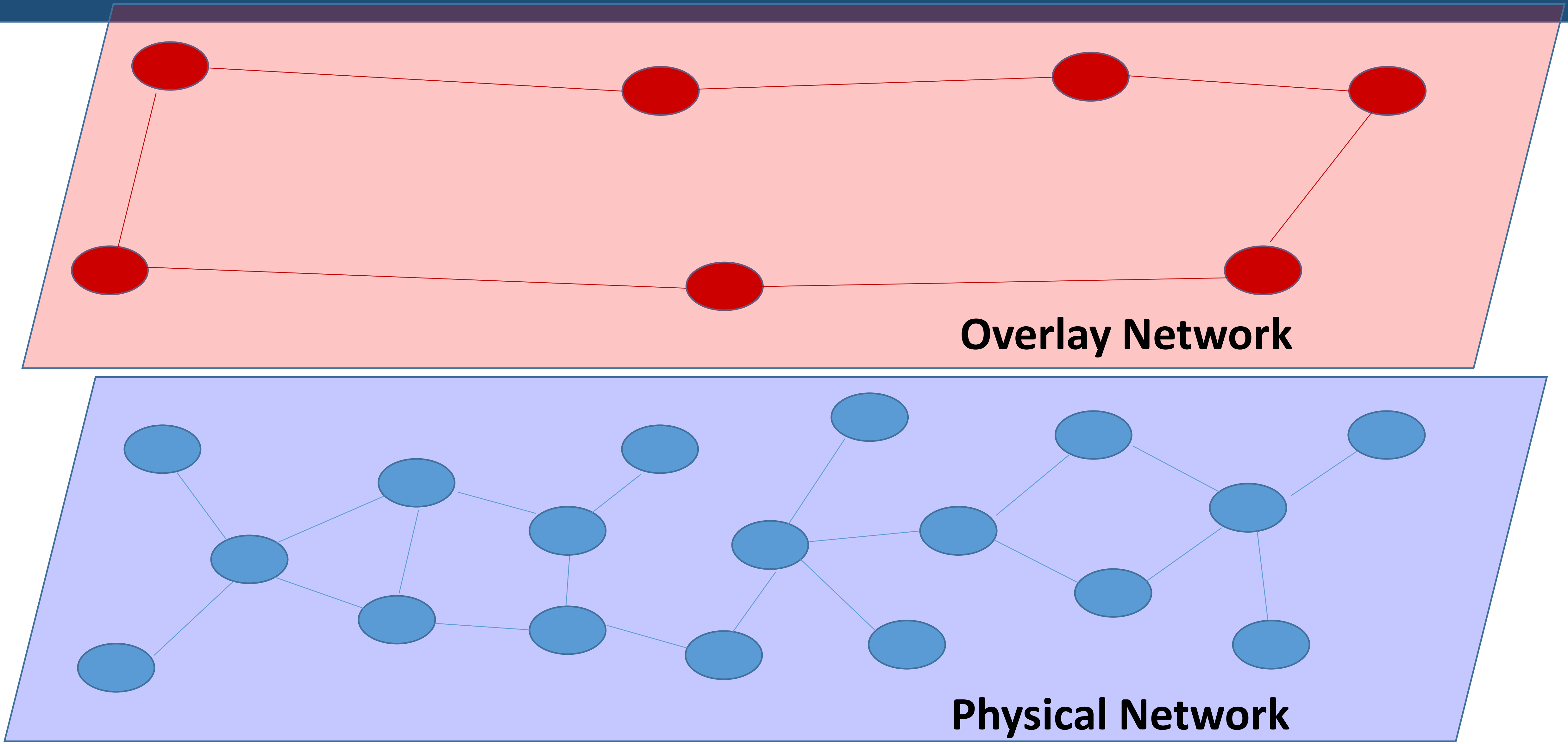
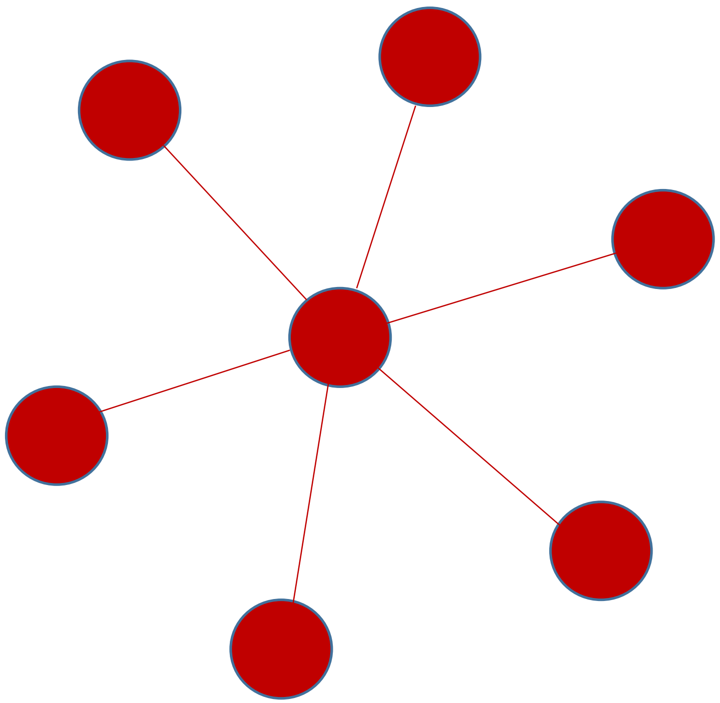
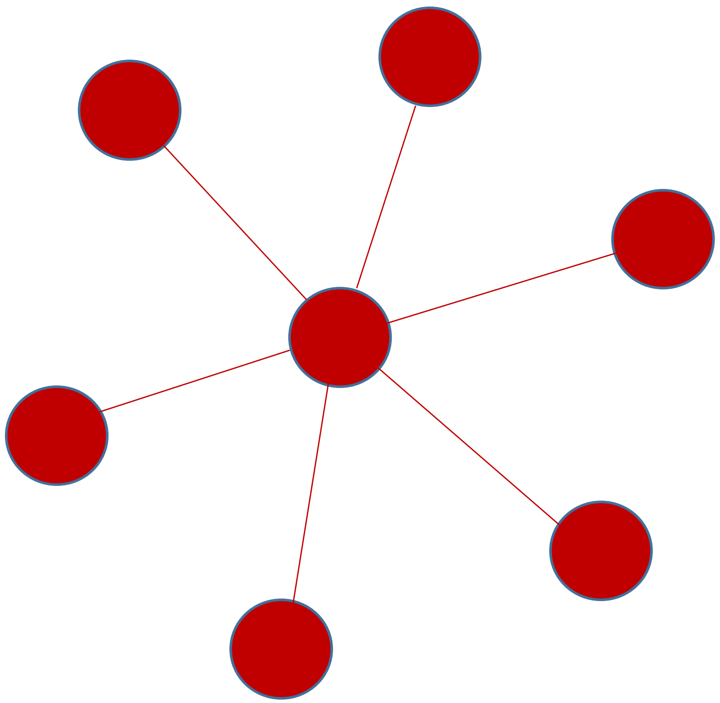


