Computer Science 425
Distributed Systems

CS 425 / ECE 428

Fall 2013

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Lecture 4

Failure Detection

Reading: Section 15.1 and parts of 2.4.2

Your new datacenter

- You've been put in charge of a datacenter (think of the Prineville Facebook DC), and your manager has told you, "Oh no! We don't have any failures in our datacenter!"
- Do you believe him/her?
- What would be your first responsibility?
- Build a failure detector
- What are some things that could go wrong if you didn't do this?

Failures are the norm

… not the exception, in datacenters.

Say, the rate of failure of one machine (OS/disk/motherboard/network, etc.) is once every 10 years (120 months) on average.

When you have 120 servers in the DC, the mean time to failure (MTTF) of the next machine is 1 month.

When you have 12,000 servers in the DC, the MTTF is about once every 7.2 hours!

To build a failure detector

- You have a few options

1. Hire 1000 people, each to monitor one machine in the datacenter and report to you when it fails.
2. Write a failure detector program (distributed) that automatically detects failures and reports to your workstation.

Which is more preferable, and why?

Two Different System Models

Whenever someone gives you a distributed computing problem, the first question you want to ask is, "What is the system model under which I need to solve the problem?"

- **Synchronous Distributed System**
  - **Each message is received within bounded time**
  - **Each step in a process takes lb < time < ub**
  - **(Each local clock's drift has a known bound)**

  Examples: Multiprocessor systems
- **Asynchronous Distributed System**
  - **No bounds on message transmission delays**
  - **No bounds on process execution**
  - **(The drift of a clock is arbitrary)**

  Examples: Internet, wireless networks, datacenters, most real systems

Failure Model

- **Process omission failure**
  - **Crash-stop (fail-stop) – a process halts and does not execute any further operations**
  - **Crash-recovery – a process halts, but then recovers (reboots) after a while**
    - **Special case of crash-stop model (use a new identifier on recovery)**
- **We will focus on *Crash-stop* failures**
  - **They are easy to detect in synchronous systems**
  - **Not so easy in asynchronous systems**

What's a failure detector?

What's a failure detector?

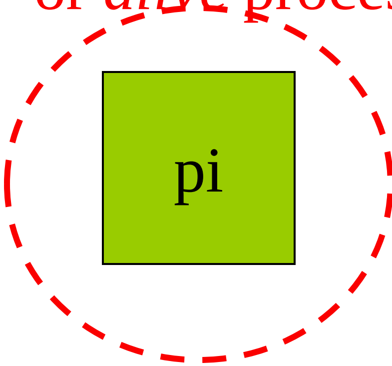
Crash-stop failure
(pj is a *failed* process)

What's a failure detector?

needs to know about pj's failure

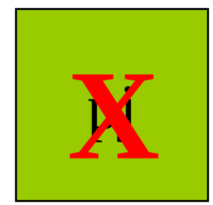
(pi is a *non-faulty* process

or *alive* process)



Crash-stop failure

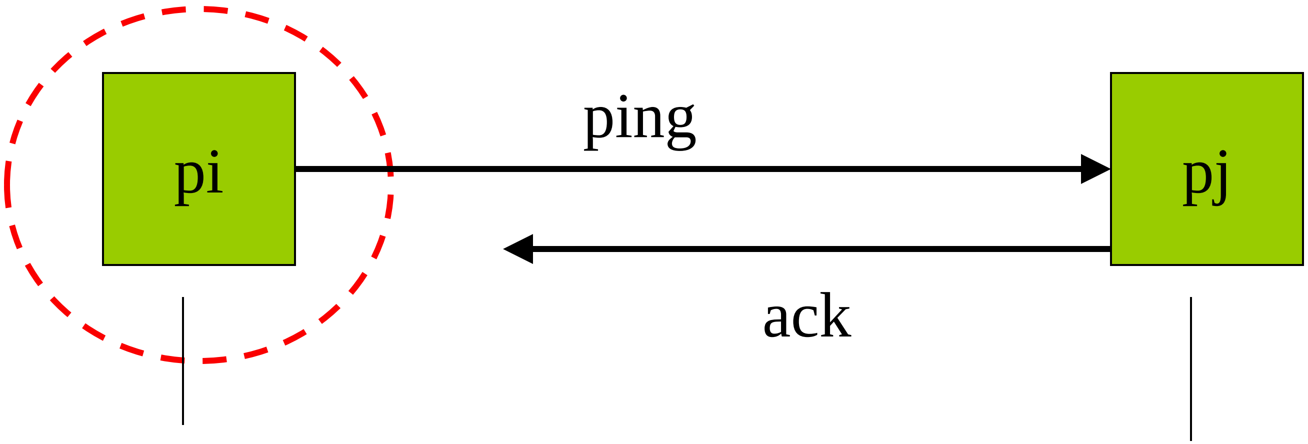
(pj is a *failed* process)



