

**William Stallings  
Computer Organization  
and Architecture  
7<sup>th</sup> Edition**

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**Chapter 7  
Input/Output**

# Input/Output Problems

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- **Wide variety of peripherals**
  - Delivering different amounts of data
  - At different speeds
  - In different formats
- **All slower than CPU and RAM**
- **Need I/O modules**

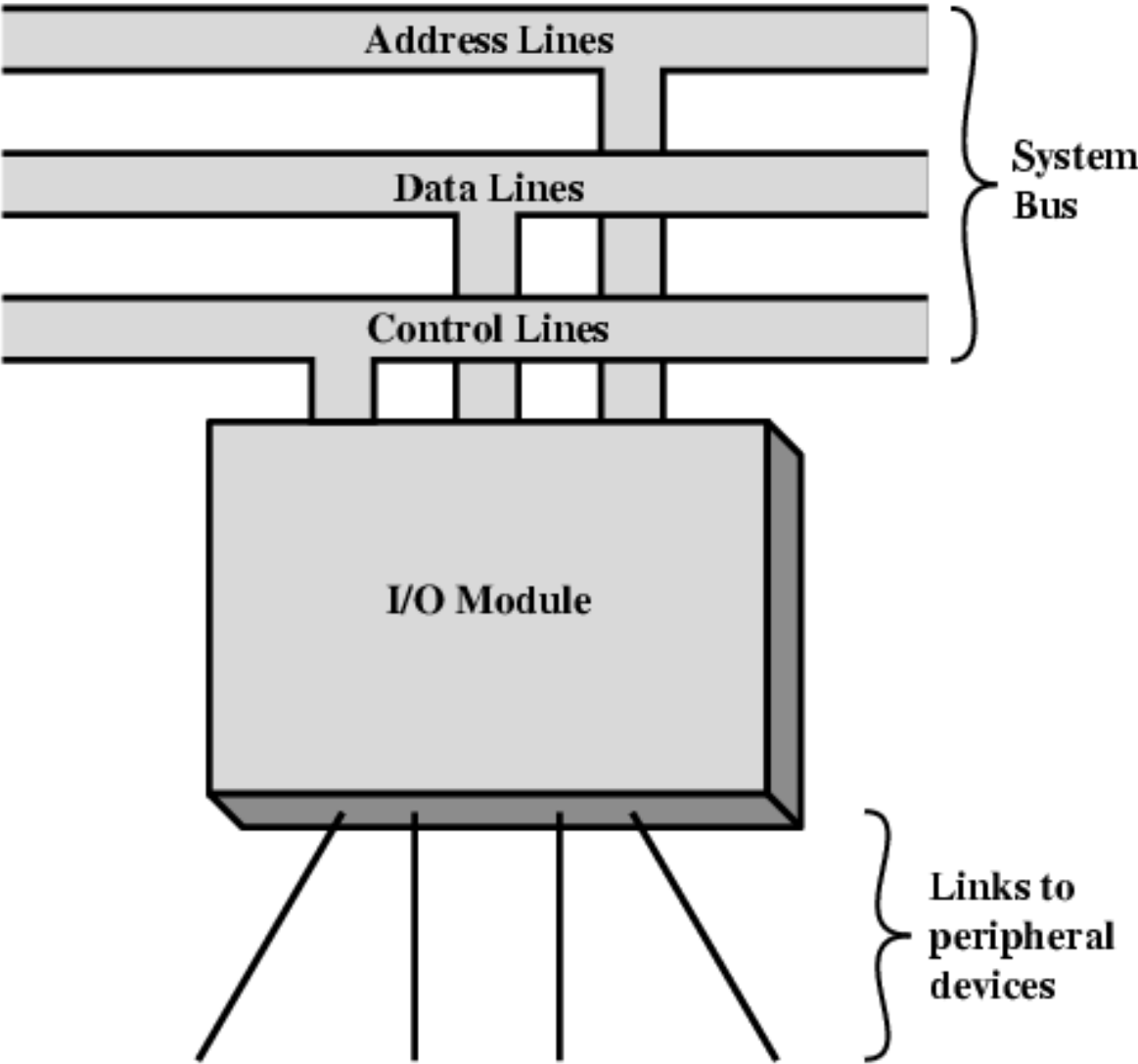
# **Input/Output Module**

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- **Interface to CPU and Memory**
- **Interface to one or more peripherals**

# Generic Model of I/O Module

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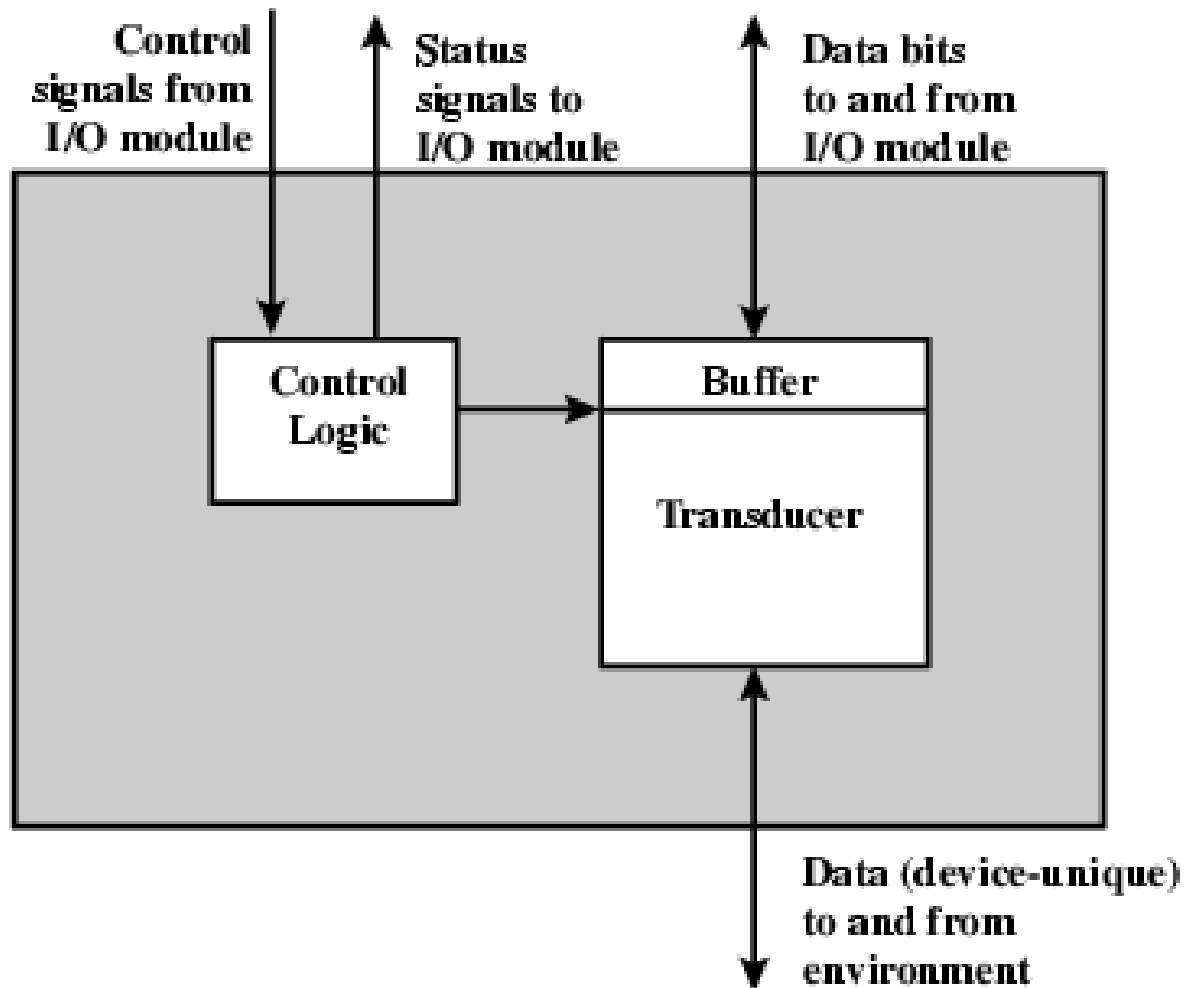
# External Devices

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- **Human readable**
  - Screen, printer, keyboard
- **Machine readable**
  - Monitoring and control
- **Communication**
  - Modem
  - Network Interface Card (NIC)

# External Device Block Diagram

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# I/O Module Function

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- Control & Timing
- CPU Communication
- Device Communication
- Data Buffering
- Error Detection

