CSCE 619-600
Networks and Distributed Processing
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Congestion Control

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Agenda

- Brief history of the Internet
- Introduction to control theory
  - Closed-loop systems
  - Examples
  - Relationship to congestion control
- Goals of congestion control
- Fairness index

History

- Not-so-distant history of the Internet shows why congestion control is important
- ARPAnet existed since the 1960s and eventually evolved into a global network by the early 1980s
- NCP (Network Control Protocol, 1970) was originally used in the ARPAnet
  - Host-to-host protocol encompassing both routing and transport-layer functions
- On January 1, 1983 the Internet switched to TCP/IP (see RFCs 791, 793)
- Major *congestion collapses* in 1983-87
  - Congestion collapse: 100% link utilization, zero throughput (see RFC 896)

History 2

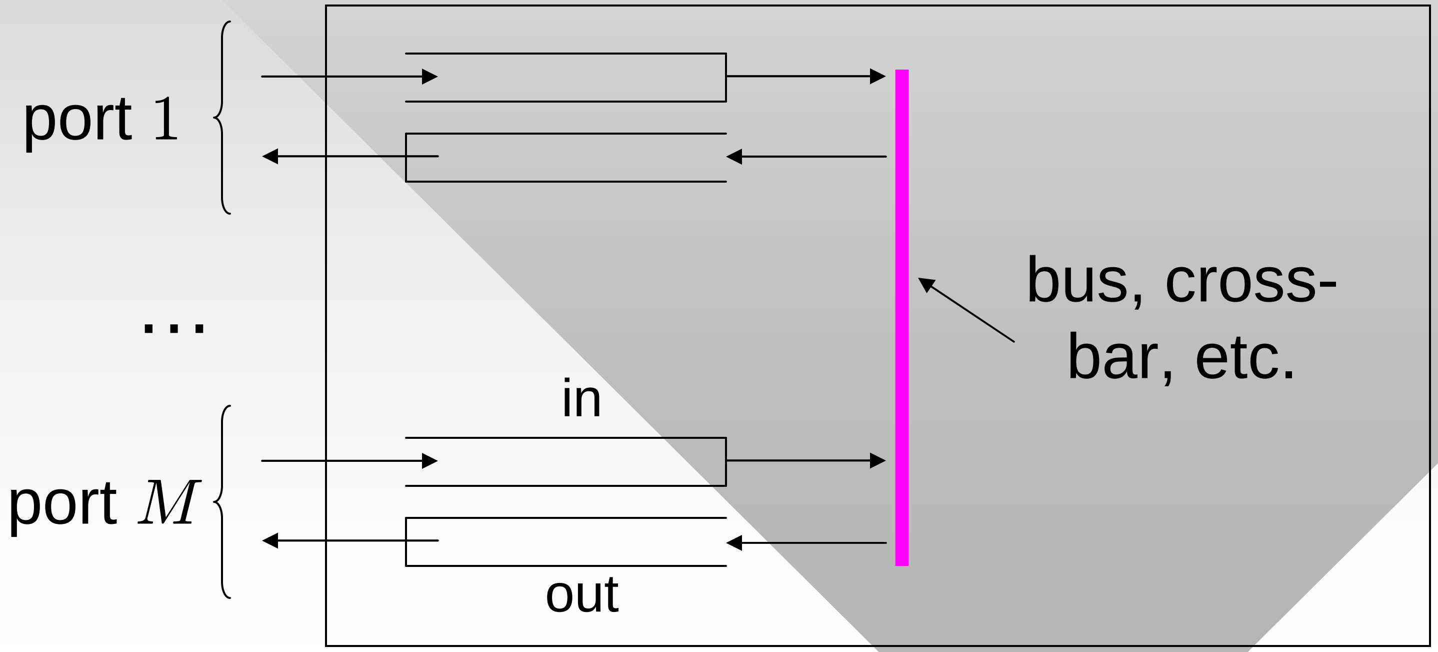
- Congestion collapses possible when retransmissions congest the links
  - Very few new packets are being injected into the network, which results in virtually 0% goodput
  - All bandwidth used on retransmitted packets
- Causes for congestion collapses
  - Poor startup behavior of TCP
  - Inadequate retransmission timeout during congestion
  - No congestion control
- The last item is our interest here