There are two main flavors of Failure Detectors…

I. Ping-Ack Protocol

needs to know about pj′s failure



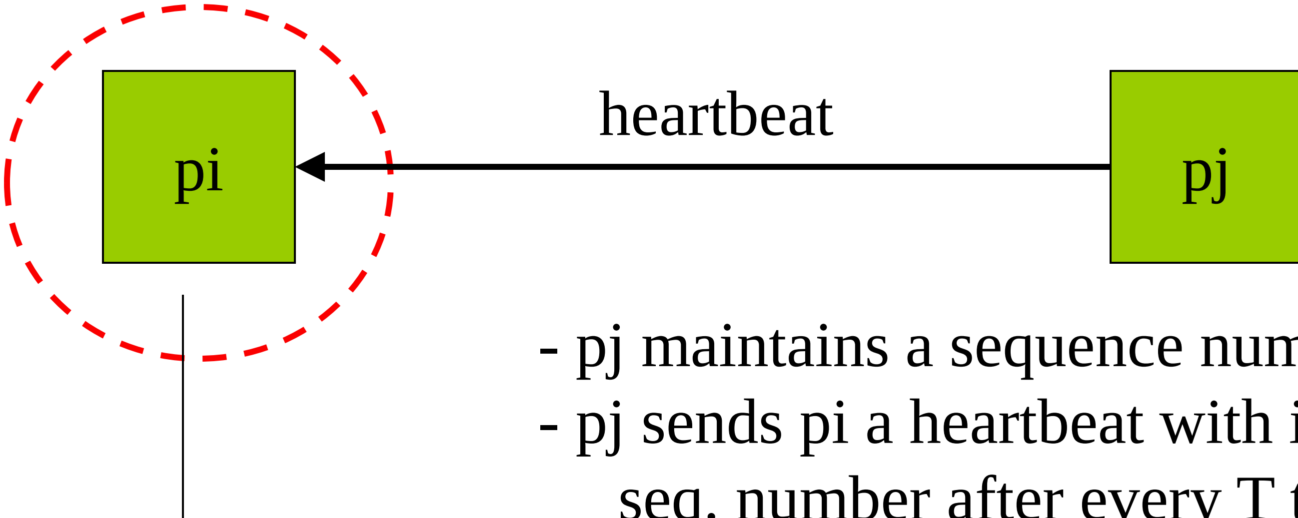
- pj replies

- pi queries pj once every T time units
- if pj does not respond within another T time units of being sent the ping, pi detects pj as failed

Worst case Detection time = 2T
If pj fails, then within T time units, pi will send it a ping message. pi will time out within another T time units.
The waiting time ‘T′ can be parameterized.

II. Heartbeating Protocol

needs to know about pj's failure



- pj maintains a sequence number
- pj sends pi a heartbeat with incremented seq. number after every T time units

-if pi has not received a new heartbeat for the past, say 3*T time units, since it received the last heartbeat, then pi detects pj as failed

*If T >> round trip time of messages, then worst case detection time ~ 3*T (why?)*

The '3' can be changed to any positive number since it is a parameter

In a Synchronous System

- **The Ping-ack and Heartbeat failure detectors are always “correct”**
  - **If a process pj fails, then pi will detect its failure as long as pi itself is alive**
- **Why?**
  - **Ping-ack: set waiting time ‘T’ to be > round—trip time upper bound**
    - **pi->pj latency + pj processing + pj->pi latency + pi processing time**
  - **Heartbeat: set waiting time ‘3*T’ to be > round—trip time upper bound**

Failure Detector Properties

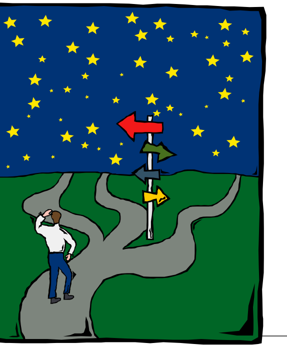
- Completeness = every process failure is eventually detected (no misses)
- Accuracy = every detected failure corresponds to a crashed process (no mistakes)
- What is a protocol that is 100% complete?
- What is a protocol that is 100% accurate?
- Completeness and Accuracy
  - Can both be guaranteed 100% in a synchronous distributed system
  - Can never be guaranteed simultaneously in an asynchronous distributed system

    Why?