## I/O Steps

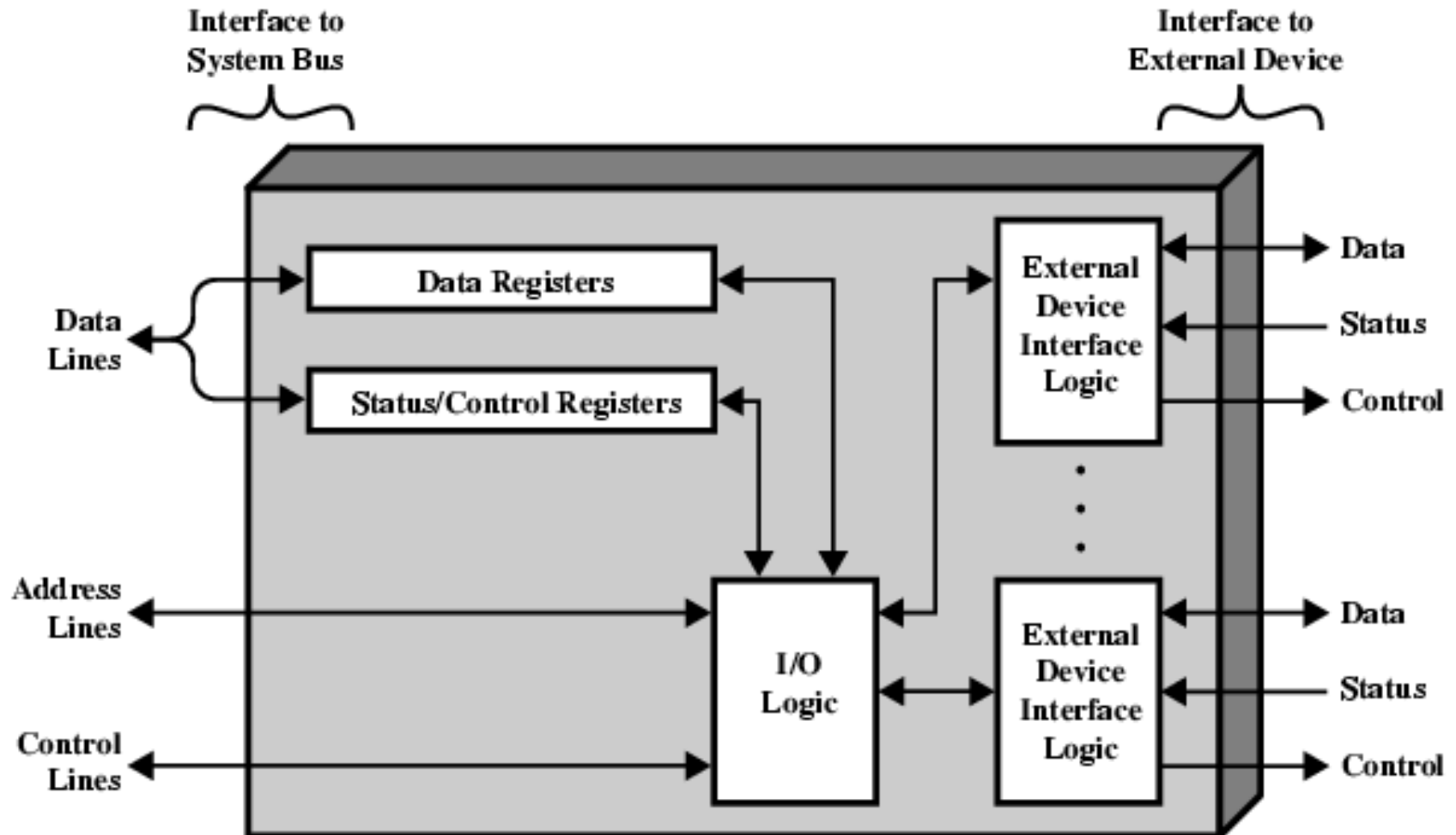
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- CPU checks I/O module device status
- I/O module returns status
- If ready, CPU requests data transfer
- I/O module gets data from device
- I/O module transfers data to CPU
- Variations for output, DMA, etc.



# I/O Module Diagram

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## I/O Module Decisions

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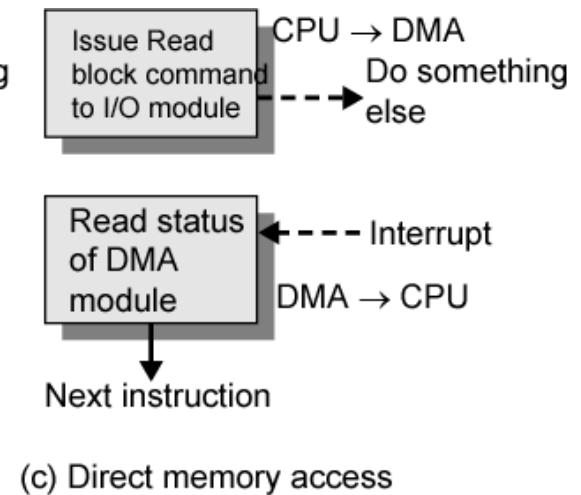
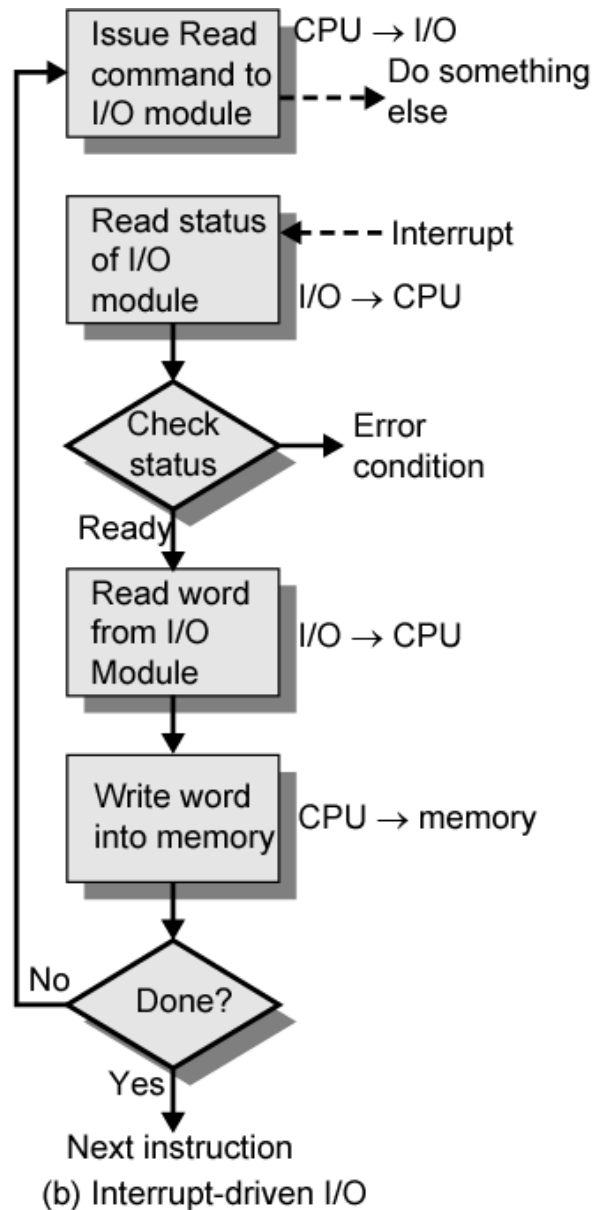
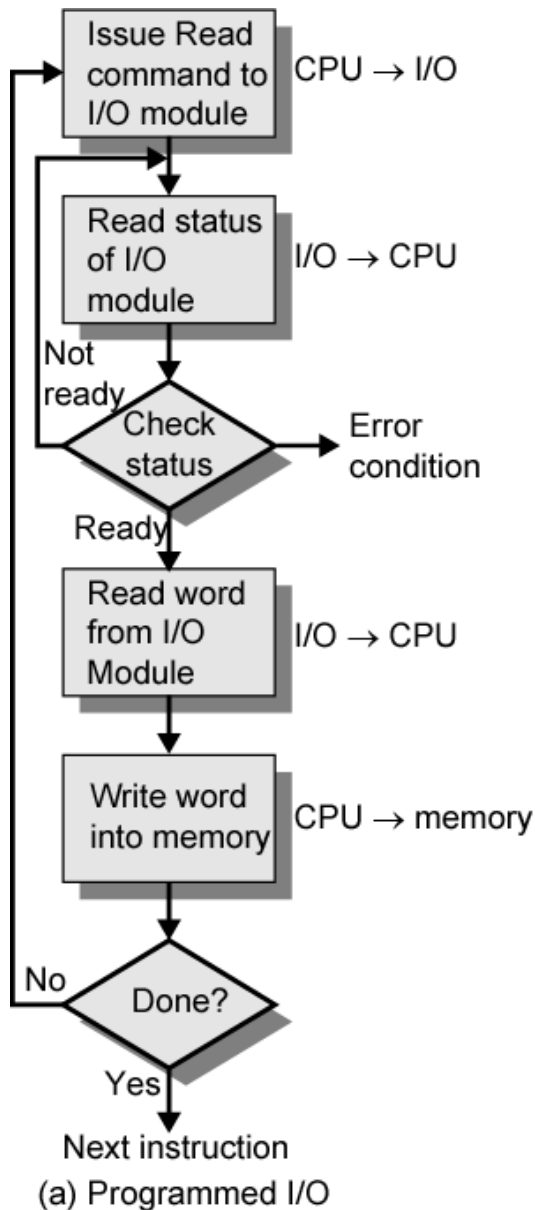
- Hide or reveal device properties to CPU
- Support multiple or single device
- Control device functions or leave for CPU
- Also O/S decisions
  - e.g. Unix treats everything it can as a file

# Input Output Techniques

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- Programmed
- Interrupt driven
- Direct Memory Access (DMA)

# Three Techniques for Input of a Block of Data



## Programmed I/O

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- CPU has direct control over I/O
  - Sensing status
  - Read/write commands
  - Transferring data
- CPU waits for I/O module to complete operation
- Wastes CPU time

## Programmed I/O - detail

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- CPU requests I/O operation
- I/O module performs operation
- I/O module sets status bits
- CPU checks status bits periodically
- I/O module does not inform CPU directly
- I/O module does not interrupt CPU
- CPU may wait or come back later

# I/O Commands

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- CPU issues address
  - Identifies module (& device if >1 per module)
- CPU issues command
  - Control - telling module what to do
    - e.g. spin up disk
  - Test - check status
    - e.g. power? Error?
  - Read/Write
    - Module transfers data via buffer from/to device

## Addressing I/O Devices

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- Under programmed I/O data transfer is very like memory access (CPU viewpoint)
- Each device given unique identifier
- CPU commands contain identifier (address)

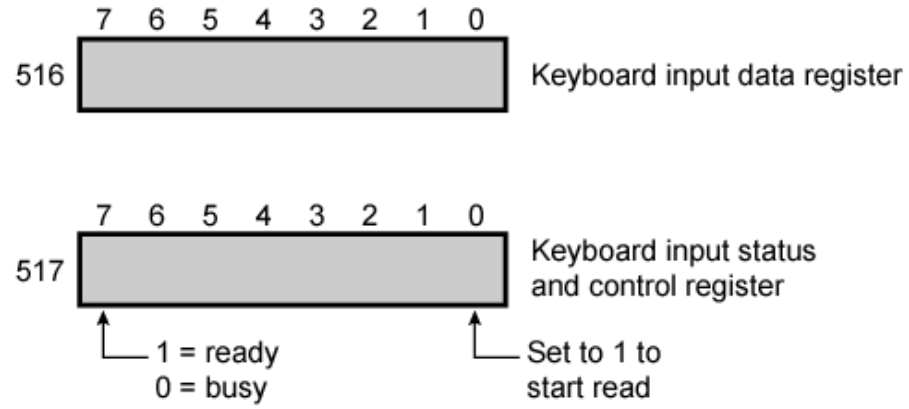


# I/O Mapping

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- **Memory mapped I/O**
  - Devices and memory share an address space
  - I/O looks just like memory read/write
  - No special commands for I/O
    - Large selection of memory access commands available
- **Isolated I/O**
  - Separate address spaces
  - Need I/O or memory select lines
  - Special commands for I/O
    - Limited set