History 3

- Read Jacobson's excellent paper to gain insight into this problem
  - V. Jacobson, "Congestion Avoidance and Control," *ACM SIGCOMM*, 1988
- What exactly is congestion?
  - Links have finite capacity
  - When the sending rates of all flows over a given link exceeds this capacity, we have congestion
- The "level" of congestion is determined both by how much the capacity is exceeded and for how long

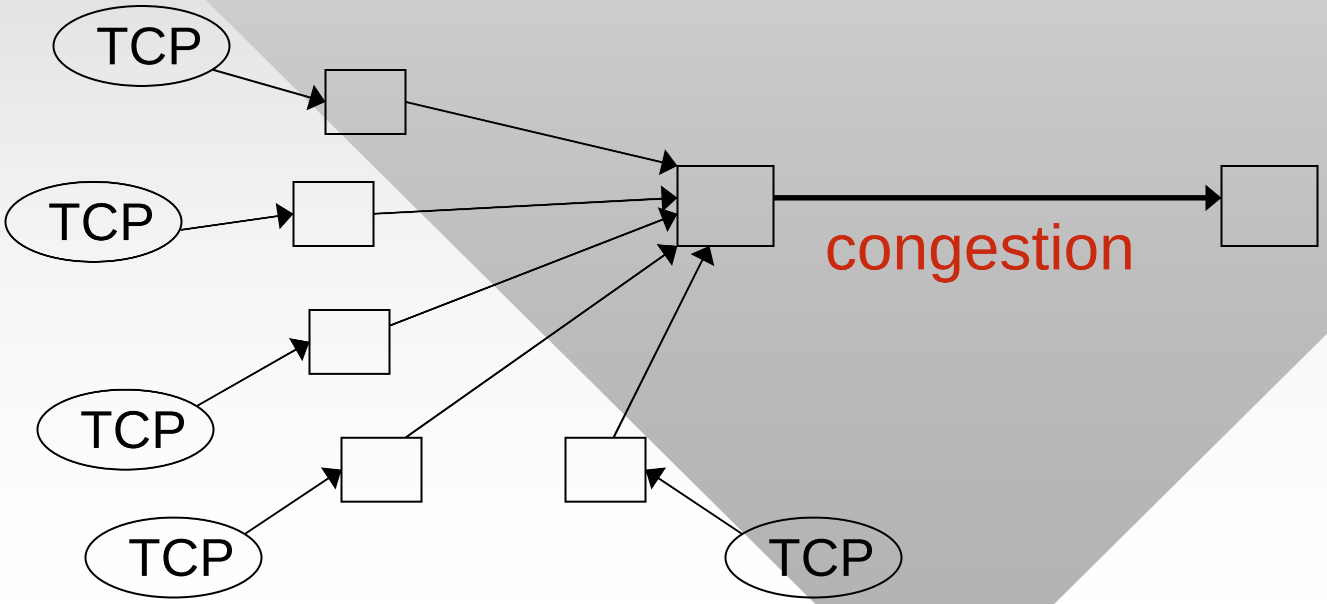
History 4

- Each router has many input and output ports
  - Each has a certain fixed capacity C_i
  - When the total rate of traffic for port i exceeds C_i, buffer i grows and eventually overflows



History 5

- Since some ports receive more traffic than others, there is a possibility that the load on port i exceeds C_i (in the worst case by a factor of $M - 1$)
  - In response to packet loss, end-flows must control their rates in a distributed fashion



History 6

- In general, designing congestion control for distributed environments (like the Internet) is challenging
  - *Distributed* means that flows have no direct information about what other flows are doing
- Remainder of semester
  - First examine theory behind congestion control
  - Then cover classical binary feedback (AIMD and TCP)
  - Finish with recent high-speed TCP models

Control Theory Basics

- Congestion control is a framework that has roots in feedback control theory
- Control theory has many applications in the physical world
  - Controlling aircraft (autopilot), aiming missiles at targets, automobile functions (ABS, cruise-control), robots, etc.
- In general, we study closed-loop control systems
  - Closed-loop means that we get feedback about our current position, which allows us to adjust future direction (or actions) taken by the system

Control Theory Basics 2

- Closed-loop system example: a missile must hit pre-defined GPS coordinates
  - Missile continuously monitors its GPS location and adjusts for wind, air density/resistance, gravity conditions, or any other random disturbances in its flight pattern
- Open-loop control does not rely on feedback
  - The actions of the system need to be pre-programmed beforehand
  - For example, missile directives can be: *keep constant acceleration equal to 3g for 2 minutes at 45 degrees to the surface and then fall vertically down*