Satisfying both Completeness and Accuracy in Asynchronous Systems

- **Impossible because of arbitrary message delays, message losses**
  - **If a heartbeat/ack is dropped (or several are dropped) from pj, then pj will be mistakenly detected as failed => inaccurate detection**
  - **How large would the T waiting period in ping-ack or 3*T waiting period in heartbeating, need to be to obtain 100% accuracy?**
  - **In asynchronous systems, delay/losses on a network link are impossible to distinguish from a faulty process**
- **Heartbeating – satisfies completeness but not accuracy (why?)**
- **Ping-Ack – satisfies completeness but not accuracy (why?)**

Completeness or Accuracy? (in asynchronous system)

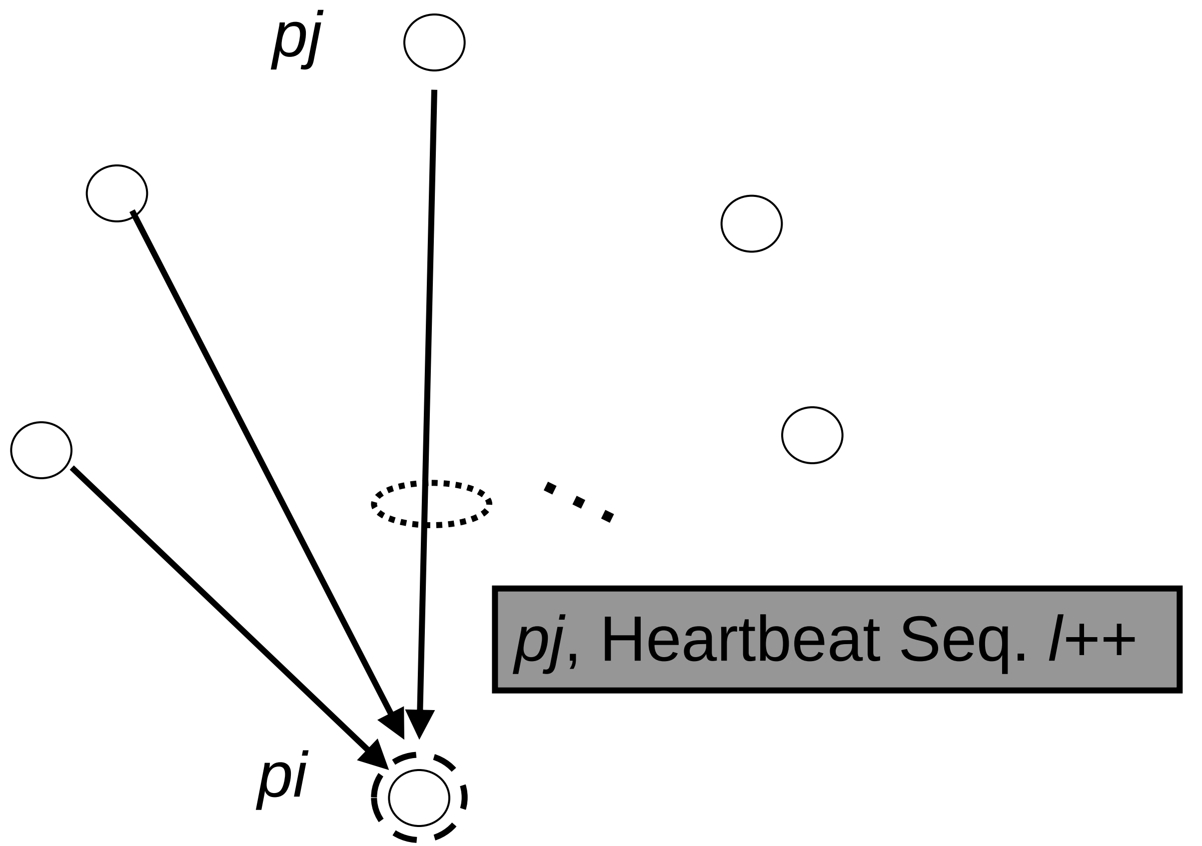


- **Most failure detector implementations are willing to tolerate some inaccuracy, but require 100% Completeness**
- **Plenty of distributed apps designed assuming 100% completeness, e.g., p2p systems**
  - **"Err on the side of caution".**
  - **Processes not "stuck" waiting for other processes**
- **But it's ok to mistakenly detect once in a while since – the victim process need only rejoin as a new process and catch up**
- **Both Hearbeating and Ping-ack provide**
  - ***Probabilistic* accuracy: for a process detected as failed, with some probability close to 1.0 (but not equal), it is true that it has actually crashed.**