# Memory Mapped and Isolated I/O



ADDRESS	INSTRUCTION	OPERAND	COMMENT	ADDRESS	INSTRUCTION	OPERAND	COMMENT
200	Load AC	"1"	Load accumulator	200	Load I/O	5	Initiate keyboard read
	Store AC	517	Initiate keyboard read	201	Test I/O	5	Check for completion
202	Load AC	517	Get status byte		Branch Not Ready	201	Loop until complete
	Branch if Sign = 0	202	Loop until ready		In	5	Load data byte
	Load AC	516	Load data byte				

(b) Isolated I/O

(a) Memory-mapped I/O

## Interrupt Driven I/O

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- Overcomes CPU waiting
- No repeated CPU checking of device
- I/O module interrupts when ready

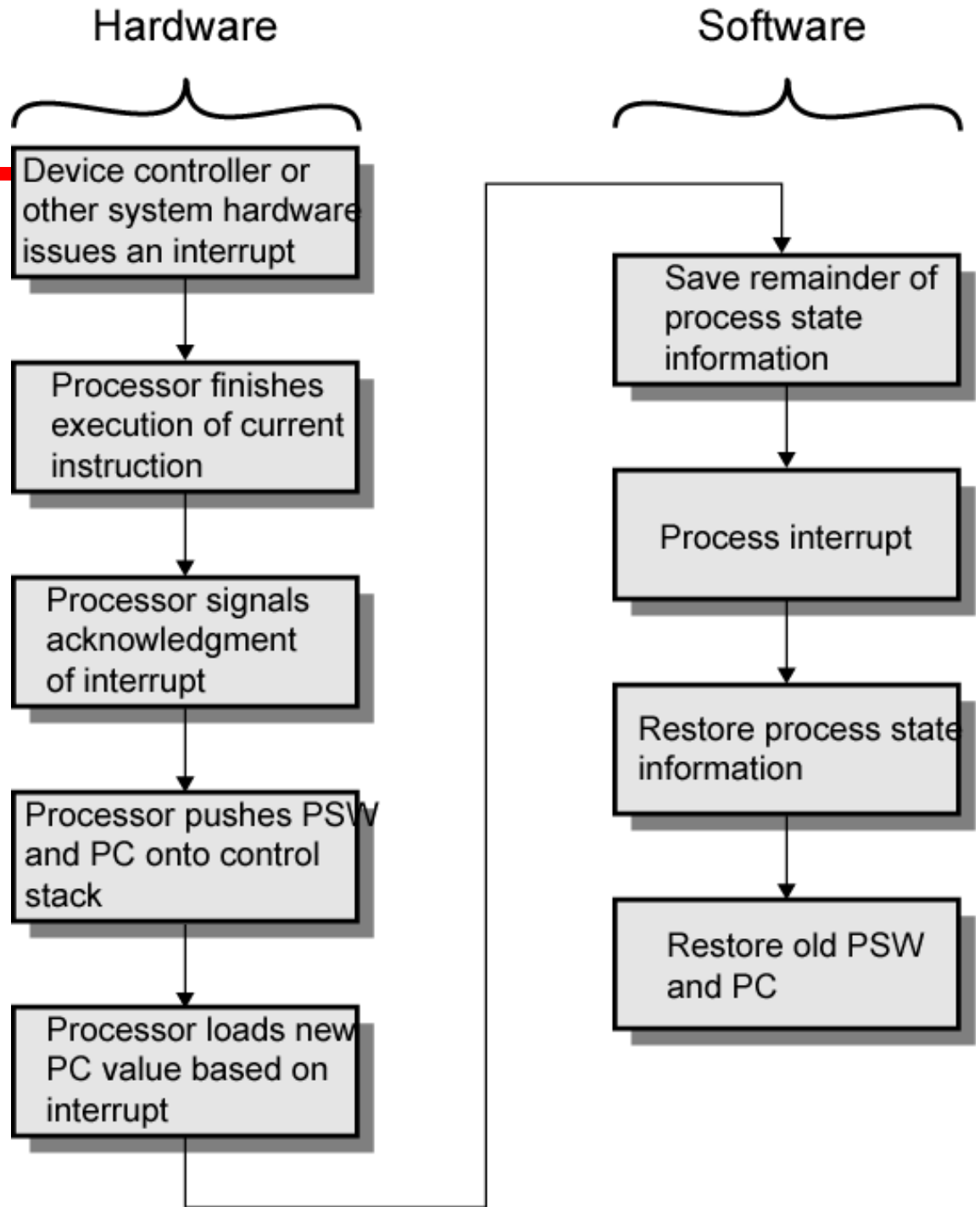
# Interrupt Driven I/O

## Basic Operation

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- CPU issues read command
- I/O module gets data from peripheral whilst CPU does other work
- I/O module interrupts CPU
- CPU requests data
- I/O module transfers data

# Simple Interrupt Processing

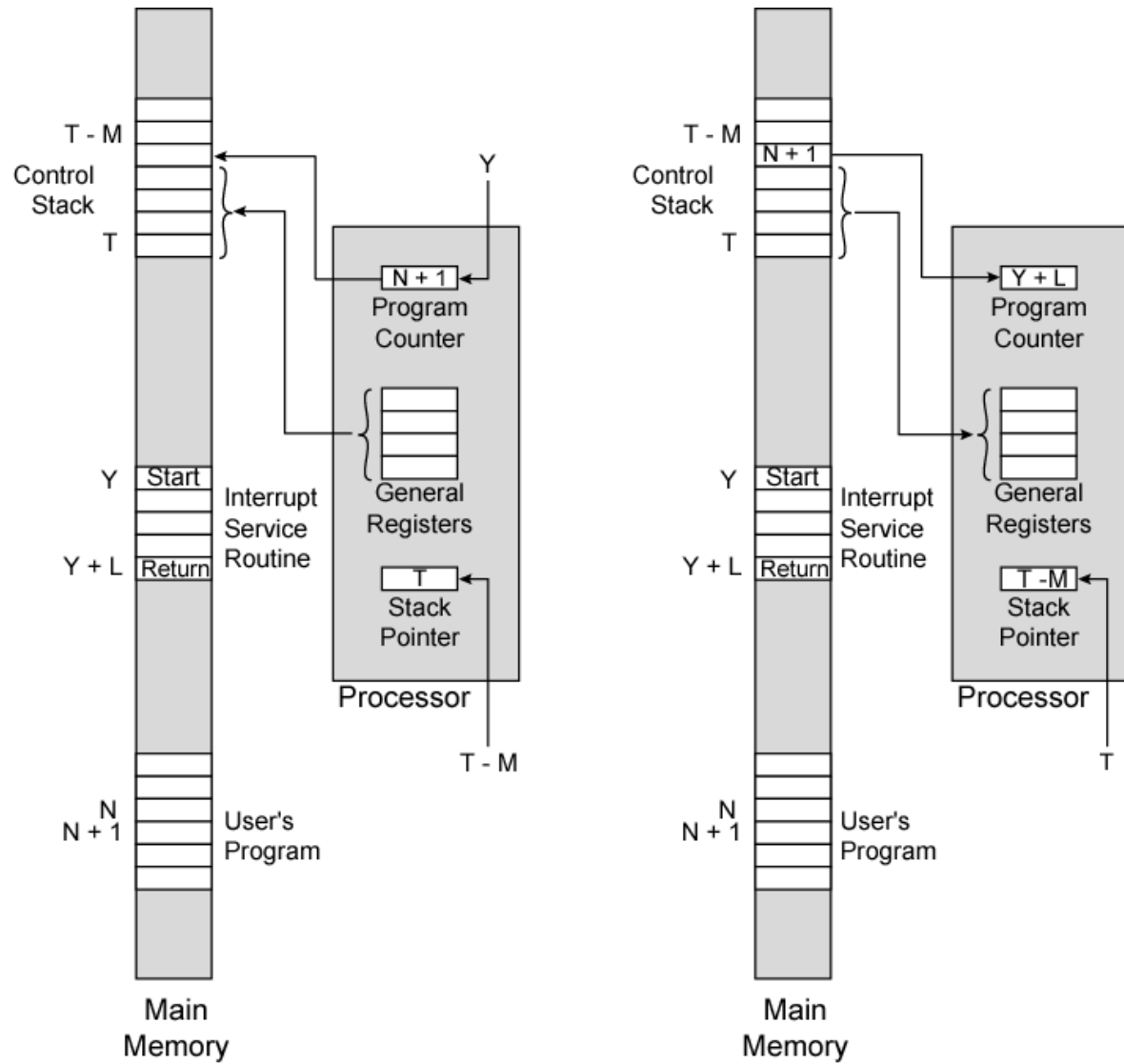


# CPU Viewpoint

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- Issue read command
- Do other work
- Check for interrupt at end of each instruction cycle
- If interrupted: -
  - Save context (registers)
  - Process interrupt
    - Fetch data & store
- See Operating Systems notes

# Changes in Memory and Registers for an Interrupt



(a) Interrupt occurs after instruction at location N

(b) Return from interrupt

## Design Issues

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- How do you identify the module issuing the interrupt?
- How do you deal with multiple interrupts?
  - i.e. an interrupt handler being interrupted



# Identifying Interrupting Module (1)

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- Different line for each module
  - PC
  - Limits number of devices
- Software poll
  - CPU asks each module in turn
  - Slow

## Identifying Interrupting Module (2)

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- **Daisy Chain or Hardware poll**
  - Interrupt Acknowledge sent down a chain
  - Module responsible places vector on bus
  - CPU uses vector to identify handler routine
- **Bus Master**
  - Module must claim the bus before it can raise interrupt
  - e.g. PCI & SCSI

## Multiple Interrupts

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- Each interrupt line has a priority
- Higher priority lines can interrupt lower priority lines
- If bus mastering only current master can interrupt

## Example - PC Bus

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- 80x86 has one interrupt line
- 8086 based systems use one 8259A interrupt controller
- 8259A has 8 interrupt lines

## Sequence of Events

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- 8259A accepts interrupts
- 8259A determines priority
- 8259A signals 8086 (raises INTR line)
- CPU Acknowledges
- 8259A puts correct vector on data bus
- CPU processes interrupt