Control Theory Basics 3

- Recurrence equations are discrete versions of differential equations
  - Typical differential equation

$$\frac{dy(t)}{dt} = F(y(t), f(t), t)$$

  - where $y(t)$ is the controlled parameter, $f(t)$ is the feedback, and t is time
  - Feedback $f(t)$ usually depends on $y(t)$
- Recurrence (difference) equation:

$$y(n+1) = y(n) + F(y(n), f(n), n)$$

Control Theory Basics 4

- Example:
  - Design a cruise control module for an automobile
  - Controlled parameter $y(t)$ is the acceleration applied to the car through its gas pedal; observed feedback $f(t)$ is the speed $v(t)$ of the vehicle
  - Goal: make the car go exactly v_d miles an hour
- Physics background
  - Acceleration $a(t)$ is the derivative of speed:

$$a(t) = \dot{v}(t)$$

  - We can also write:

$$v(t) = \int_0^t a(u)du$$

Control Theory Basics 5

- Example (continued)
  - Suppose the system is ideal, which means that the applied acceleration $y(t)$ immediately translates into a change in speed:

$$\dot{v}(t) = y(t)$$

model of the system

  - Then how do we adjust acceleration based on the sampled speed $v(t)$?

$$\dot{y}(t) = F(v(t))$$

controller

  - In this case, the feedback is vehicle speed $f(t) = v(t)$ and function $F(.)$ can be:

$$F(v(t)) = -\alpha(v(t) - v_d) = -\alpha e(t)$$

error term

controller gain

Control Theory Basics 6

- Example (continued)
  - Is the previous system of equations stable?

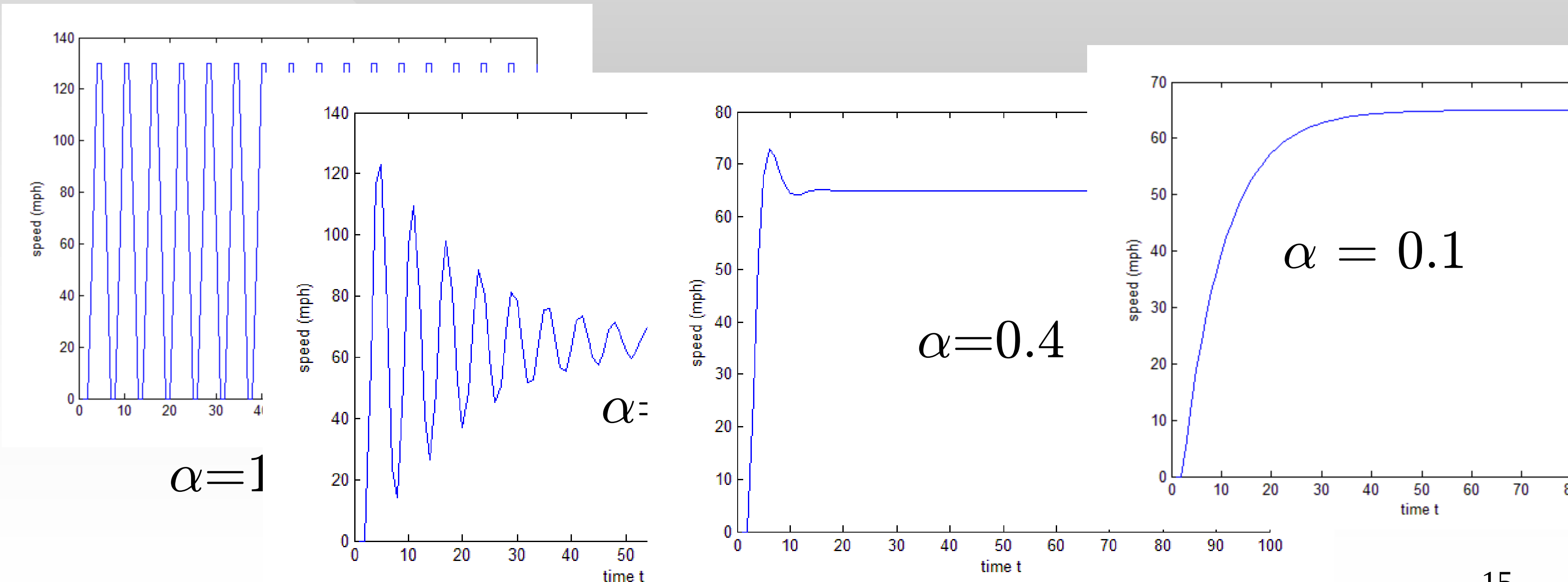
$$\begin{cases} \dot{v}(t) & = & y(t) \\ \dot{y}(t) & = & -\alpha(v(t) - v_d) \end{cases}$$