Failure Detection in a Distributed System

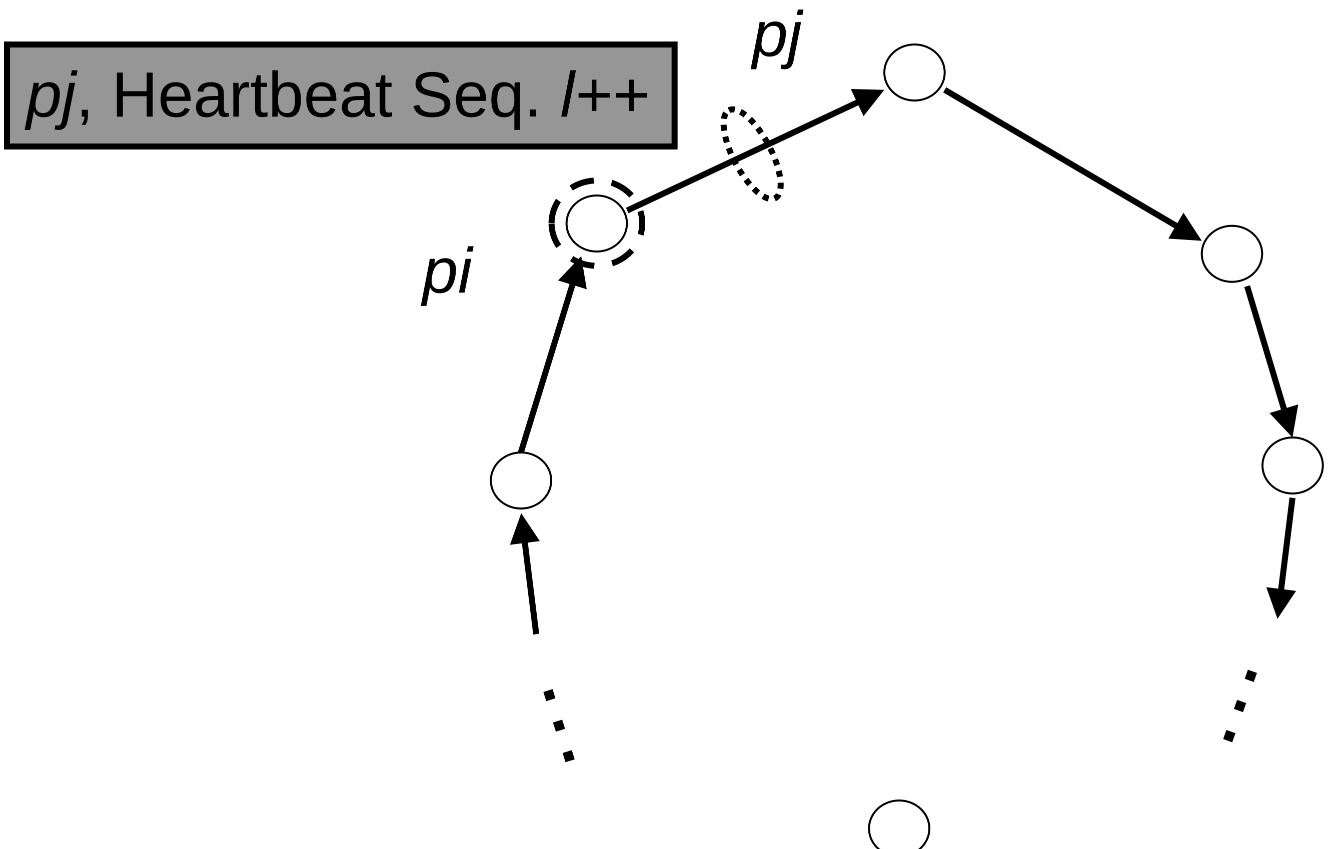
- That was for one process pj being detected and one process pi detecting failures
- Let's extend it to an entire distributed system
- Difference from original failure detection is
  - We want failure detection of not merely one process (*pj*), but *all* processes in system