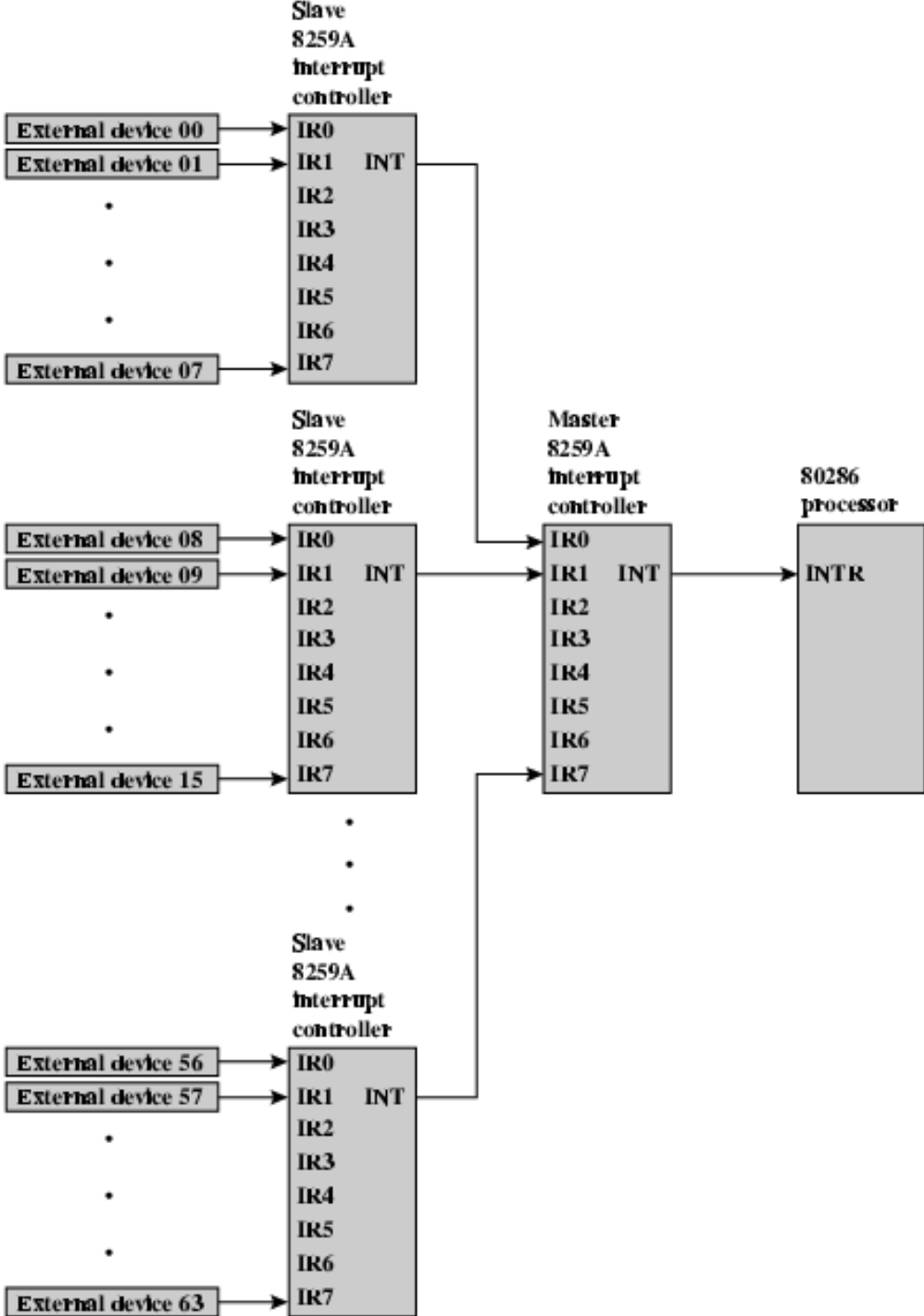
# ISA Bus Interrupt System

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- ISA bus chains two 8259As together
- Link is via interrupt 2
- Gives 15 lines
  - 16 lines less one for link
- IRQ 9 is used to re-route anything trying to use IRQ 2
  - Backwards compatibility
- Incorporated in chip set

# 82C59A Interrupt Controller

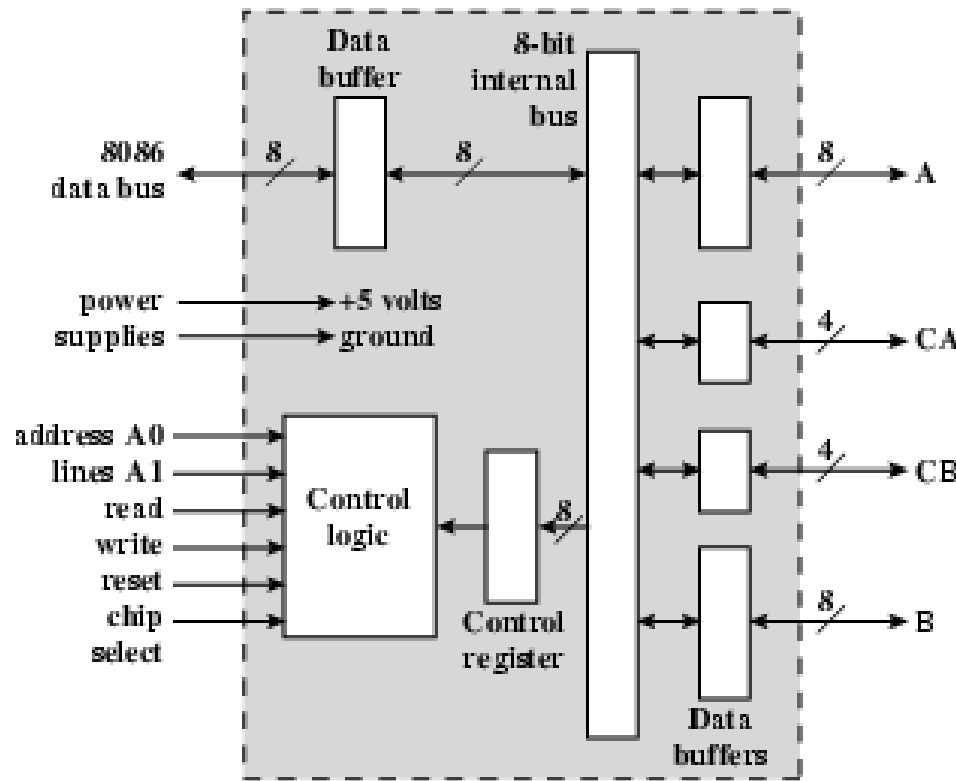
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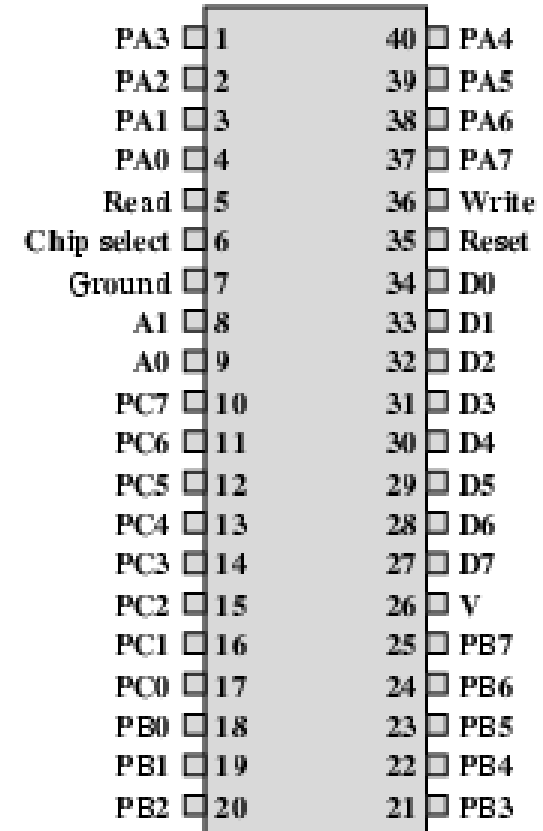
# Intel 82C55A

## Programmable Peripheral Interface

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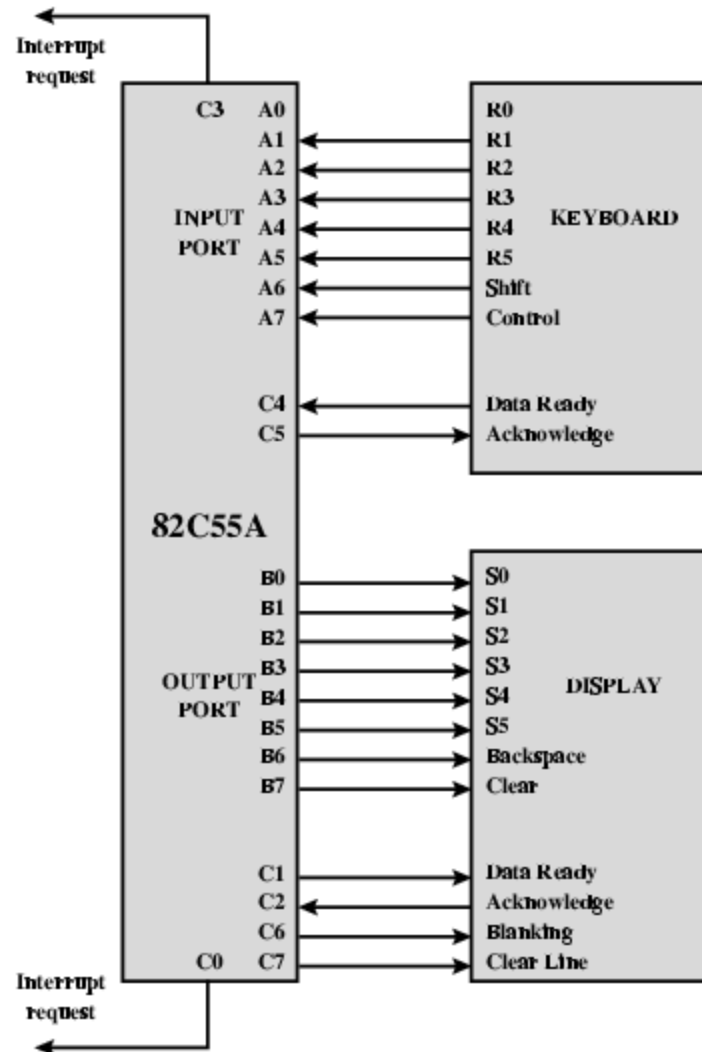
(a) Block diagram



(b) Pin layout



# Keyboard/Display Interfaces to 82C55A



# Direct Memory Access

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- Interrupt driven and programmed I/O require active CPU intervention
  - Transfer rate is limited
  - CPU is tied up
- DMA is the answer