Typical Topology over an Overlay Network



Star

Typical Topology over an Overlay Network



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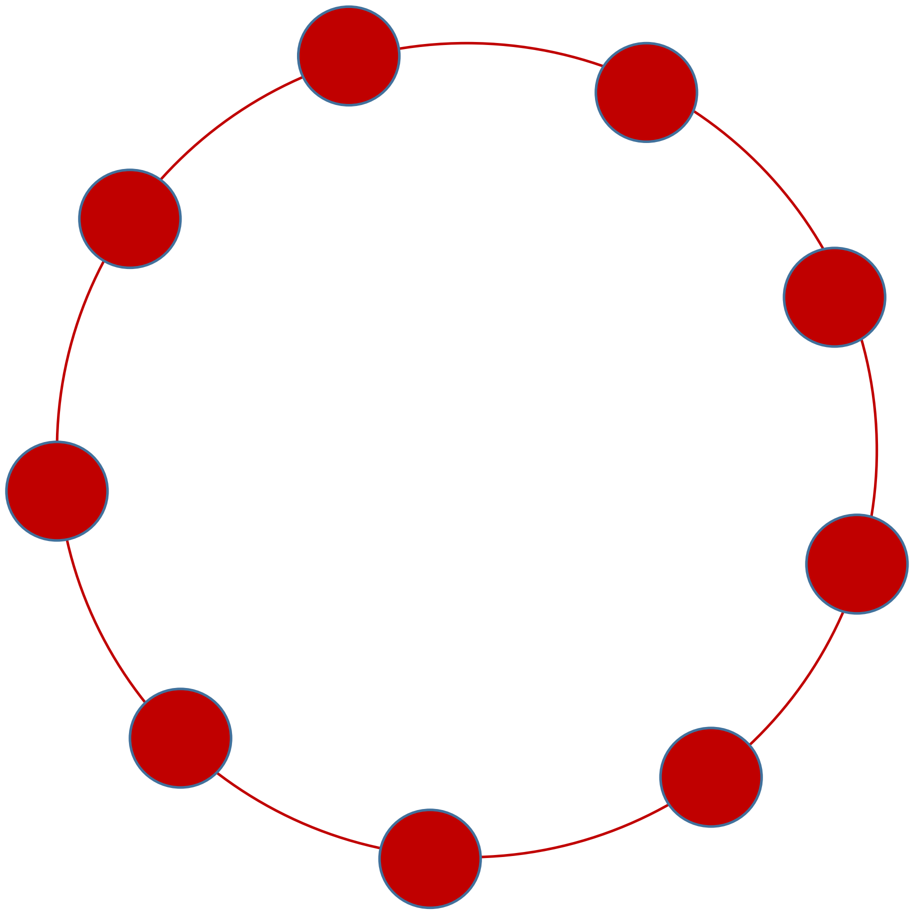
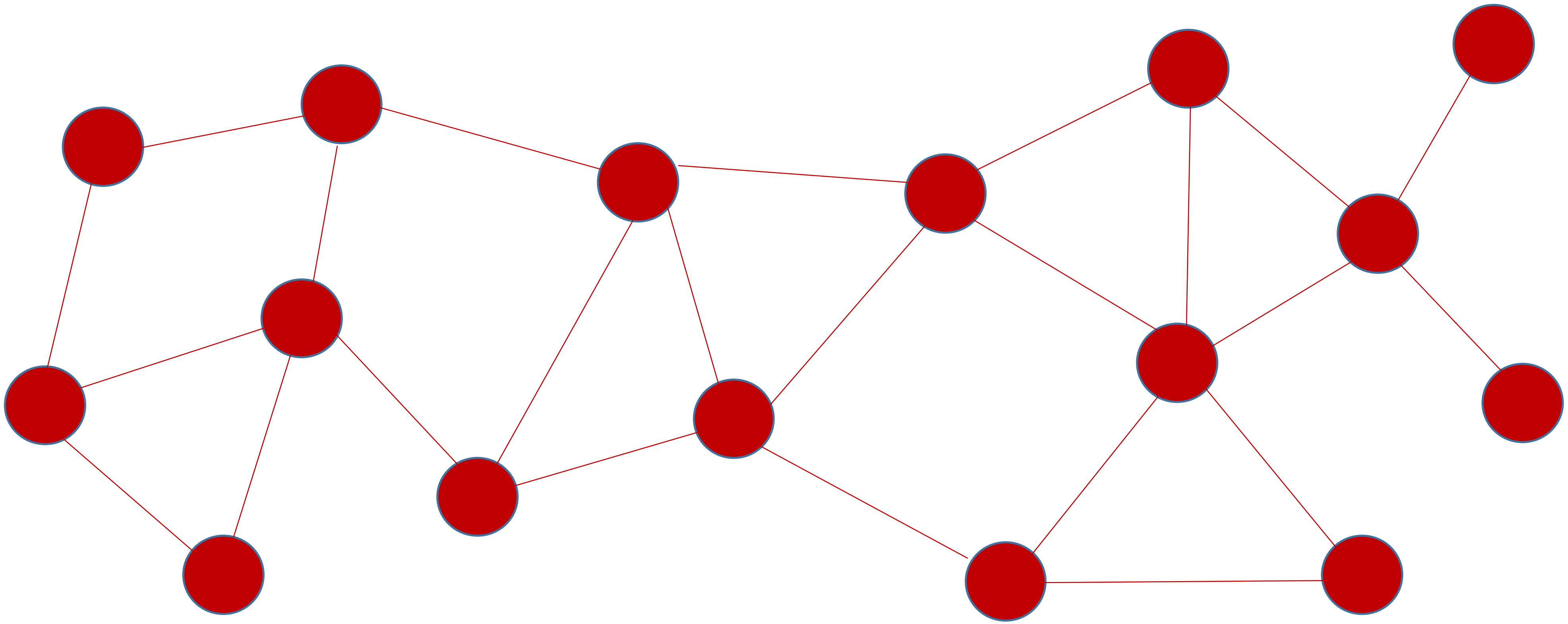


Ring

Typical Topology over an Overlay Network



Mesh

Communication Paradigm – The Gossip Protocol

- In a distributed system, the typical model of communication is through message broadcast (an <u>overlay broadcast</u>).
  - How do you broadcast the message when all the nodes are not directly connected to each other over the overlay network?

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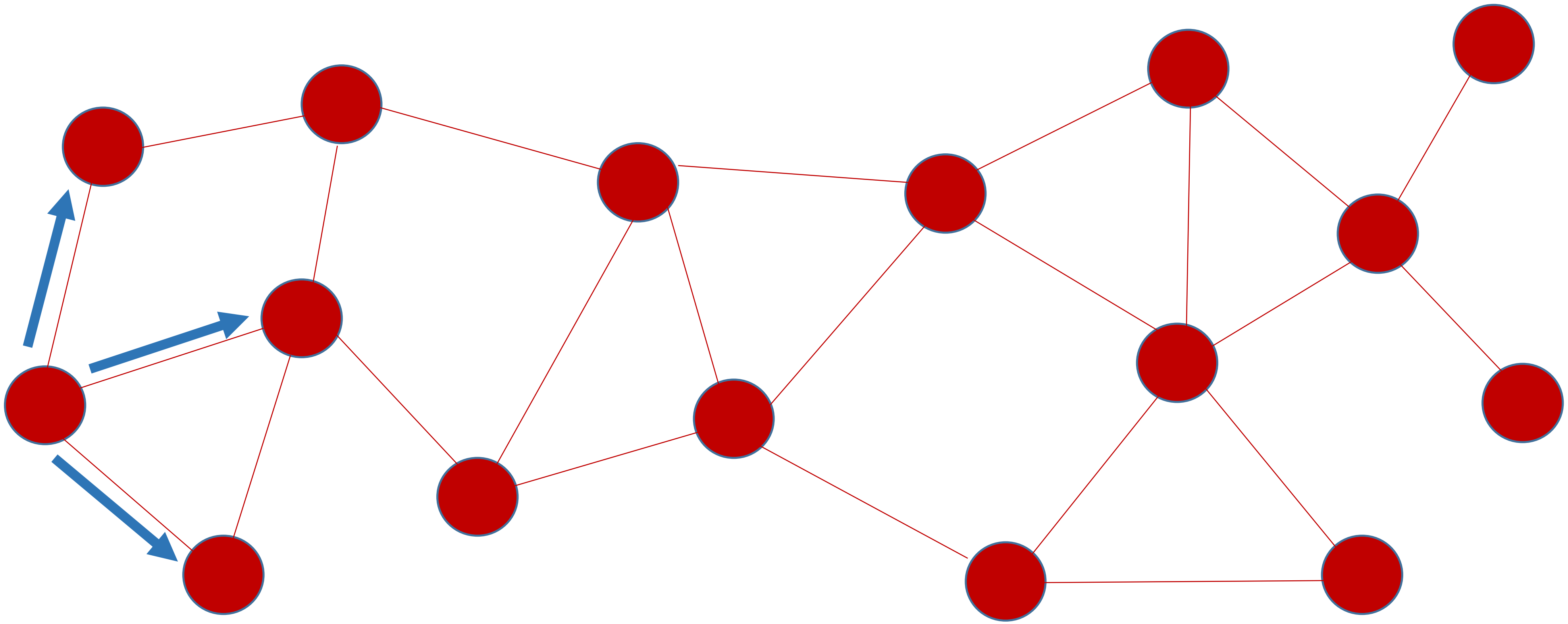
  - Propagate messages based on the way epidemics spread
  - **Gossip**: Think of the office workers spreading rumors

The Gossip Protocol



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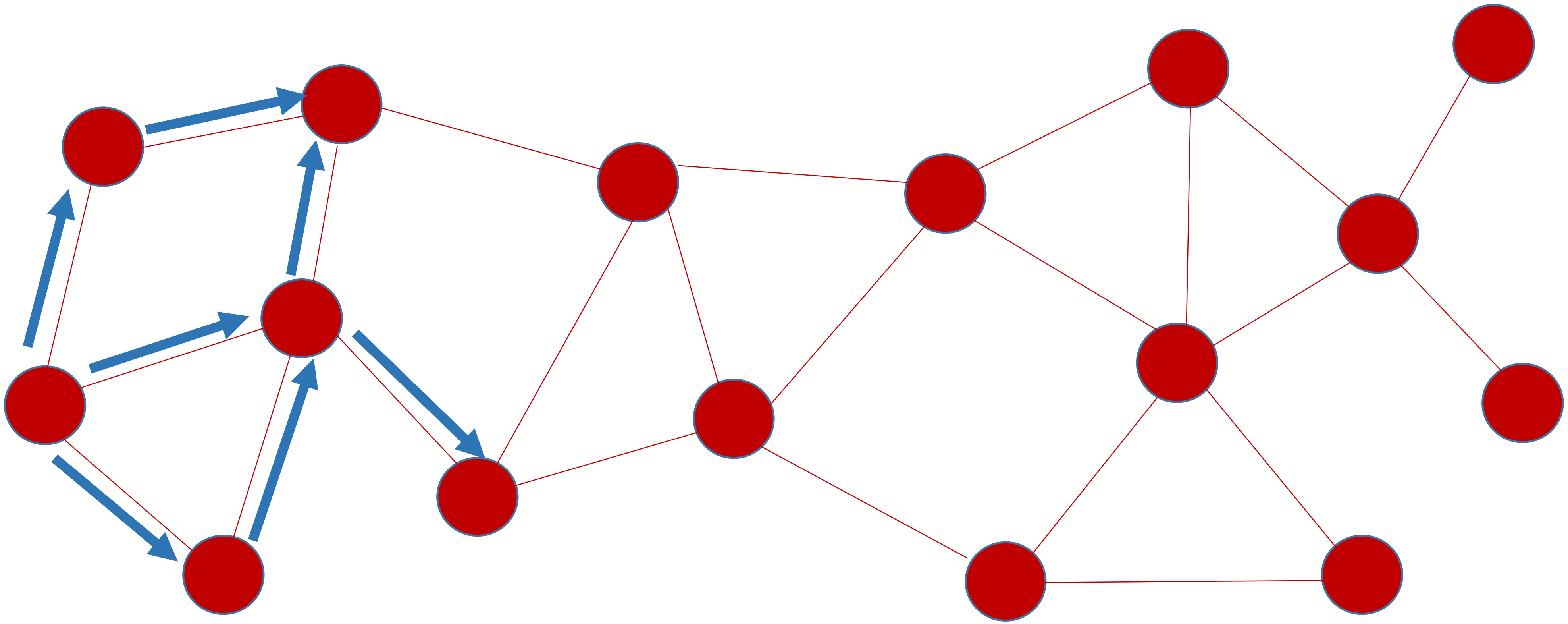

