Wrapup

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Course Goals

- Build a functioning IP router

- Learn about
  - Network systems architecture
  - Hardware/software systems
  - Embedded systems design

Embedded Systems

- Often part of a larger device (embedded)
- Often interfaces with other components (sensors & actuators) to form a complete system
  - Real-time control?
- Often performs fixed / limited functions
  - If re-programmable, computer code is infrequently changed
- Often has simplified design to save $$ / power
  - Not over-provisioned like general-purpose systems

Implementation Options

- Software-oriented
  - General-purpose CPU
  - Embedded processor or system-on-a-chip
  - What are my computation requirements?
  - Do I need hardware assist units?
- Hardware-oriented
  - Fixed logic (ASICs)
  - Reconfigurable logic (FPGAs)
- Combination of hardware and software

Embedded Systems Design

- Design embedded systems first!
- Pick right implementation strategy based on design requirements
  - Software-only (general-purpose CPU)
  - Software on embedded processor
    - System-on-a-chip (hardware assist units)
  - Custom fixed hardware (ASIC)
  - Reconfigurable hardware (FPGA)
- Class projects
  - Implement a router in < 1 semester
  - Chosen strategy is a compromise between performance, implementation time, and education
  - Using both FPGA and software together introduces you to embedded system design issues that exist in all fields, not just networking

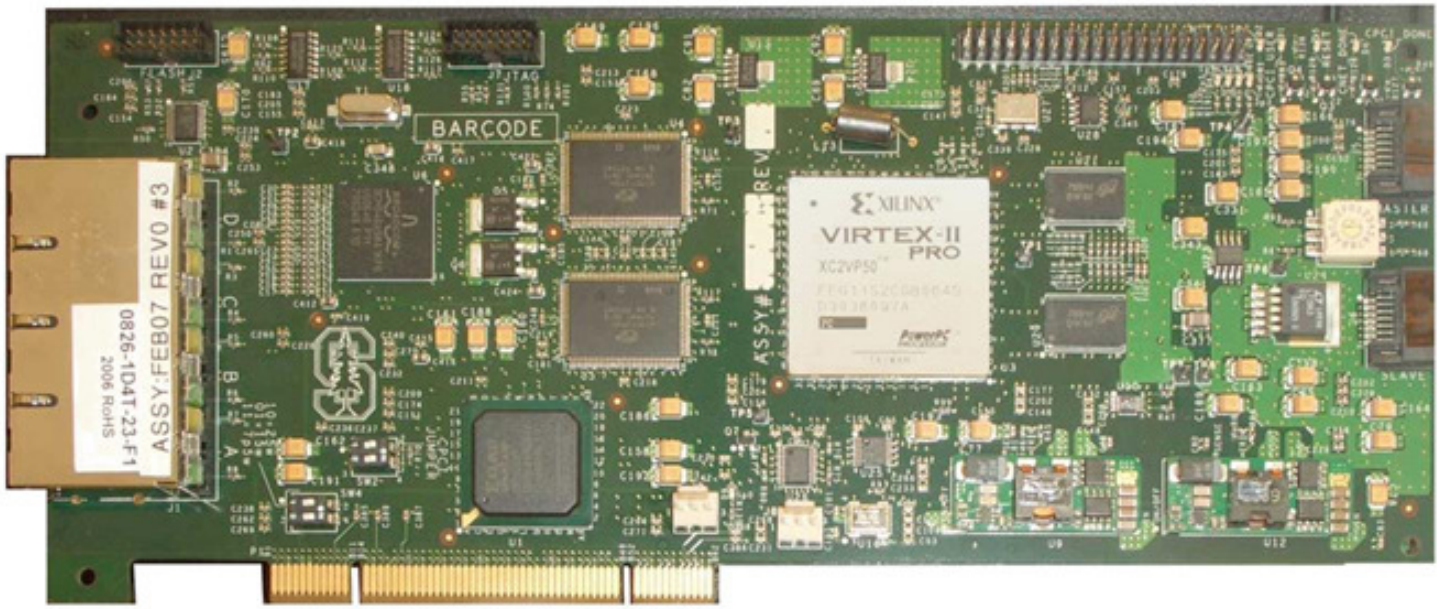
Network Systems Architecture

- Specialized systems for networking
  - Network interfaces
  - Switches
  - Routers
  - …
- Typically a combination of software control and special-purpose hardware for packet processing
  - Network processors
  - Lightweight microprocessors with custom hardware