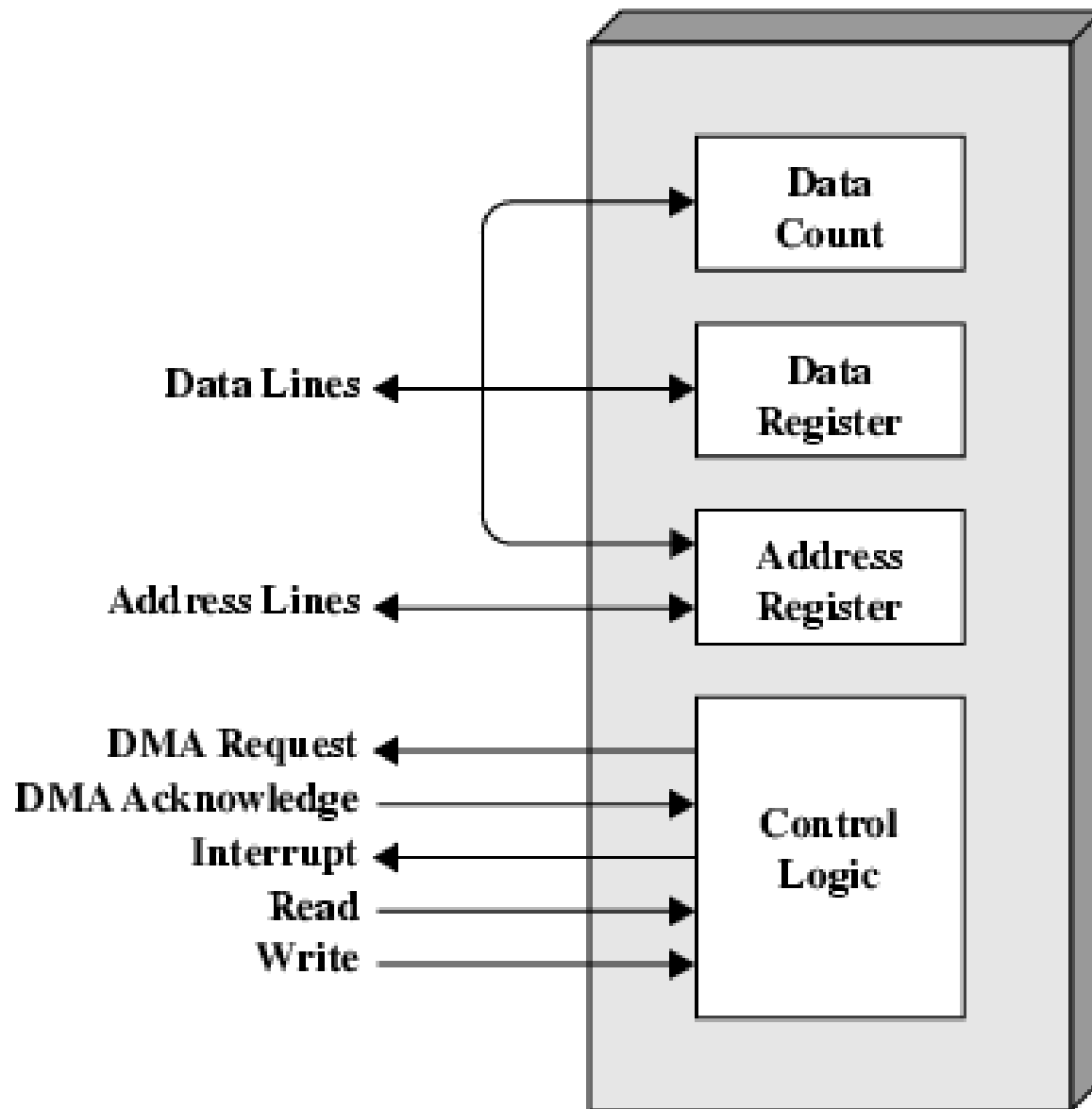
## DMA Function

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- Additional Module (hardware) on bus
- DMA controller takes over from CPU for I/O

# Typical DMA Module Diagram

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# DMA Operation

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- CPU tells DMA controller: -
  - Read/Write
  - Device address
  - Starting address of memory block for data
  - Amount of data to be transferred
- CPU carries on with other work
- DMA controller deals with transfer
- DMA controller sends interrupt when finished

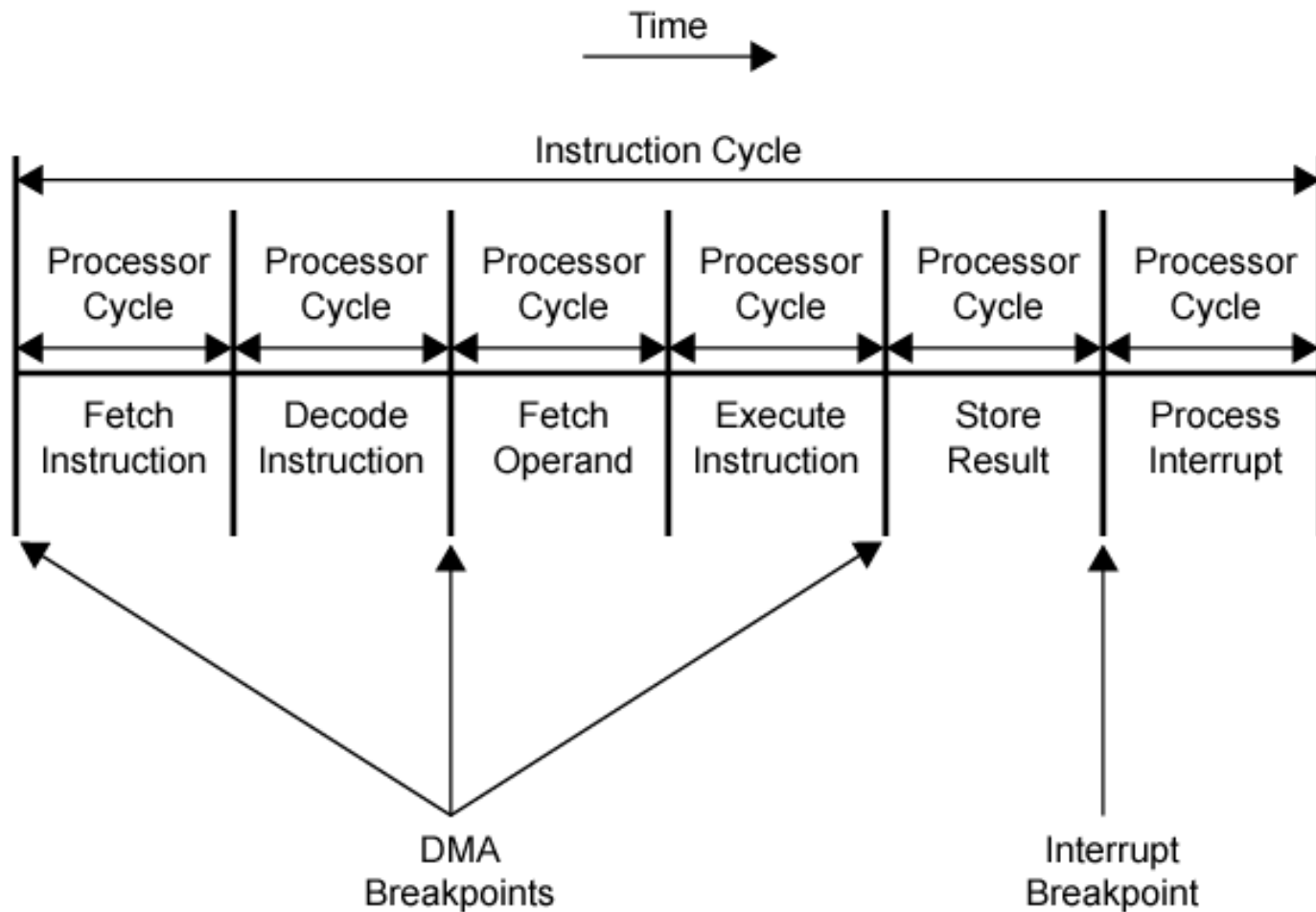
# DMA Transfer Cycle Stealing

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- DMA controller takes over bus for a cycle
- Transfer of one word of data
- Not an interrupt
  - CPU does not switch context
- CPU suspended just before it accesses bus
  - i.e. before an operand or data fetch or a data write
- Slows down CPU but not as much as CPU doing transfer

# DMA and Interrupt Breakpoints During an Instruction Cycle

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## Aside

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- What effect does caching memory have on DMA?
- What about on board cache?
- Hint: how much are the system buses available?



# DMA Configurations (1)

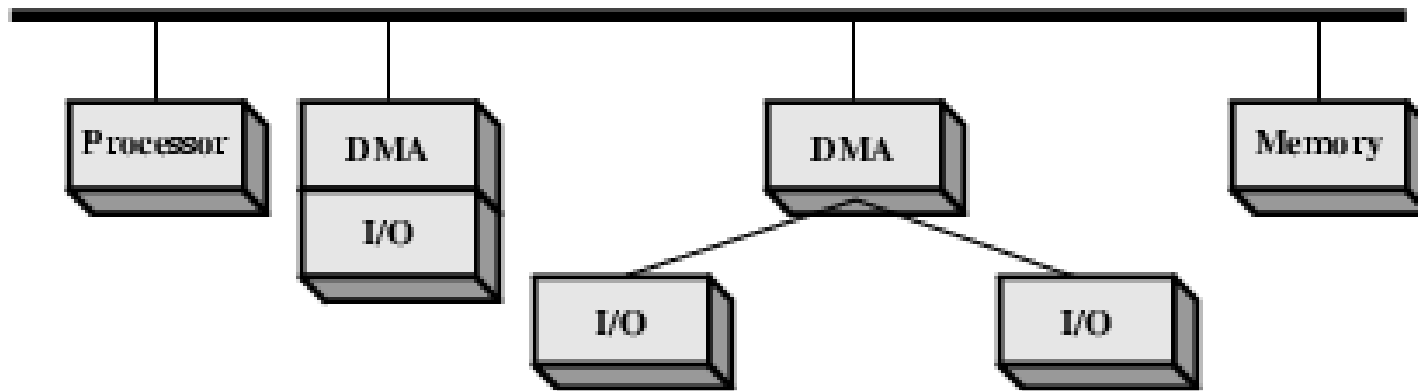
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- Single Bus, Detached DMA controller
- Each transfer uses bus twice
  - I/O to DMA then DMA to memory
- CPU is suspended twice