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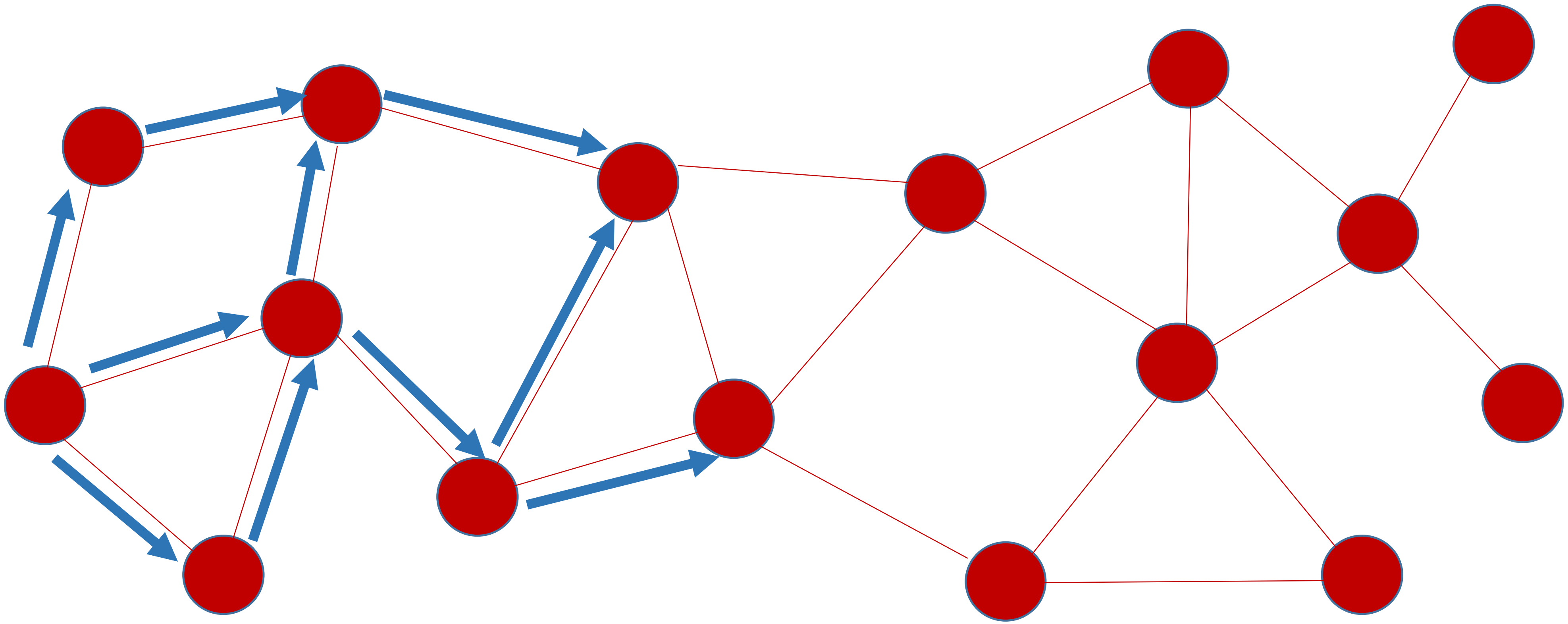

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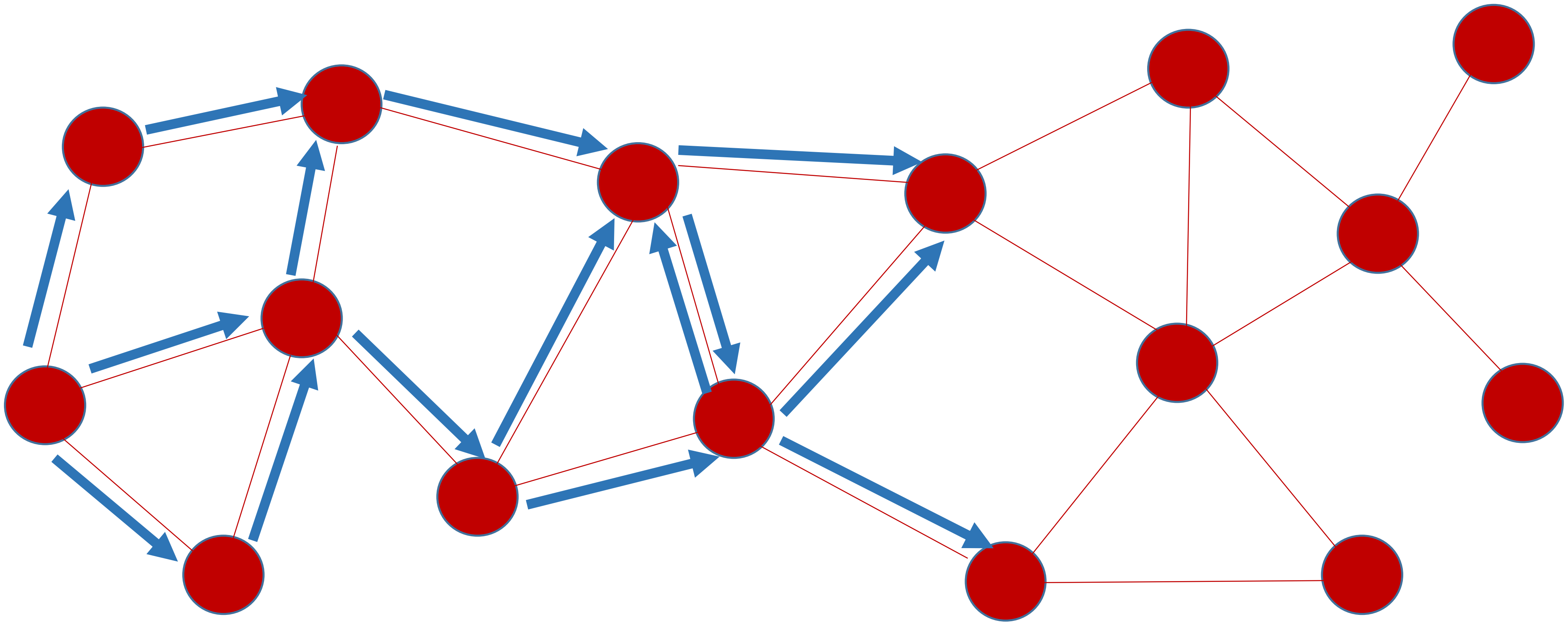