Centralized Heartbeating



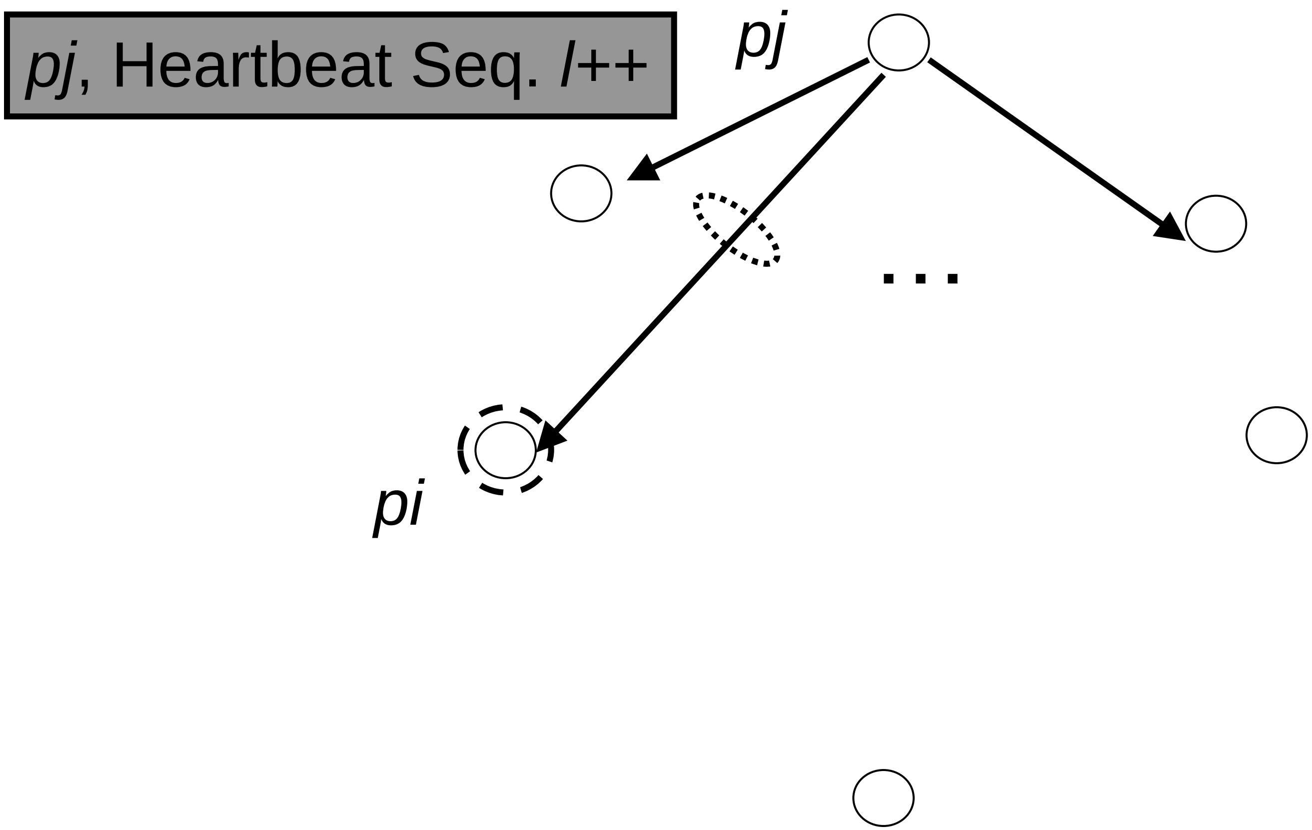
Downside?

Ring Heartbeating



No SPOF (single point of failure)
Downside?

All-to-All Heartbeating



Advantage: Everyone is able to keep track of everyone
Downside?

Efficiency of Failure Detector: Metrics

- **Bandwidth: the number of messages sent in the system during steady state (no failures)**
  - **Small is good**
- **Detection Time**
  - **Time between a process crash and its detection**
  - **Small is good**
- **Scalability: How do bandwidth and detection properties scale with N, the number of processes?**
- **Accuracy**
  - **Large is good (lower inaccuracy is good)**