## DMA Configurations (2)

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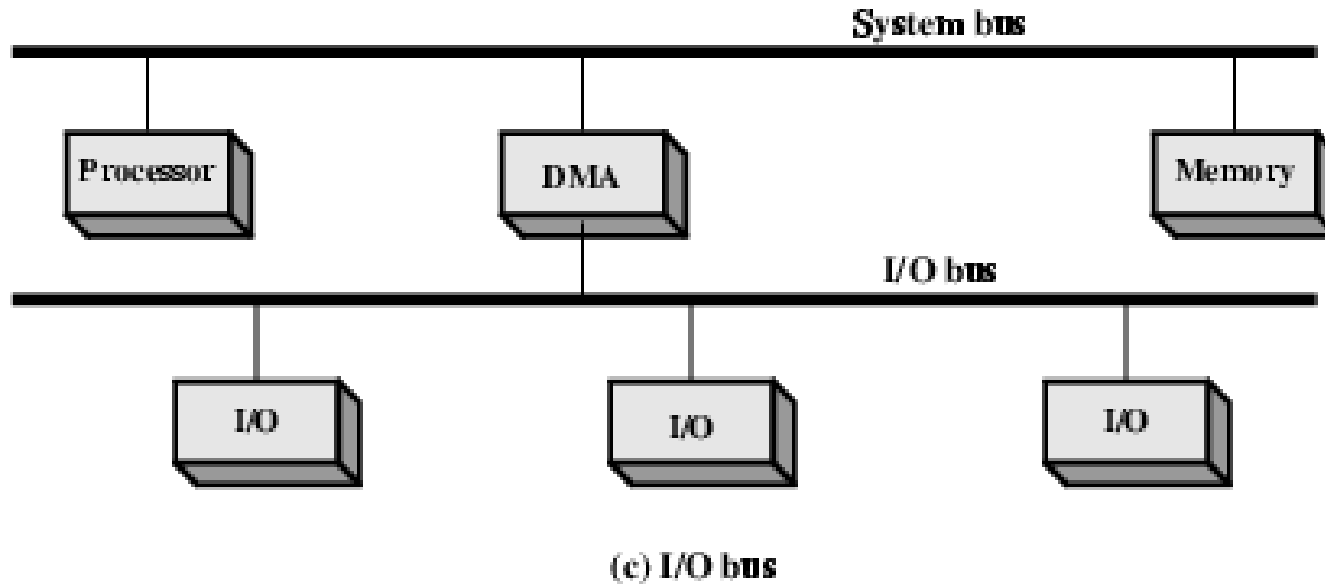


(b) Single-bus, Integrated DMA-I/O

- Single Bus, Integrated DMA controller
- Controller may support  $>1$  device
- Each transfer uses bus once
  - DMA to memory
- CPU is suspended once

## DMA Configurations (3)

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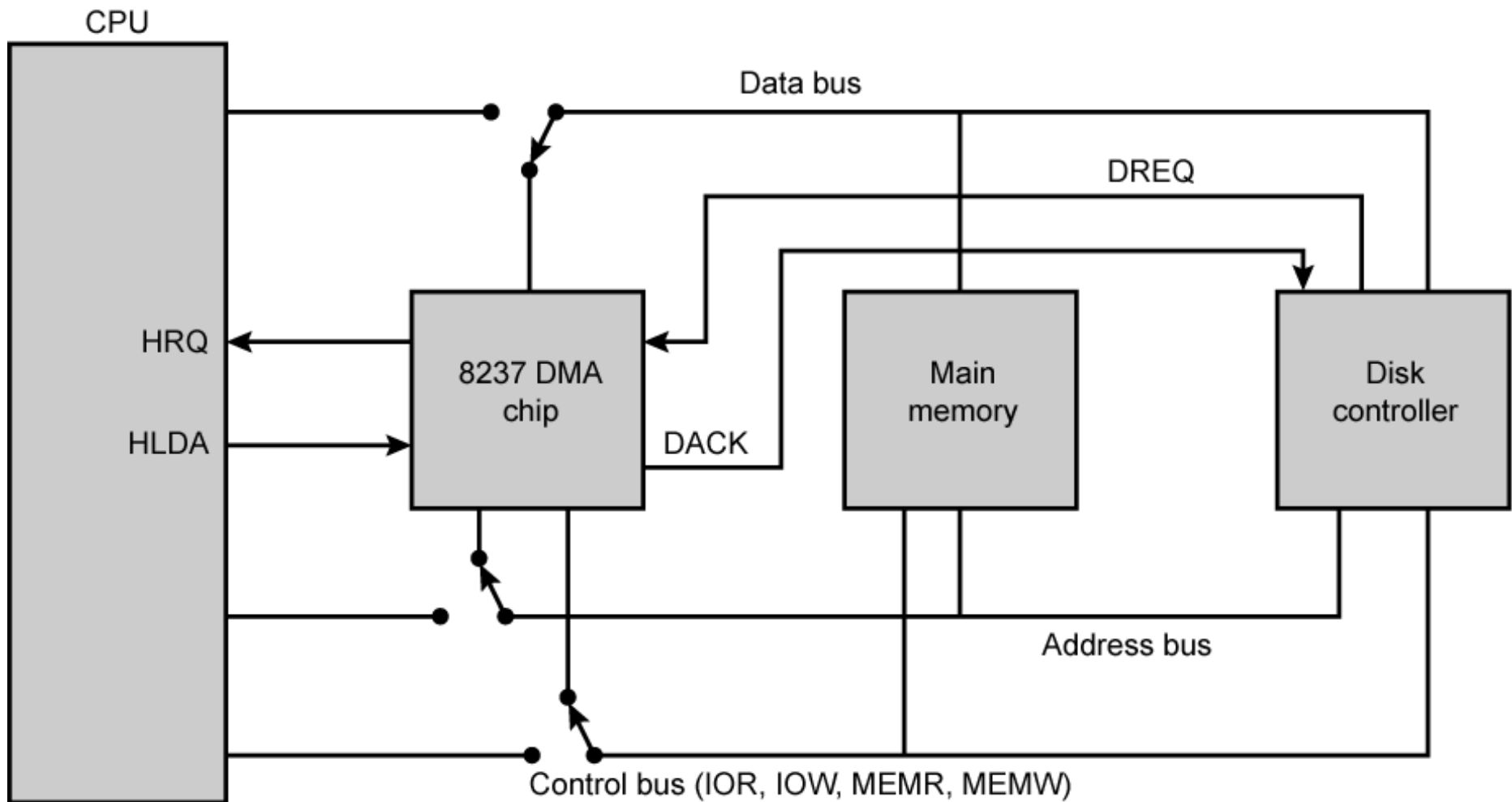
- Separate I/O Bus
- Bus supports all DMA enabled devices
- Each transfer uses bus once
  - DMA to memory
- CPU is suspended once

# Intel 8237A DMA Controller

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- Interfaces to 80x86 family and DRAM
- When DMA module needs buses it sends HOLD signal to processor
- CPU responds HLDA (hold acknowledge)
  - DMA module can use buses
- E.g. transfer data from memory to disk
  1. Device requests service of DMA by pulling DREQ (DMA request) high
  2. DMA puts high on HRQ (hold request),
  3. CPU finishes present bus cycle (not necessarily present instruction) and puts high on HDLA (hold acknowledge). HOLD remains active for duration of DMA
  4. DMA activates DACK (DMA acknowledge), telling device to start transfer
  5. DMA starts transfer by putting address of first byte on address bus and activating MEMR; it then activates IOW to write to peripheral. DMA decrements counter and increments address pointer. Repeat until count reaches zero
  6. DMA deactivates HRQ, giving bus back to CPU

# 8237 DMA Usage of Systems Bus



DACK = DMA acknowledge  
DREQ = DMA request  
HLDA = HOLD acknowledge  
HRQ = HOLD request

## Fly-By

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- While DMA using buses processor idle
- Processor using bus, DMA idle
  - Known as fly-by DMA controller
- Data does not pass through and is not stored in DMA chip
  - DMA only between I/O port and memory
  - Not between two I/O ports or two memory locations
- Can do memory to memory via register
- 8237 contains four DMA channels
  - Programmed independently
  - Any one active
  - Numbered 0, 1, 2, and 3

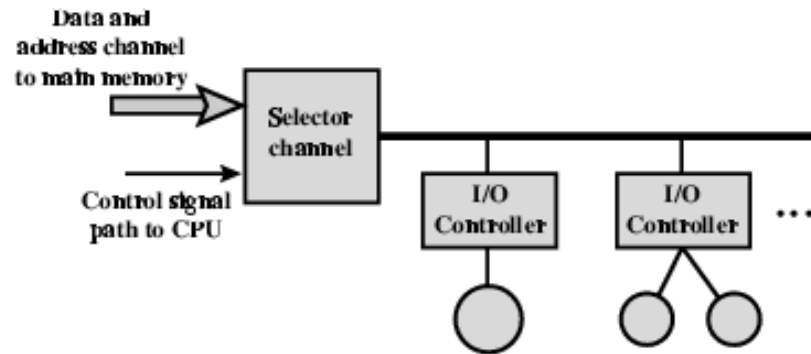
## I/O Channels

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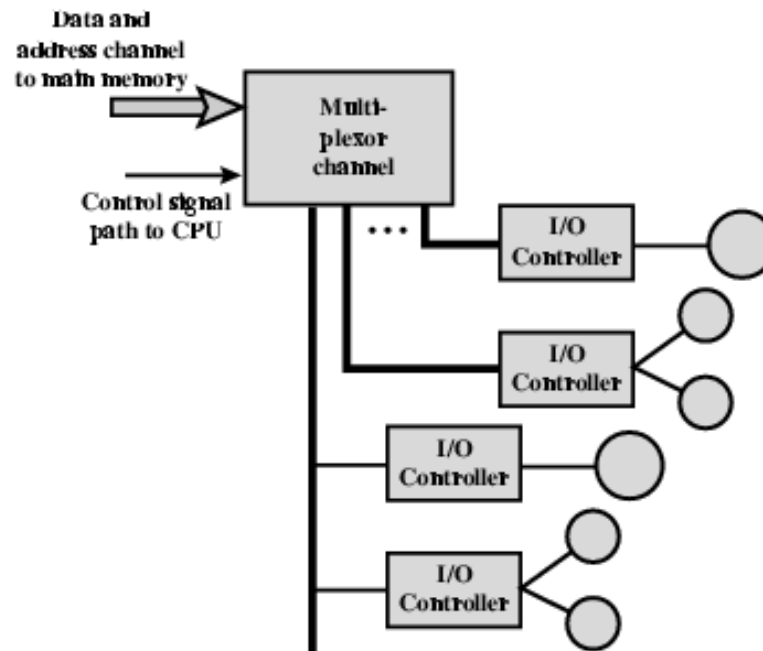
- I/O devices getting more sophisticated
- e.g. 3D graphics cards
- CPU instructs I/O controller to do transfer
- I/O controller does entire transfer
- Improves speed
  - Takes load off CPU
  - Dedicated processor is faster