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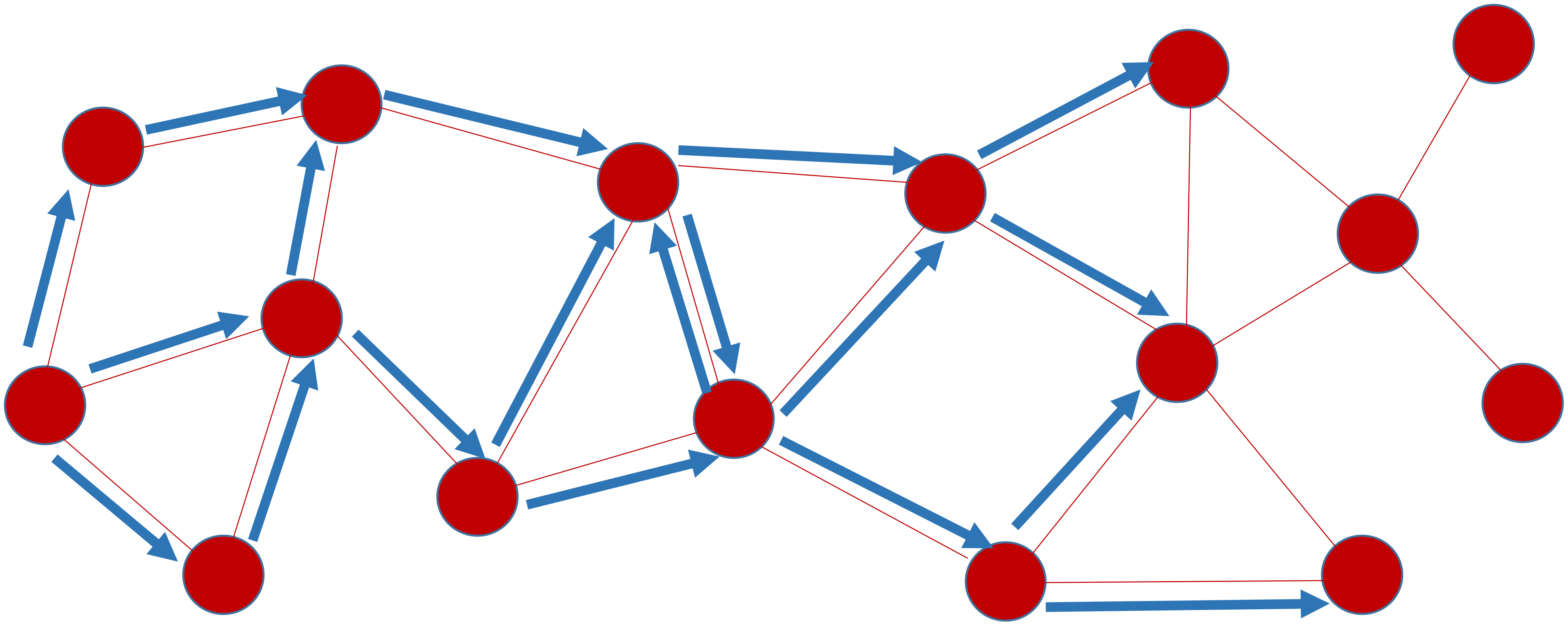

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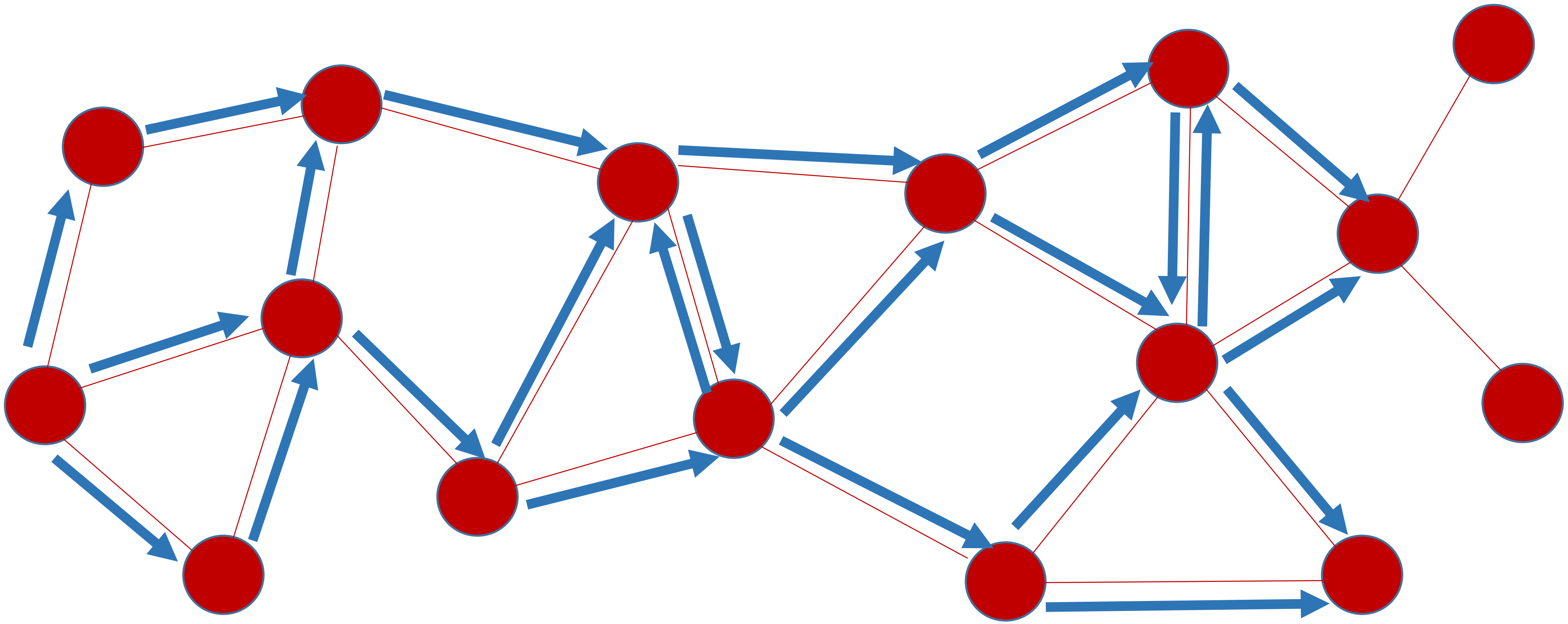

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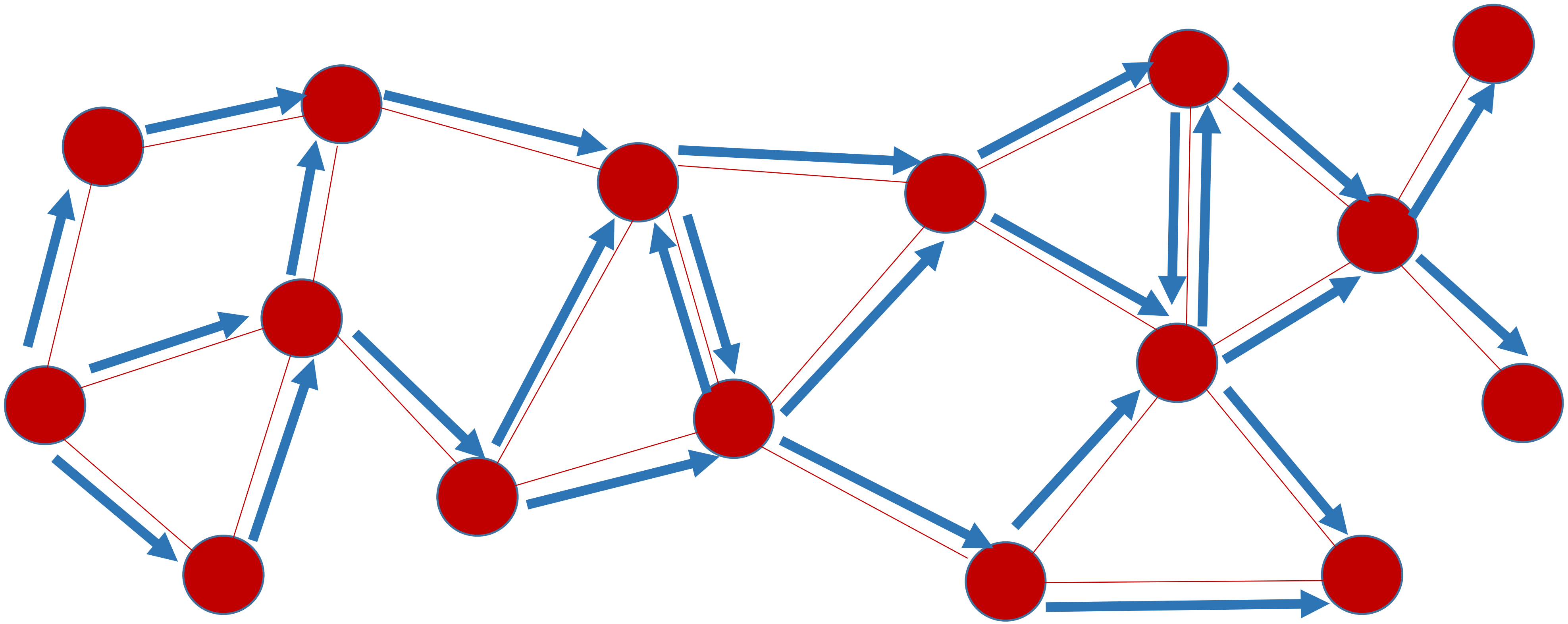

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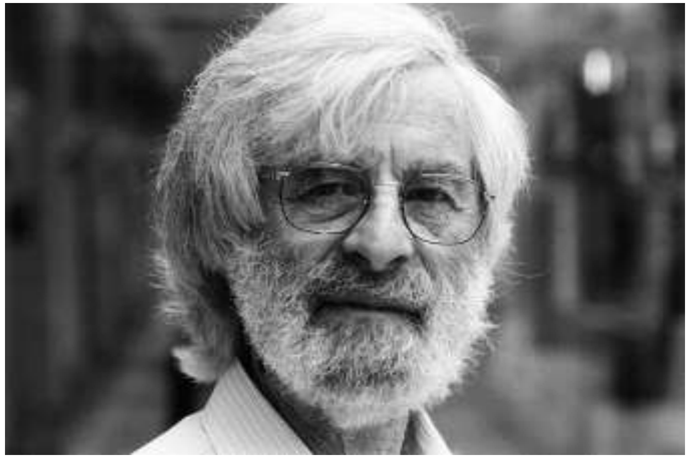
- **The Gossip Protocol:**
  - Propagate messages based on the way epidemics spread
  - **Gossip**: Think of the office workers spreading rumors
  - More like a flooding, possibility of receiving duplicate information
  - Widely used in several distributed systems – distributed database consistency, distributed consensus protocols (state machine replication), Internet routing (think of the way routing messages are disseminated)

What is a Distributed System?