Accuracy metrics

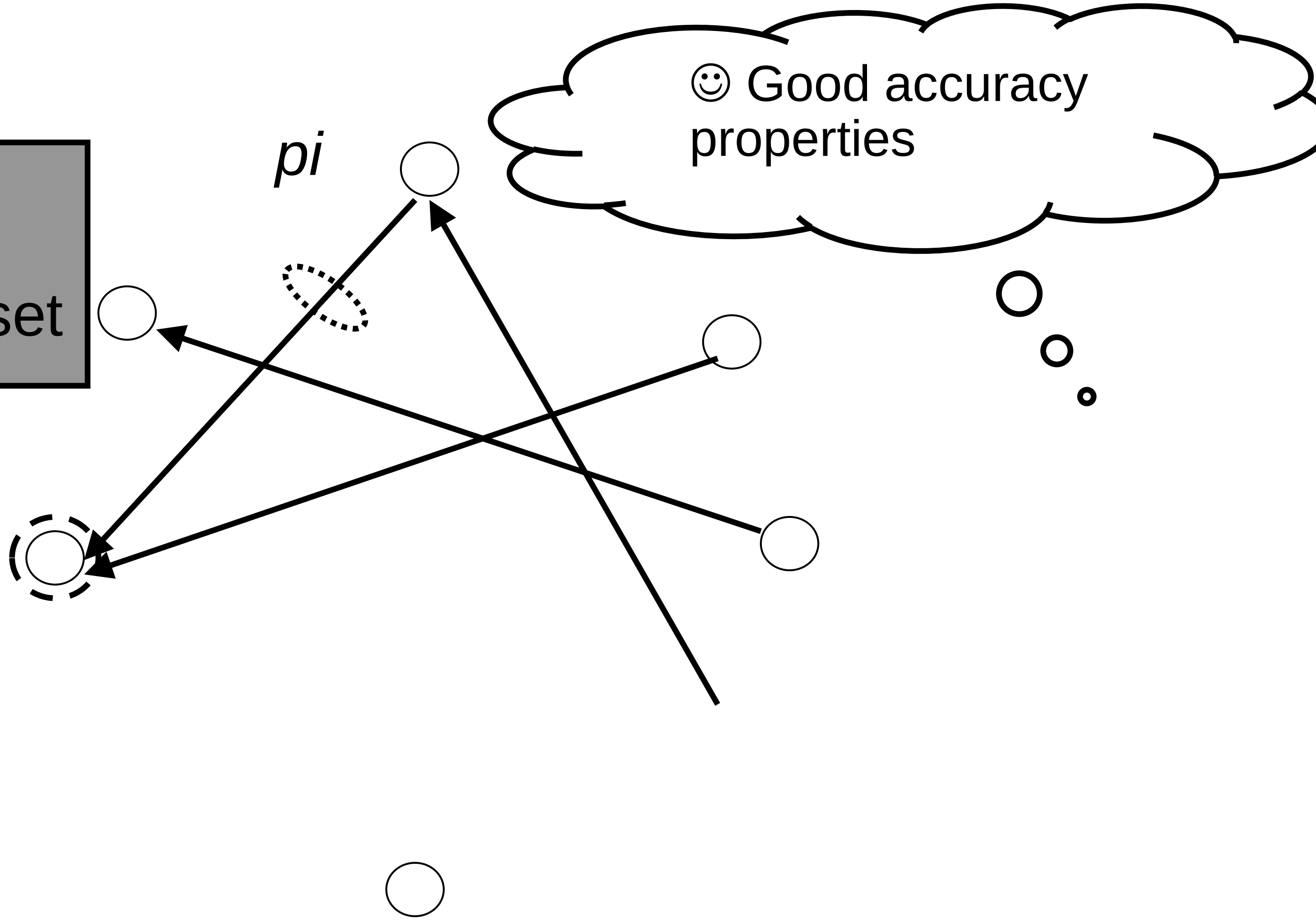
- **False Detection Rate/False Positive Rate (inaccuracy)**
  - Multiple possible metrics
  - 1. Average number of failures detected per second, when there are in fact no failures
  - 2. Fraction of failure detections that are false
- **Tradeoffs: If you increase the T waiting period in ping-ack or 3*T waiting period in heartbeating what happens to:**
  - Detection Time?
  - False positive rate?
  - Where would you set these waiting periods?

Membership Protocols

- **Maintain a list of other alive (non-faulty) processes at *each process* in the system**
- **Failure detector is a component in membership protocol**
  - **Failure of pj detected -> delete pj from membership list**
  - **New machine joins -> pj sends message to everyone -> add pj to membership list**
- **Flavors**
  - **Strongly consistent: all membership lists identical at all times (hard, may not scale)**
  - **Weakly consistent: membership lists not identical at all times**
  - **<u>Eventually consistent</u>: membership lists always moving towards becoming identical eventually (scales well)**