# I/O Channel Architecture

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(a) Selector



(b) Multiplexor



# Interfacing

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- Connecting devices together
- Bit of wire?
- Dedicated processor/memory/buses?
- E.g. FireWire, InfiniBand

# IEEE 1394 FireWire

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- High performance serial bus
- Fast
- Low cost
- Easy to implement
- Also being used in digital cameras, VCRs and TV

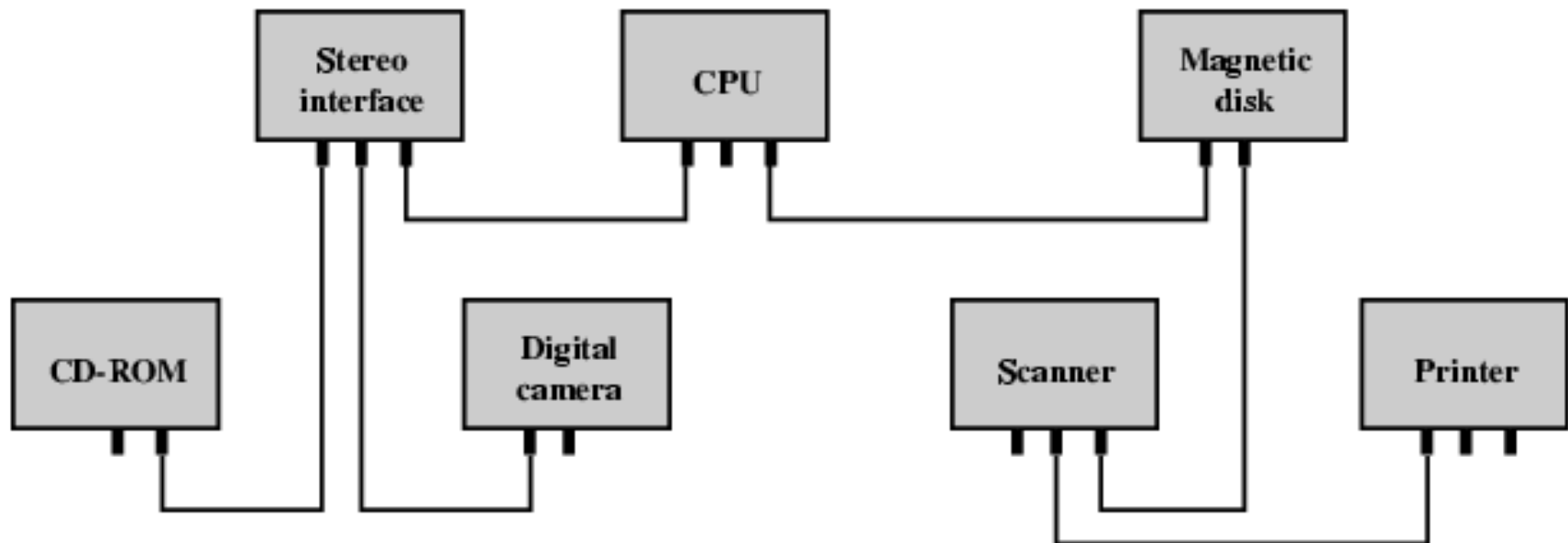
# FireWire Configuration

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- Daisy chain
- Up to 63 devices on single port
  - Really 64 of which one is the interface itself
- Up to 1022 buses can be connected with bridges
- Automatic configuration
- No bus terminators
- May be tree structure

# Simple FireWire Configuration

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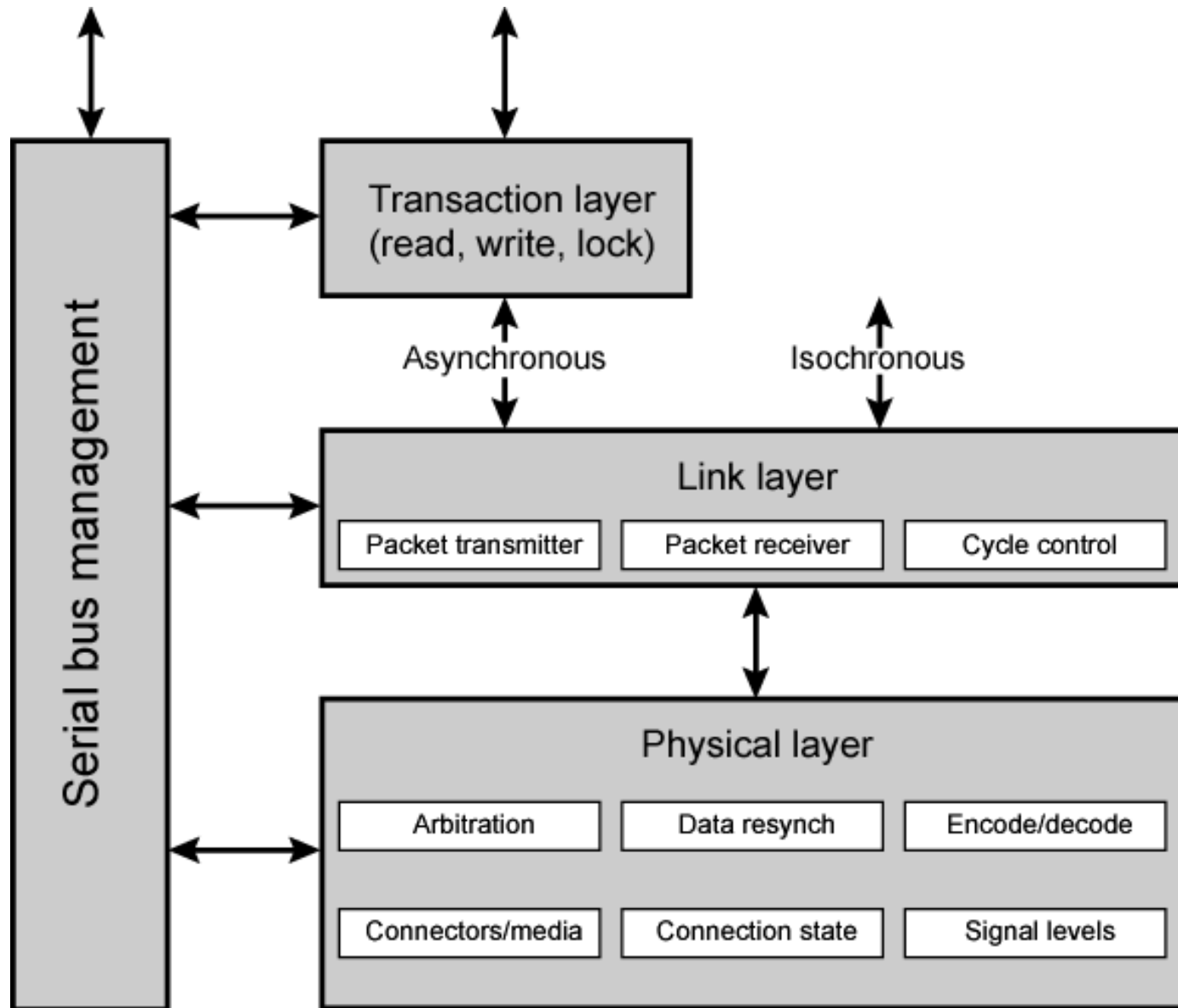
# FireWire 3 Layer Stack

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- Physical
  - Transmission medium, electrical and signaling characteristics
- Link
  - Transmission of data in packets
- Transaction
  - Request-response protocol

# FireWire Protocol Stack

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# FireWire - Physical Layer

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- Data rates from 25 to 400Mbps
- Two forms of arbitration
  - Based on tree structure
  - Root acts as arbiter
  - First come first served
  - Natural priority controls simultaneous requests
    - i.e. who is nearest to root
  - Fair arbitration
  - Urgent arbitration

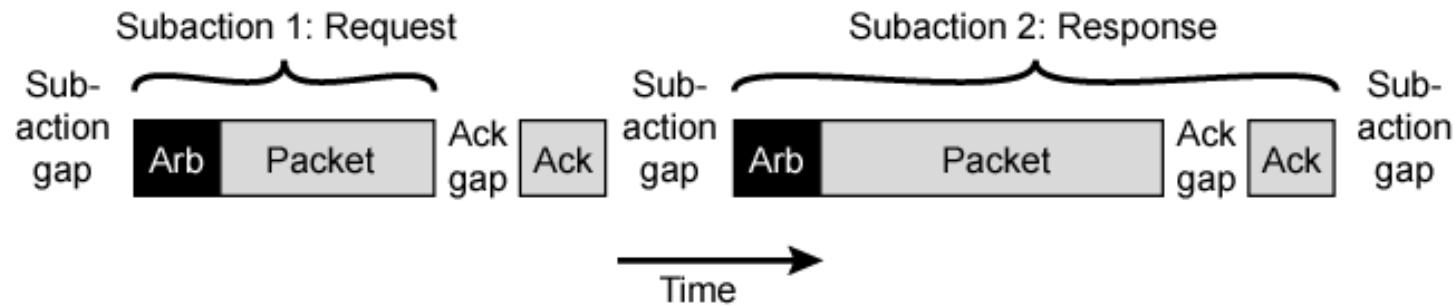
# FireWire - Link Layer

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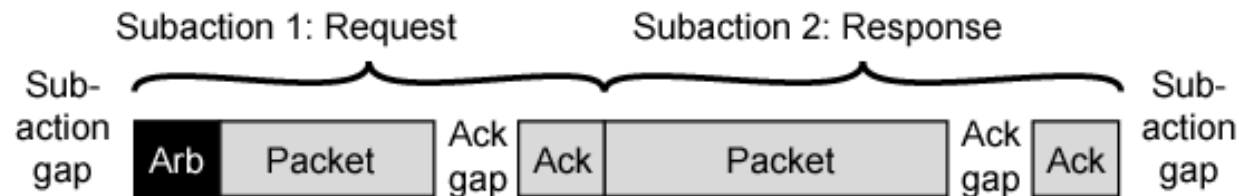
- Two transmission types
  - Asynchronous
    - Variable amount of data and several bytes of transaction data transferred as a packet
    - To explicit address
    - Acknowledgement returned
  - Isochronous
    - Variable amount of data in sequence of fixed size packets at regular intervals
    - Simplified addressing
    - No acknowledgement