"*A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable*"

-- Leslie Lamport



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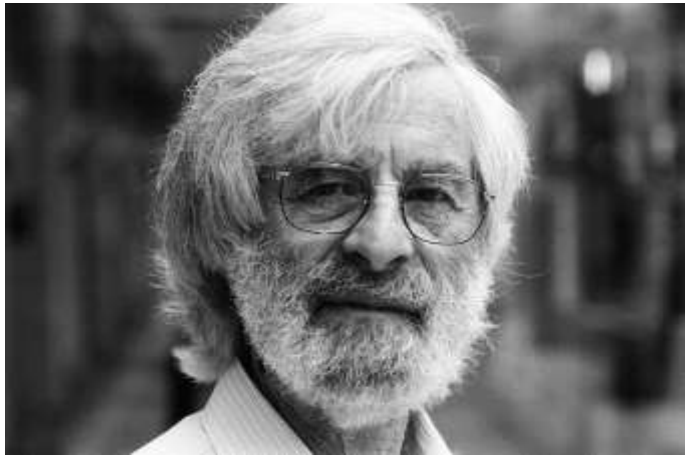
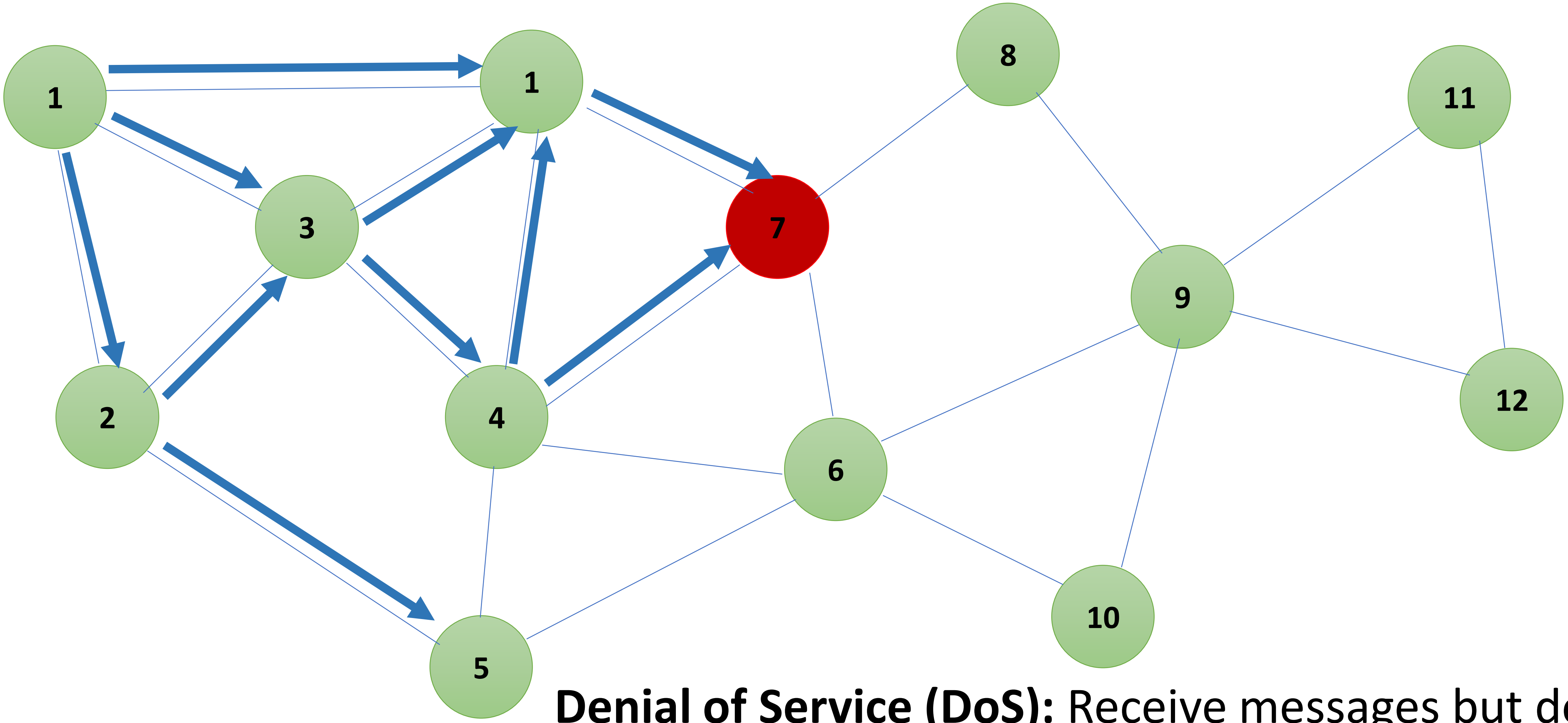


Type of Faults in a Distributed System

- **Crash Faults:**
  - A device stops responding suddenly
  - Hardware or software faults
  - May or may not recover later on (Crash-stop or Crash-recover)
  - (Network faults) A link fails instead of the entire node

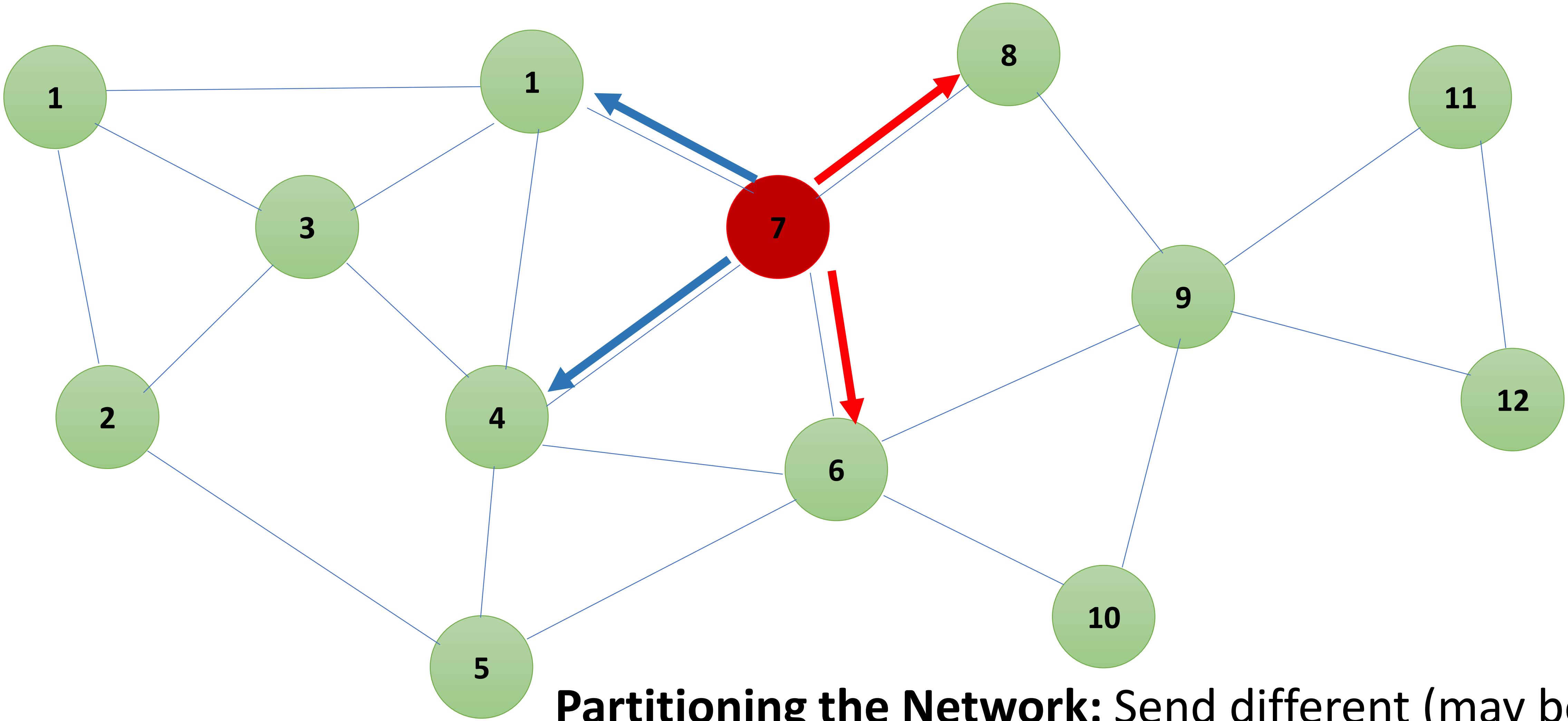
- **Byzantine Faults**
  - Nodes start misbehaving – forward different information to different peers
  - Internal or external attacks
  - Much more severe to handle compared to crash faults