Course Perspective

- Focus on IP routers
- Performance is a major design consideration for real routers
- We focused on functionality
  - Control plane
    - ARP, ICMP, etc.
  - Data plane
    - Packet forwarding

Stanford's NetFPGA



- Network interface
- Hub
- Learning switch
- IP router

Ethernet

- Link layer protocol
- Hubs
  - Broadcast all traffic
- Switches
  - Learn host locations
  - Spanning trees
- VLANs, performance, scaling, …

Ethernet Drawbacks

- Locating computers
  - Do we really want to broadcast across the Internet?
- Preventing loops
  - Do we really want to rebuild an Internet-wide spanning tree whenever the topology changes?
    - Do we want a tree topology at all?
  - Do we really want packets to live forever if loops remain?
- Unreachable computers
  - What happens if the destination is unreachable?
  - I.e., it doesn't exist, is turned off, is broken, …

The Internet Protocol

- Datagram
  - Each packet is individually routed
  - Packets may be fragmented or duplicated
    - Due to underlying networks
- Connectionless
  - No guarantee of delivery in sequence
- Unreliable
  - No guarantee of delivery
  - No guarantee of integrity of data
- Best effort
  - Only drop packets when necessary
  - No time guarantee for delivery

Understanding IP

- Datagram lifetimes
  - Time-to-live
- Handling disparate link layers
  - Fragmentation
- IP integrity
  - Header checksum
- What do datagrams look like?
  - Header format
- Addressing

IP Addresses

- IP version 4 addresses are 32-bits
  - Version 6 address are 128 bits
- Every network interface has at least one IP address
  - A computer might have 2 or more IP addresses
  - A router has many IP addresses
  - These addresses can be assigned statically or dynamically
- IP addresses are hierarchical
  - Address is composed of a network ID and a host ID
  - www.rice.edu: 128.42.206.11

Subnetting

- Divide the network within an organization
  - Consider organization's network to be a collection of many smaller networks
- Internet routers don't need to know about subnetting within an organization
  - Just route their traffic to the organization

Classless InterDomain Routing

- CIDR introduced in 1993
  - Meant to provide more flexible routing
  - Eliminate dependences on “class” networks in routing
- “Supernetting”
  - Combine multiple contiguous networks into one larger network
  - Effectively reduces the number of entries needed in each routing table
  - Inverse of subnetting which takes one larger network and breaks it into multiple contiguous smaller networks

Address Resolution Protocol

- Find link layer address given a network layer address
  - i.e., what is the Ethernet address for a given IP address?
- Every IP node (hosts and routers) have an ARP table
  - Mapping from IP to Ethernet addresses on their LAN
  - May be incomplete
  - Can include both static and dynamic entries

Forwarding a Packet in a Router

- Lookup destination IP address in forwarding table
  - Yields a next hop port and IP address
  - What if it doesn't?
- Lookup next hop IP address in ARP table
  - Yields a next hop MAC address
  - What if it doesn't?
- Forward modified packet out the next hop port with the next hop MAC address

Internet Control Message Protocol

- Primarily used to communicate errors among routers and hosts
  - IP datagram errors
  - Communicate routing information/errors
  - Communicate diagnostics
- Not used by applications
  - Applications communicate application-level errors using higher level protocols
  - Ping and traceroute are the exceptions

An IP Router

- You have all built (almost) the core of a functioning IP router!

- Verify packet integrity
- Use ARP to determine Ethernet addresses
- Use ICMP to report errors, respond to echo requests
- Forward IP packets

Routers

- Deal mostly with network (e.g., IP) and link (e.g., Ethernet) layers
  - Best-effort, unreliable delivery
  - Point-to-point communication with other routers/hosts
- More sophisticated network systems have emerged that blur the boundaries
  - Route traffic
  - Have knowledge of transport (e.g., TCP) and application (e.g., HTTP) layers

“Real” Routers

- Images from Cisco Web Site

What is missing from your routers?

- Dynamic routing
  - OSPF and BGP
- Quality of Service
  - Simple low/high priority traffic
  - Automatic recognition of traffic types
- “Virtual” Networks
  - Virtual private network (VPN)
  - Multi-protocol label switching (MPLS)
- Many other possible features
  - Network address translation
  - Encryption/decryption
  - Load balancing
  - …

Schedule

- Class
  - Project meetings on Wednesday
  - No class Friday – Yale Patt visiting
- Projects
  - Hardware router and software UI due Friday at midnight
  - Remaining tasks:
    - Integration of software and hardware + final report
    - Individual meetings with instructors