- A more fundamental issue arises when the system is not perfectly known
  - Suppose the wind, various hills, and friction reduce the applied acceleration by some unknown constant a_f:

$$\begin{cases} \dot{v}(t) & = & y(t) - a_f \\ \dot{y}(t) & = & -\alpha(v(t) - v_d) \end{cases}$$

Control Theory Basics 7

- Another controller
$$\begin{cases} v(n) &= v(n-1) + y(n-1) \\ y(n) &= -\alpha(v(n-1) - v_d) \end{cases}$$
  - Where does the system evolve under the above control actions? Does it reach the desired speed? Does it stabilize or does it oscillate?



Control Theory Basics 8

- If the equation depends on history beyond current time n, it is called delayed
  - Often abbreviated DDE (Delayed Differential Equation):

$$\frac{dy(t)}{dt} = F(y(t), y(t-D), f(t), t), D > 0$$

- DDEs are significantly more complex than ordinary differential equations (ODEs)

Control Theory Basics 9

- In the discrete case, we have a similar form:

$$y(n+1) = y(n) + F(y(n), y(n-D), f(n), n)$$

- Finally, when the feedback itself is delayed, we have these two versions:

$$\frac{dy(t)}{dt} = F(y(t), y(t-D), f(t-D), t)$$
$$y(n+1) = y(n) + F(y(n), y(n-D), f(n-D), n)$$

- Congestion control falls into this category
  - Feedback is provided by network routers (can be packet loss, explicit feedback, or something else) that is delayed by propagation and queuing delays of the path

Control Theory Basics 10

- Definition: when $F(.)$ does not explicitly depend on time t (step n), the equation is called *homogeneous*
  - This is the case in most congestion control, so we often omit t (or n) from the general form
- Definition: if function $F(.)$ is linear in variables y and f, the control equation is said to be *linear*
- Examples
  - Non-homogenous, but linear: $\dot{y}(t) = y + t^2$
  - Homogeneous, non-linear, delayed