Byzantine Faults



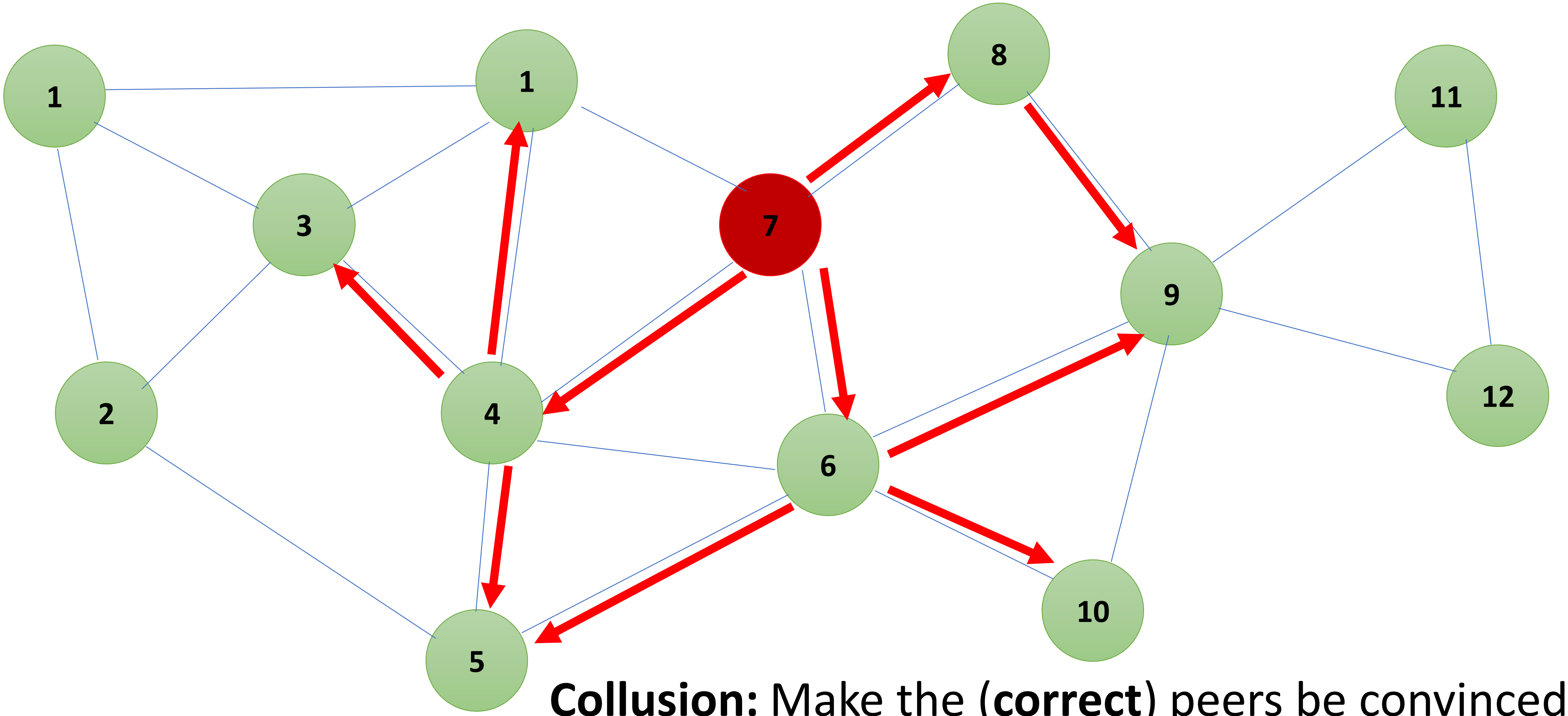
Denial of Service (DoS): Receive messages but do not propagate them further

Byzantine Faults



Partitioning the Network: Send different (may be conflicting) information to different peers

Byzantine Faults



Collusion: Make the (**correct**) peers be convinced on a misinformation, that they start spreading

Network Behavior

- **Reliable (Perfect) Links:**
  - A message is received if and only if it is sent
  - Reordering of messages is possible
- **Fair-loss Links:**
  - Message may be lost, reordered, or duplicated
  - A message is received eventually if retries are allowed
- **Arbitrary Links:**
  - Links under active adversary
  - A malicious adversary can interfere with the message (eavesdrop, modify, replay, spoof)

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SSL/TLS

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Retry (at network level), deDUP

SSL/TLS

Mode of Communication – Synchronous vs Asynchronous

- **The "Tom and Jerry" of distributed computing :**

- **Synchronous:**
  - **"Instantaneous"** message delivery, asymptotic upper bound on message delay
  - Sender is **blocked** until the message is delivered
  - There exists a global clock with a consistent clock rate
- **Asynchronous:**
  - No asymptotic bound on the message delay
  - Sender does not get blocked – messages are received eventually
  - No global clock or consistent clock rate

Impact of Failures based on the Mode of Communication

- **Failures over Synchronous Channels**
  - You can put a threshold on the message delay
  - You do not receive a message within the threshold ->
    You know that something has happened – may be a failure!

Impact of Failures based on the Mode of Communication

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  - You can put a threshold on the message delay
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- **Failures over Asynchronous Channels**
  - There is no bound on the message delay!
  - You do not receive a message -> You do not know whether there is a failure, or the message is in transit ...

Synchronous and Asynchronous Nodes

- **Synchronous Nodes:**
  - Nodes execute algorithms at a known speed
  - Asymptotic upper bound on the execution time
- **Asynchronous Nodes:**
  - Nodes can pause algorithm execution arbitrarily
  - No timing guarantees on the execution of the code
- All combinations are possible
  - (synchronous/asynchronous) nodes over (synchronous/asynchronous) communication channels

Partially Synchronous

- **Complete Synchronous** and **Complete Asynchronous** are more of a theoretical concept
  - Practical networks have a predictable upper bound, the network occasionally deviates from that bound (congestion, retransmission of a lost packet, network or route reconfiguration)
  - Nodes typically execute code with a predictable speed with occasional deviations (such as OS scheduling problem, pause of garbage collection, thrashing, etc.)

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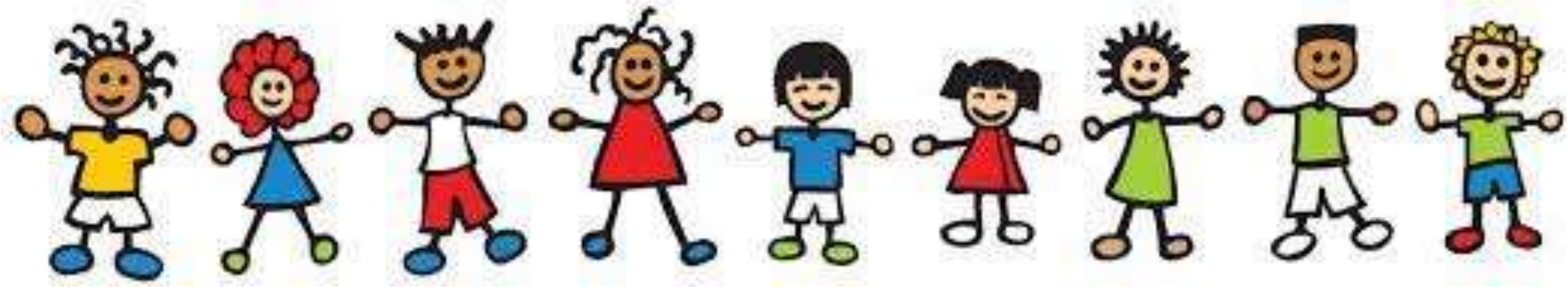
Other parts of Computer Science use the terminologies "Synchronous" and "Asynchronous" differently

System Model for Any Distributed Algorithm

- **Network**
  - Reliable
  - Fair-loss
  - Arbitrary
- **Timing**
  - Synchronous
  - Partially Synchronous
  - Asynchronous
- **Failures**
  - Crash-stop
  - Crash-recovery
  - Byzantine

- **Pick one for each of the three parts**
- **All bets are off if your assumptions are wrong, so be careful!**