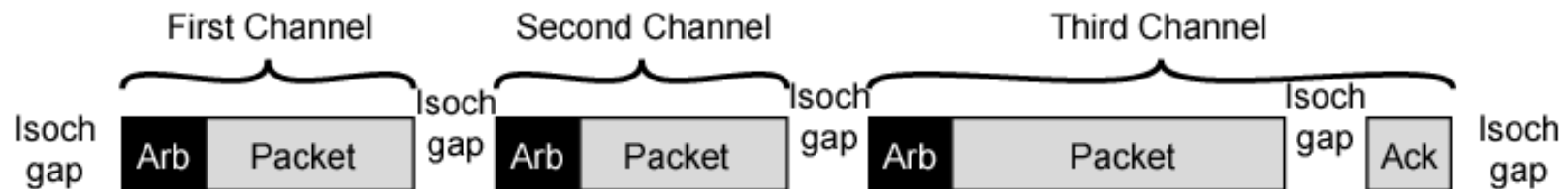
# FireWire Subactions



(a) Example asynchronous subaction



(b) Concatenated asynchronous subactions



(c) Example isochronous subactions

# InfiniBand

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- I/O specification aimed at high end servers
  - Merger of Future I/O (Cisco, HP, Compaq, IBM) and Next Generation I/O (Intel)
- Version 1 released early 2001
- Architecture and spec. for data flow between processor and intelligent I/O devices
- Intended to replace PCI in servers
- Increased capacity, expandability, flexibility

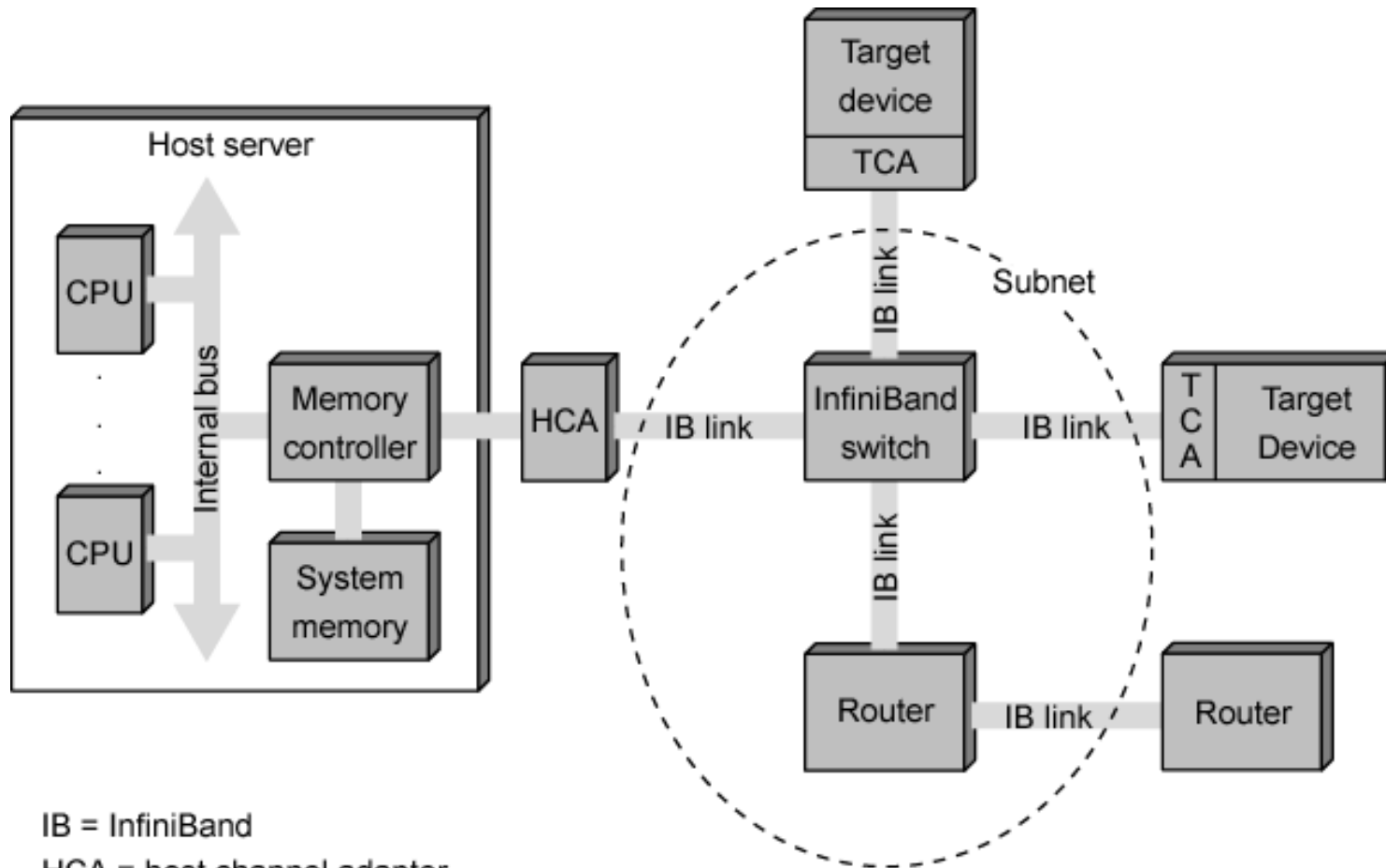
# InfiniBand Architecture

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- Remote storage, networking and connection between servers
- Attach servers, remote storage, network devices to central fabric of switches and links
- Greater server density
- Scalable data centre
- Independent nodes added as required
- I/O distance from server up to
  - 17m using copper
  - 300m multimode fibre optic
  - 10km single mode fibre
- Up to 30Gbps

# InfiniBand Switch Fabric

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IB = InfiniBand

HCA = host channel adapter

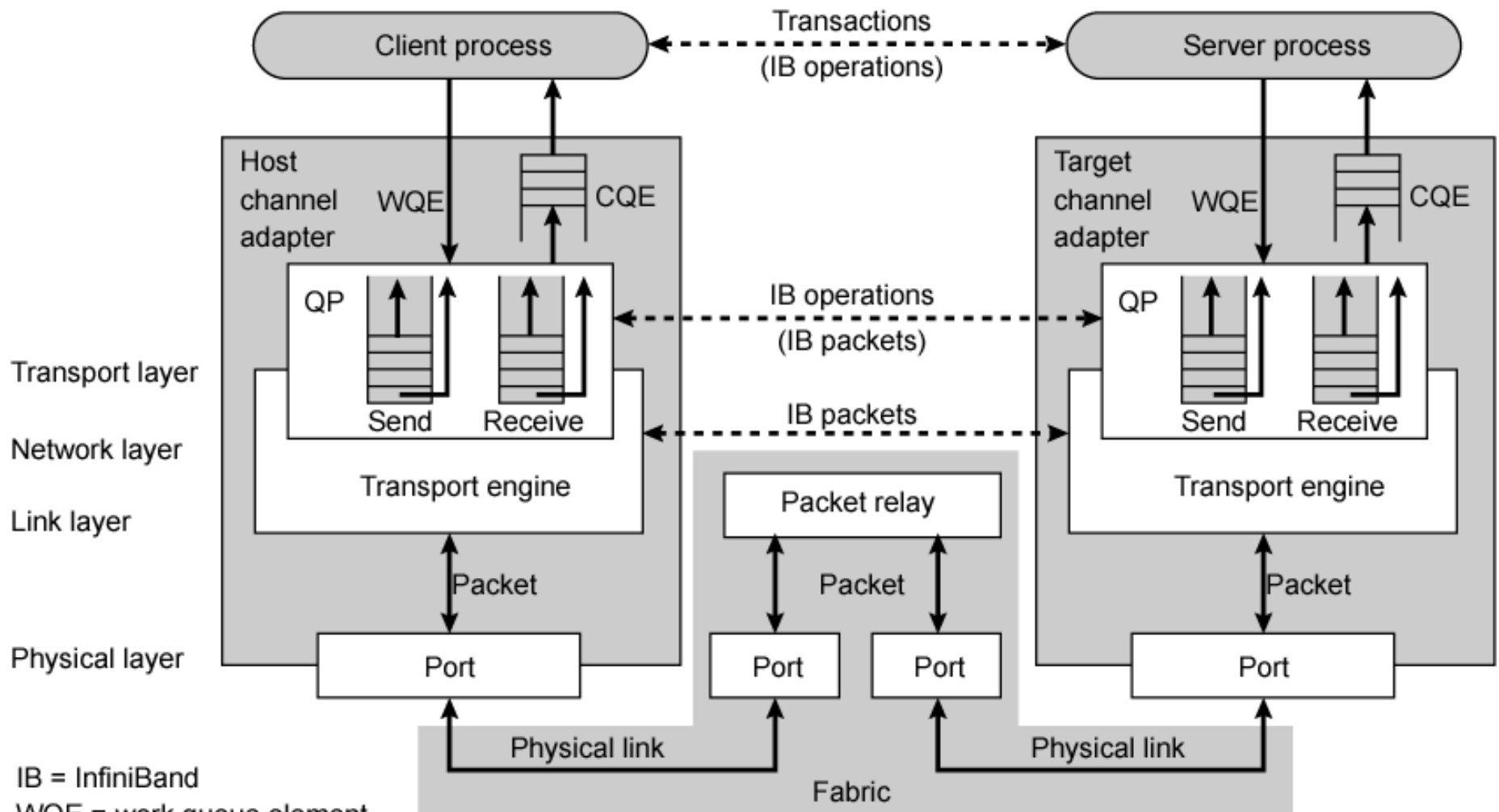
TCA = target channel adapter

## InfiniBand Operation

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- 16 logical channels (virtual lanes) per physical link
- One lane for management, rest for data
- Data in stream of packets
- Virtual lane dedicated temporarily to end to end transfer
- Switch maps traffic from incoming to outgoing lane

# InfiniBand Protocol Stack



IB = InfiniBand  
 WQE = work queue element  
 CQE = completion queue entry  
 QP = queue pair

## Foreground Reading

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- Check out Universal Serial Bus (USB)
- Compare with other communication standards e.g. Ethernet