Gossip-style Membership

Array of
Heartbeat Seq. *l*
for member subset



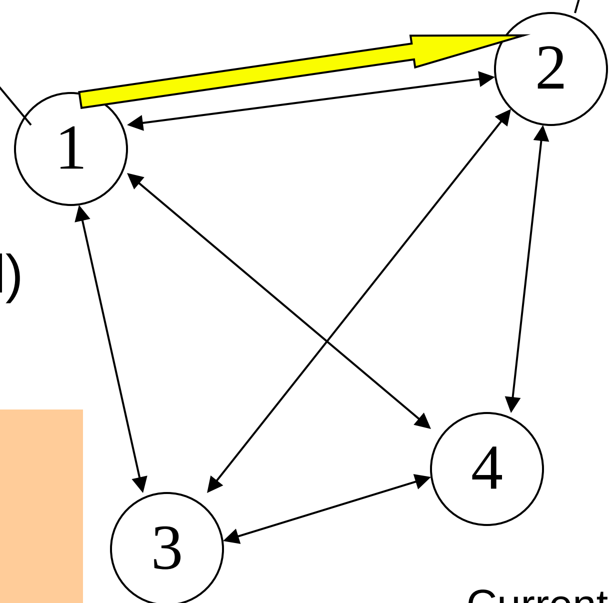
Gossip-Style Failure Detection

1	10120	66
2	10103	62
3	10098	63
4	10111	65

Address

Heartbeat Counter

Time (local)



1	10118	64
2	10110	64
3	10090	58
4	10111	65

1	10120	70
2	10110	64
3	10098	70
4	10111	65

Current time : 70 at node 2

(asynchronous clocks)

Protocol

- Each process maintains a membership list
- Each process periodically increments its own heartbeat counter
- Each process periodically gossips its membership list
- On receipt, the heartbeats are merged, and local times are updated

Fig and animation by: Dongyun Jin and Thuy Ngyuen

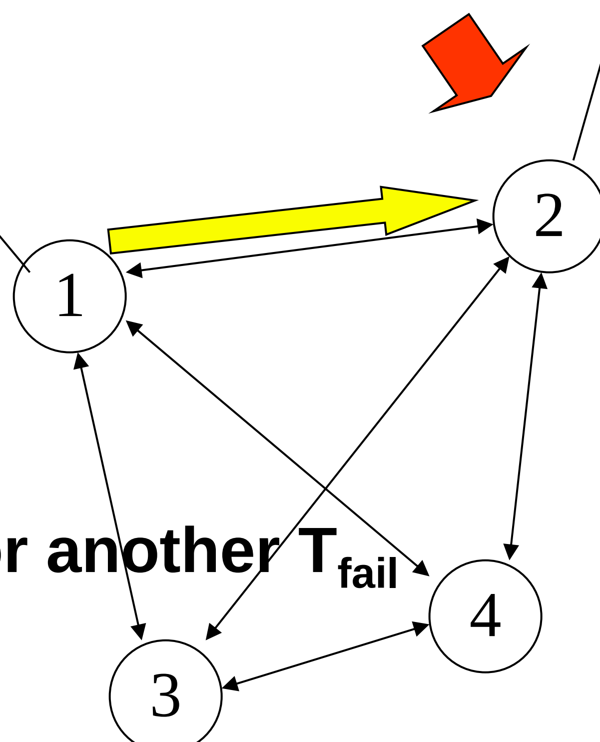
Gossip-Style Failure Detection

- **Well-known result (you'll see it in a few months)**
  - **In a group of N processes, it takes O(log(N)) time for a heartbeat update to propagate to everyone with high probability**
  - **Very robust against failures – even if a large number of processes crash, most/all of the remaining processes still receive all heartbeats**
- **Failure detection: If the heartbeat has not increased for more than T_{fail} seconds, the member is considered failed**
  - **T_{fail} usually set to O(log(N)).**
- **But entry not deleted immediately: wait another $T_{cleanup}$ seconds (usually = T_{fail})**
- **Why not delete it immediately after the T_{fail} timeout?**

Gossip-Style Failure Detection

- **What if an entry pointing to a failed node is deleted right after T_{fail} (=24) seconds?**