Muddy Children Puzzle



N number of children playing, k gets muddy

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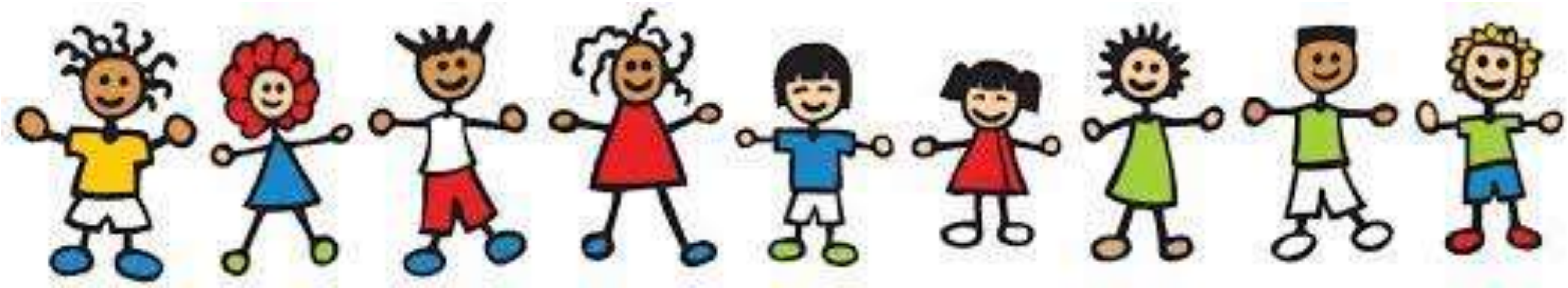
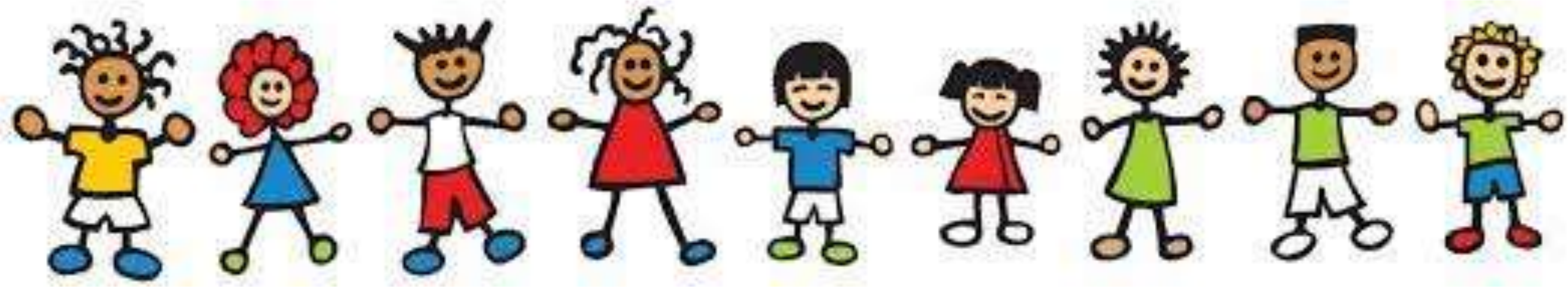


N number of children playing, k gets muddy

Each can observe all others, do not know their own states

- **Network:** Reliable (Children and intelligent and truthful)
- **Failures:** None
- **Timing:** Synchronous (They answer simultaneously based on the observations from the immediate past rounds)

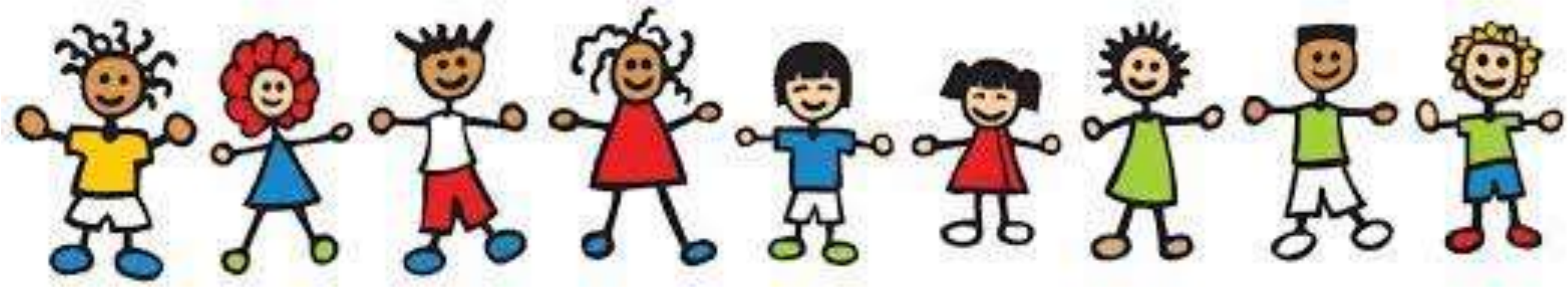
Muddy Children Puzzle



N number of children playing, k gets muddy

At least one of you is muddy. Do you know if you are muddy?

Muddy Children Puzzle



N number of children playing, k gets muddy

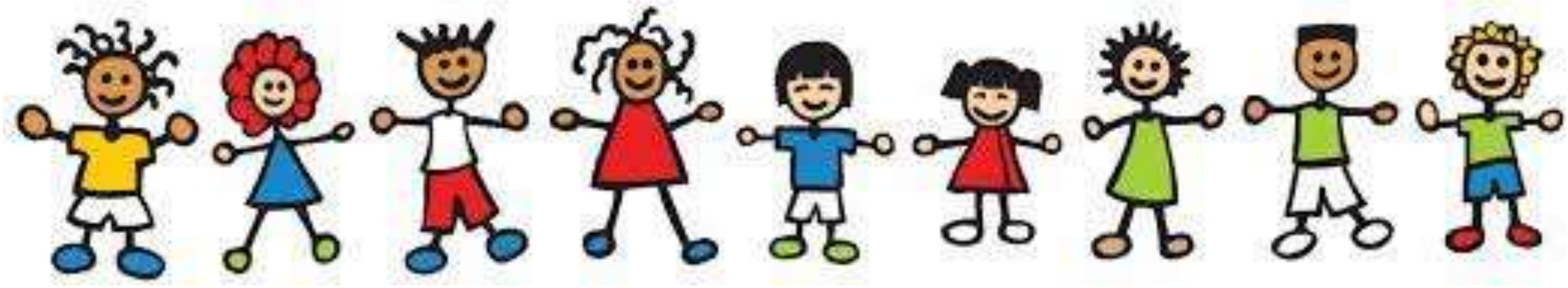
Information sources for the children

- Observing others (cannot observe himself or herself)
- Hearing what others say

Can infer based on previous rounds

- Only answers "**Yes**" (I know) / "No" (I do not know)

Muddy Children Puzzle

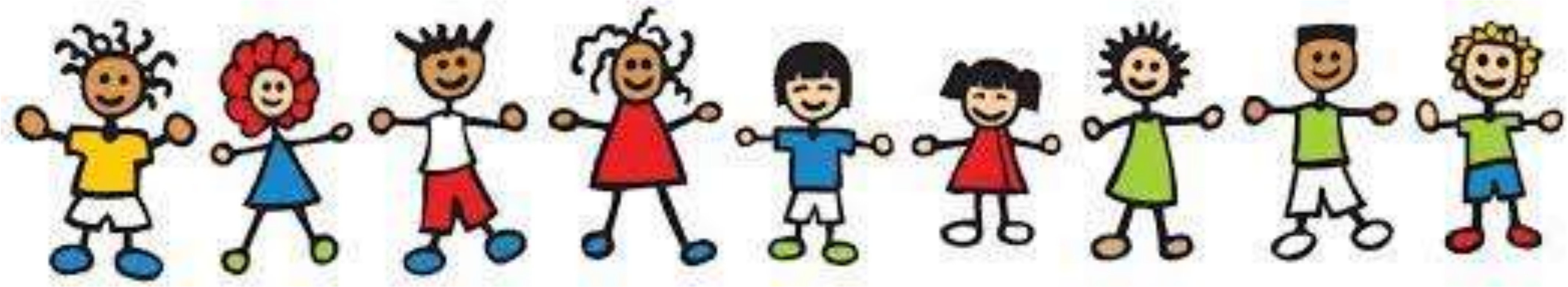


N number of children playing, k gets muddy

The protocol works at rounds. At every round, the children answer **"Yes"/"No" (Synchronous)**

How many rounds do you need to get the correct answers from all muddy children?

Muddy Children Puzzle



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k

Muddy Children Puzzle, k = 1

N number of children playing, k gets muddy

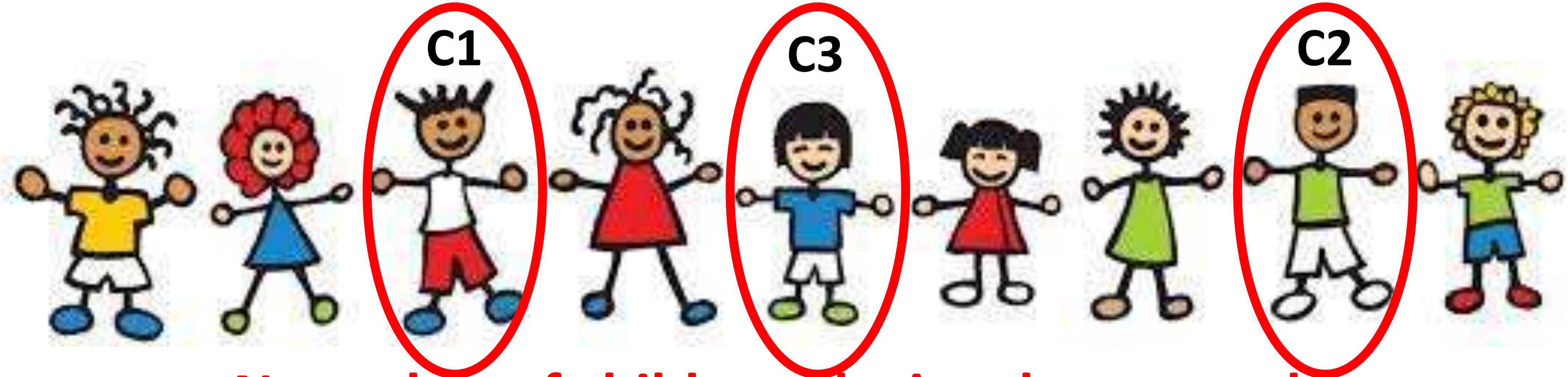
- Muddy child observes all others are clean
- Father said someone is muddy
- The child answers "Yes"
- Others hear the muddy child, confirms

Muddy Children Puzzle, k = 2

N number of children playing, k gets muddy

- <u>Round 1</u>: All says "No" as they are unsure as each muddy child sees one other muddy child (father said at least one)
- The two muddy children realizes that they are muddy, as others said no so they must have seen another muddy child
- <u>Round 2</u>: Muddy children answer "Yes", others also follow.