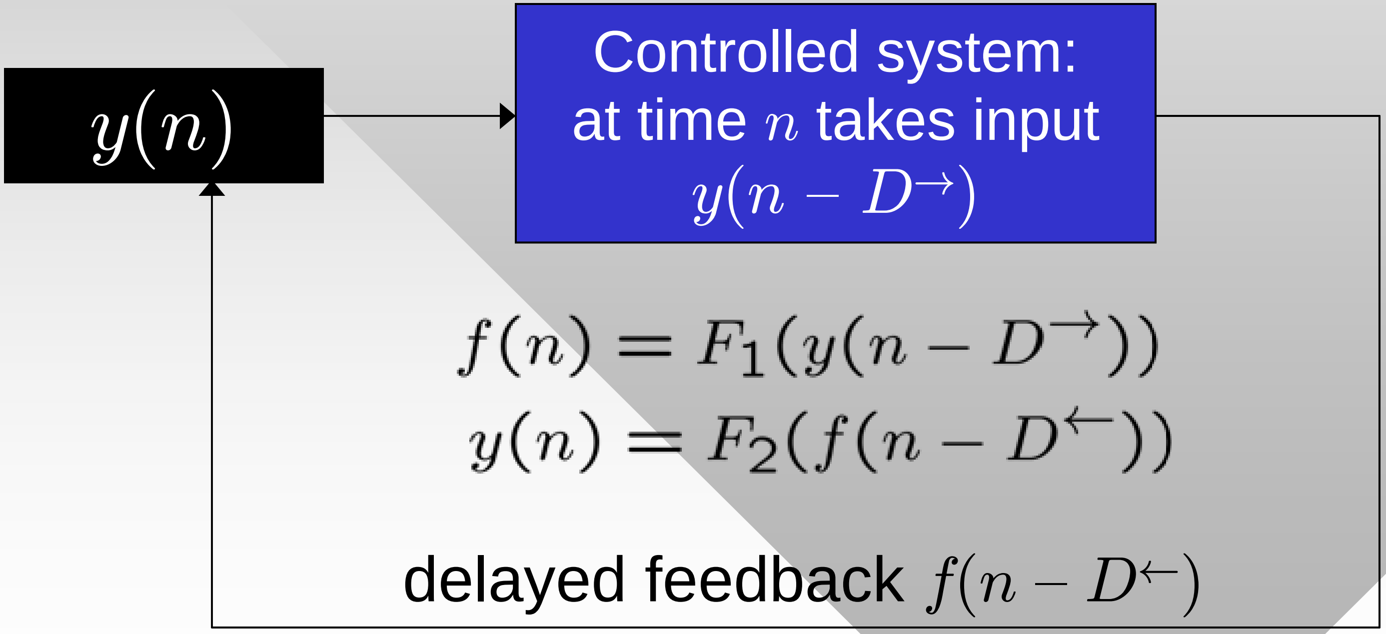
$$\dot{y}(t) = -y^3(t - D) + C$$

  - And an equivalent recurrence:

$$y(n+1) = y(n) - y^3(n - D) + C$$

Control Theory Basics 11

- Assume $D^{\rightarrow}$ is the forward delay from sender to router and $D^{\leftarrow}$ is the backward delay
  - Feedback $f(n)$ depends on rate $y(n-D^{\rightarrow})$ seen by the router and new rate $y(n)$ depends on $f(n-D^{\leftarrow})$

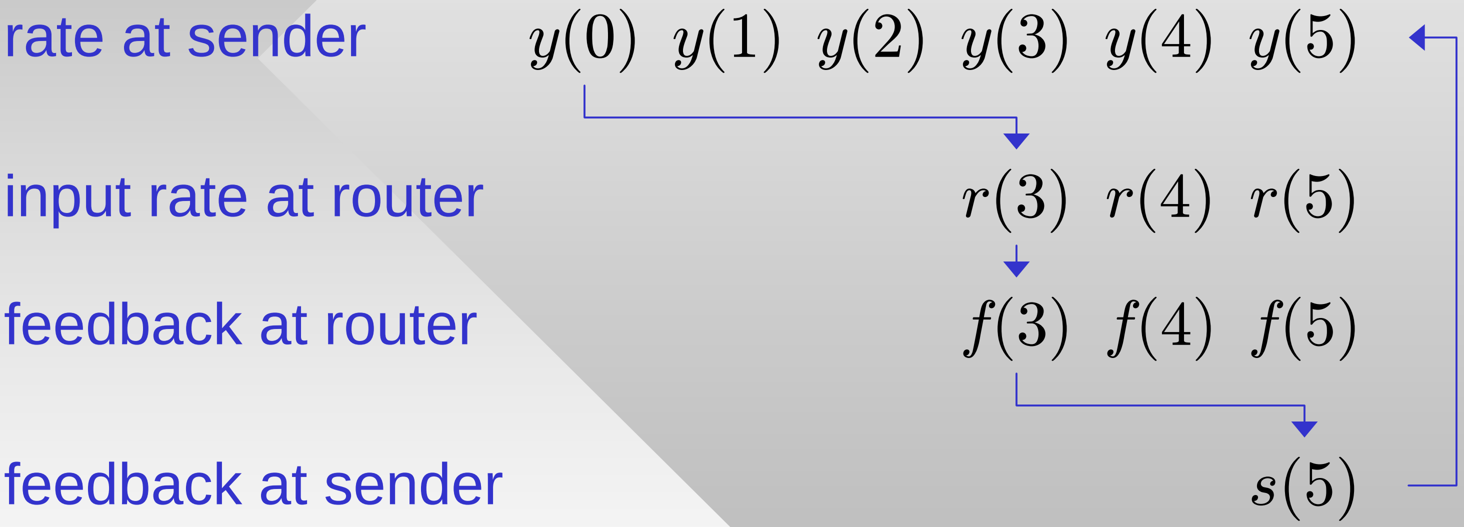


$$f(n) = F_1(y(n - D^{\rightarrow}))$$
$$y(n) = F_2(f(n - D^{\leftarrow}))$$

$$y(n) = F_2(F_1(y(n - D^{\rightarrow} - D^{\leftarrow})))$$

Control Theory Basics 12

- Example: one flow with $D^{\rightarrow} = 3,\ D^{\leftarrow} = 2$



- This explains why $y(n)$ is a function of its own value RTT time units ago, i.e., $y(n - D^{\rightarrow} - D^{\leftarrow})$