1	10120	66
2	10103	62
3	10098	55
4	10111	65



1	10120	66
2	10110	64
3	10098	75
4	10111	65

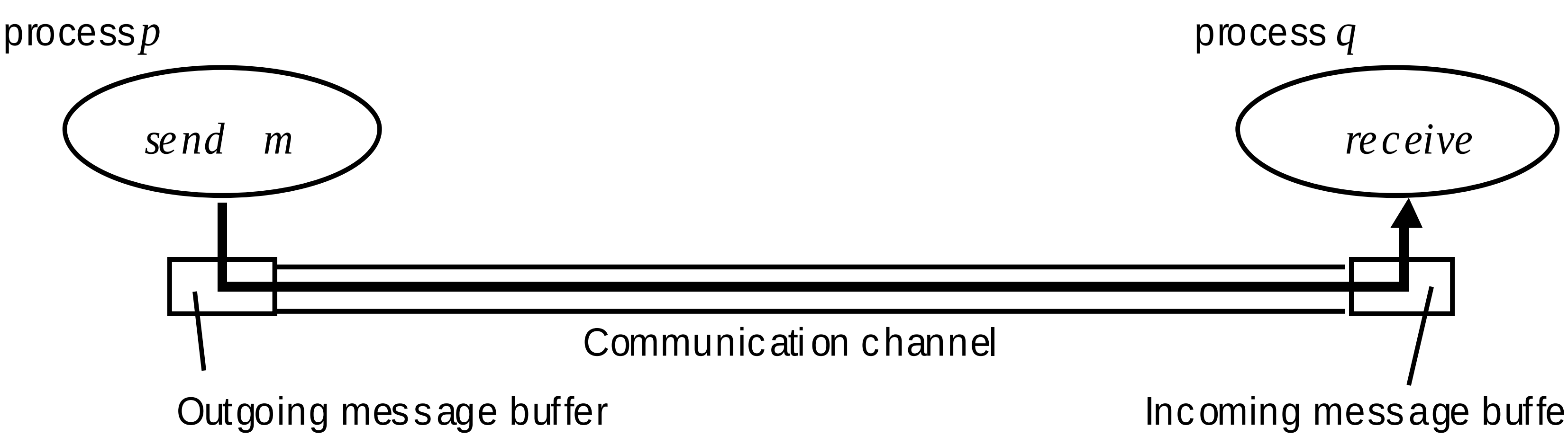
Current time : 75 at node 2

- **Fix: remember for another T_{fail}**

Other Types of Failures

- Let's discuss the other types of failures
- Failure detectors exist for them too (but we won't discuss those)

Processes and Channels



Other Failure Types

- **Communication omission failures**
  - **Send-omission: loss of messages between the sending process and the outgoing message buffer (both inclusive)**
    - **What might cause this?**
  - **Channel omission: loss of message in the communication channel**
    - **What might cause this?**
  - **Receive-omission: loss of messages between the incoming message buffer and the receiving process (both inclusive)**
    - **What might cause this?**

Other Failure Types

❑ Arbitrary failures

- Arbitrary process failure: arbitrarily omits intended processing steps or takes unintended processing steps.
- Arbitrary channel failures: messages may be corrupted, duplicated, delivered out of order, incur extremely large delays; or non-existent messages may be delivered.

- Above two are Byzantine failures, e.g., due to hackers, man-in-the-middle attacks, viruses, worms, etc., and even bugs in the code
- A variety of Byzantine fault-tolerant protocols have been designed in literature!

Omission and Arbitrary Failures

Class of failure	*Affects*	*Description*
Fail-stop or Crash-stop	Process	Process halts and remains halted. Other processes may detect this state.
Omission	Channel	A message inserted in an outgoing message buffer never arrives at the other end's incoming message buffer.
Send-omission	Process	A process completes a *send*, but the message is not put in its outgoing message buffer.
Receive-omission	Process	A message is put in a process's incoming message buffer, but that process does not receive it.
Arbitrary (Byzantine)	Process or channel	Process/channel exhibits arbitrary behaviour: it may send/transmit arbitrary messages at arbitrary times, commit omissions; a process may stop or take an incorrect step.

Summary

- **Failure Detectors**
- **Completeness and Accuracy**
- **Ping-ack and Heartbeating**
- **Gossip-style**
- **Suspicion, Membership**

Next Week

- **Reading for Next Two Lectures: Sections 14.1-14.5**
  - **Time and Synchronization**
  - **Global States and Snapshots**

- **HW1 already out, due Sep 19th**
- **MP1 already out, due 9/15: By now you should**
  - **Be in a group (send email to us at cs425-ece428-staff@mx.uillinois.edu TODAY, subject line: "425 MP group"), use Piazza to find partners**
  - **Have a basic design.**
  - **If you've already started coding, you're doing well.**

Optional - Suspicion

- Augment failure detection with suspicion count
- Ex: In all-to-all heartbeating, suspicion count = number of machines that have timed out waiting for heartbeats from a particular machine M
  - When suspicion count crosses a threshold, declare M failed
  - Issues: Who maintains this count? If distributed, need to circulate the count
- Lowers mistaken detections (e.g., message dropped, Internet path bad), e.g., in Cassandra key-value store
- Can also keep much longer-term failure counts, and use this to blacklist and greylist machines, e.g., in OpenCorral CDN