Muddy Children Puzzle, k = 3



N number of children playing, k gets muddy

- All says "No" up to Round 2.
- If C1 was clean, C2 and C3 must have answered "Yes" after Round 2. C1 understand that (s)he is not clean. So, in Round 3, (s)he replies with a "Yes" at Round 3. Same for C2 and C3.

Common Knowledge

N number of children playing, k gets muddy

- "At least one of you is muddy" - Do the children need this information for k > 1 ?

Common Knowledge

N number of children playing, k gets muddy

- **"At least one of you is muddy" - Do the children need this information for k > 1 ?**
    - Say, for k = 2, C1 observes C2, but does not know whether C2 observed C1, thus can understand k ≥ 1 (k = 1 or k = 2)

Do We Need the Common Knowledge?

N number of children playing, k gets muddy

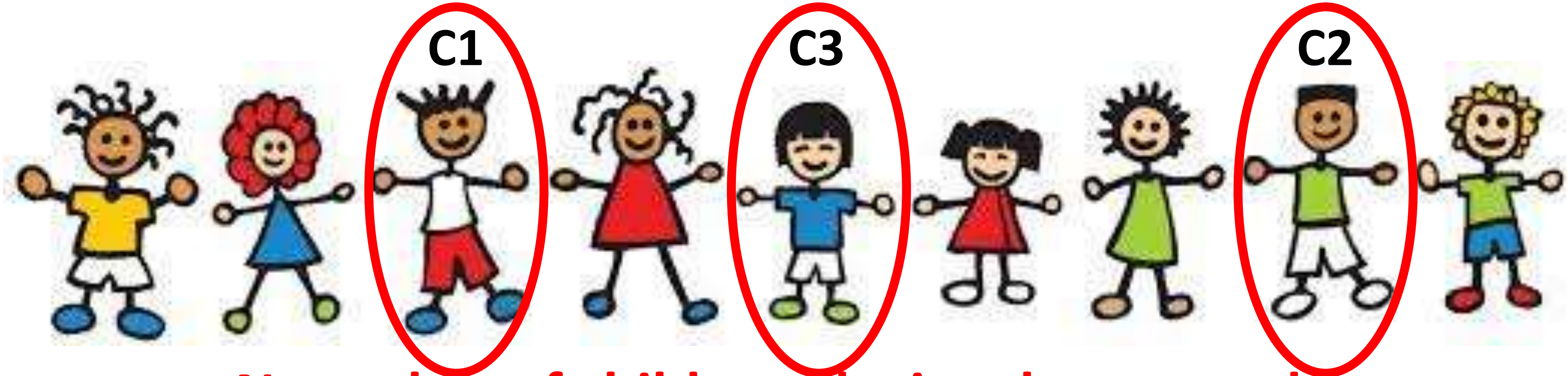
- **Common knowledge**: $k \geq 1$
- Without common knowledge
  - C1 can observe C2 muddy
  - But C2 can still say "No" even if (s)he observes C1 to be clean, as C2 does not know whether $k = 0$ or $k = 1$

Valid sequence with the common knowledge …

N number of children playing, k gets muddy

- **Common knowledge**: $k \geq 1$
- R1: Cannot decide whether k=1 or k=2; I see at least one other muddy, does not know my state **=>** all says "No" **=>** $k \neq 1$ as everyone (including the muddy child) sees at least one other muddy

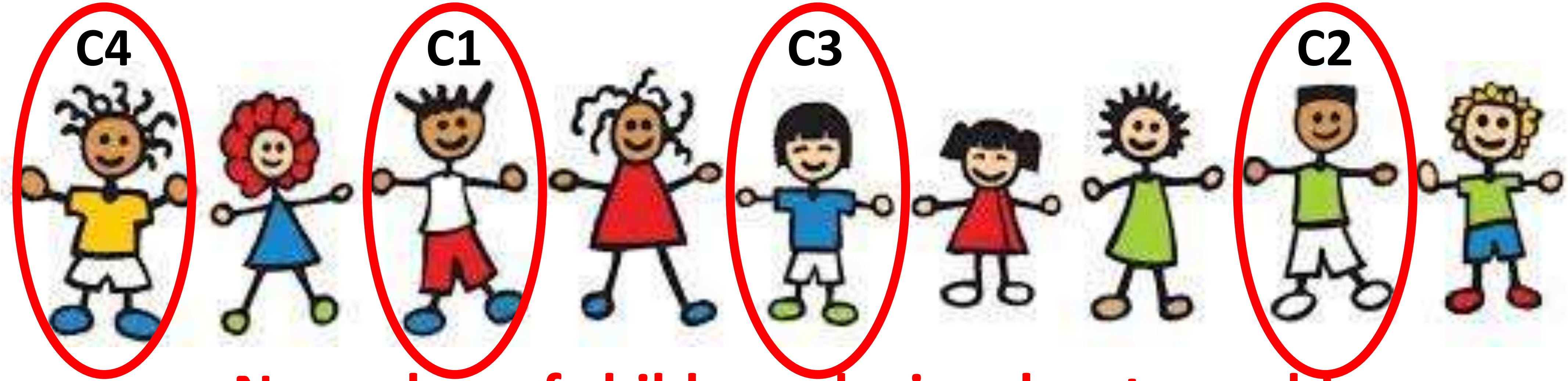
Valid sequence with the common knowledge ...



N number of children playing, k gets muddy

- R2: Cannot decide whether k=2 or k=3; I see at least two others muddy, does not know my state **=>** all says "No" **=>** k ≠ 2 as everyone (including the muddy children) sees at least two other muddy

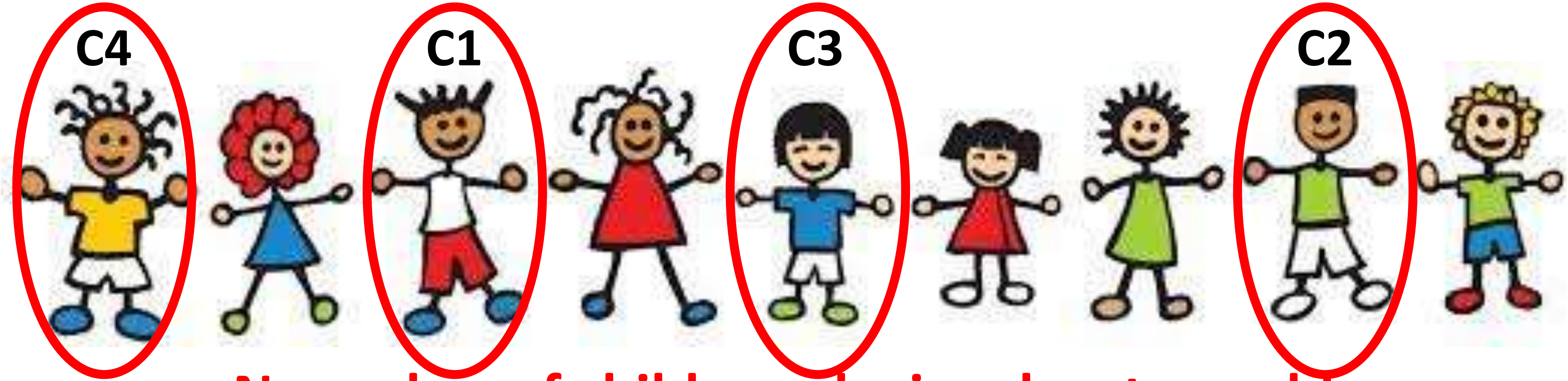
Valid sequence with the common knowledge ...



N number of children playing, k gets muddy

- R3: Cannot decide whether k=3 or k=4; I see at least three others muddy, does not know my state => all says "No" => k ≠ 3 as everyone (including the muddy children) sees at least two other muddy

Valid sequence with the common knowledge …



N number of children playing, k gets muddy

- The sequence progresses until there is a "Yes", i.e., some muddy children confirm themselves as muddy while observing k-1 other muddy children

Knowledge Hierarchy in Distributed System

- The knowledge of an agent (who runs the protocol) depends on
  - The starting / initial knowledge (may be the common knowledge)
  - The history of knowledge that it observed from the start

- **Common knowledge:** The "Publicly known" fact
  - Each can assume **others know it**
  - $k \geq 1$ is the common knowledge when the father mentions that "*at least one of you are muddy*"

Knowledge Hierarchy in Distributed System

- **Distributed knowledge:** The knowledge that is "distributed" among the members of the group, known by someone in the group
  - A node **cannot assume** that others know it
  - $k \geq 1$ is the distributed knowledge when the father does not mention anything, and the knowledge is purely based on the observation

- We'll see next how, starting from a common knowledge, an agent can uplift in the knowledge hierarchy with the help of distributed knowledge based on observations

- **Reference**: *Joseph Y. Halpern and Yoram Moses. 1990.* ***Knowledge and common knowledge in a distributed environment****. J. ACM 37, 3 (July 1990)*

Happy Learning