



PCI-SIG® Architecture Overview

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What's all this PCI stuff anyway?

- Presentation will cover basic concepts and their evolution from PCI™ through PCI-X™ to PCI Express®
 - ✓ Specs written assuming designers have these key background concepts
 - ✓ High level overview of PCI, PCI-X, PCI Express, and I/O Virtualization
 - ✓ Brief description of compliance program

PCI Background



Revolutionary AND Evolutionary

■ PCI

✓ Revolutionary

- Plug and Play jumperless configuration (BARs)
- Unprecedented bandwidth
 - 32-bit / 33MHz – 133MB/sec
 - 64-bit / 66MHz – 533MB/sec
- Designed from day 1 for bus-mastering adapters

✓ Evolutionary

- System BIOS maps devices then operating systems boot and run without further knowledge of PCI
- PCI-aware O/S could gain improved functionality



Revolutionary AND Evolutionary

■ PCI-X

✓ Revolutionary

- Unprecedented bandwidth
 - Up to 1066MB/sec with 64-bit / 133MHz
- Registered bus protocol
 - Eased electrical timing requirements
- Brought split transactions into PCI “world”

✓ Evolutionary

- PCI compatible at hardware *AND* software levels
- PCI-X 266/533 added as “mid-life” performance bump
 - 2133MB/sec at PCI-X 266 and 4266MB/sec at PCI-X 533



Revolutionary AND Evolutionary

- PCI Express (aka PCIe®)

- ✓ Revolutionary

- Unprecedented bandwidth
 - x1: 500MB/sec in *EACH* direction
 - x16: 8000MB/sec in *EACH* direction
 - “Relaxed” electricals due to serial bus architecture
 - Point-to-point, low voltage, dual simplex with embedded clocking

- ✓ Evolutionary

- PCI compatible at software level
 - Configuration space, Power Management, etc
 - Of course, PCIe-aware O/S can get more functionality
 - Transaction layer familiar to PCI/PCI-X designers
 - System topology matches PCI/PCI-X
 - PCIe 2.0 doubled bandwidth from 250MB/s/lane to 500MB/s/lane
 - PCIe 3.0 will double again to 1GB/s/lane!

PCI Concepts



PCI Concepts

- Address spaces
 - ✓ Memory – 64-bit
 - ✓ I/O – 32-bit (non-burstable since PCI-X)
 - ✓ Configuration (“Config”) – Bus/Device/Function

- Key configuration space regs/concepts
 - ✓ Base Address Registers (BARs)
 - 64-bit vs 32-bit addressing
 - ✓ Linked list of capabilities

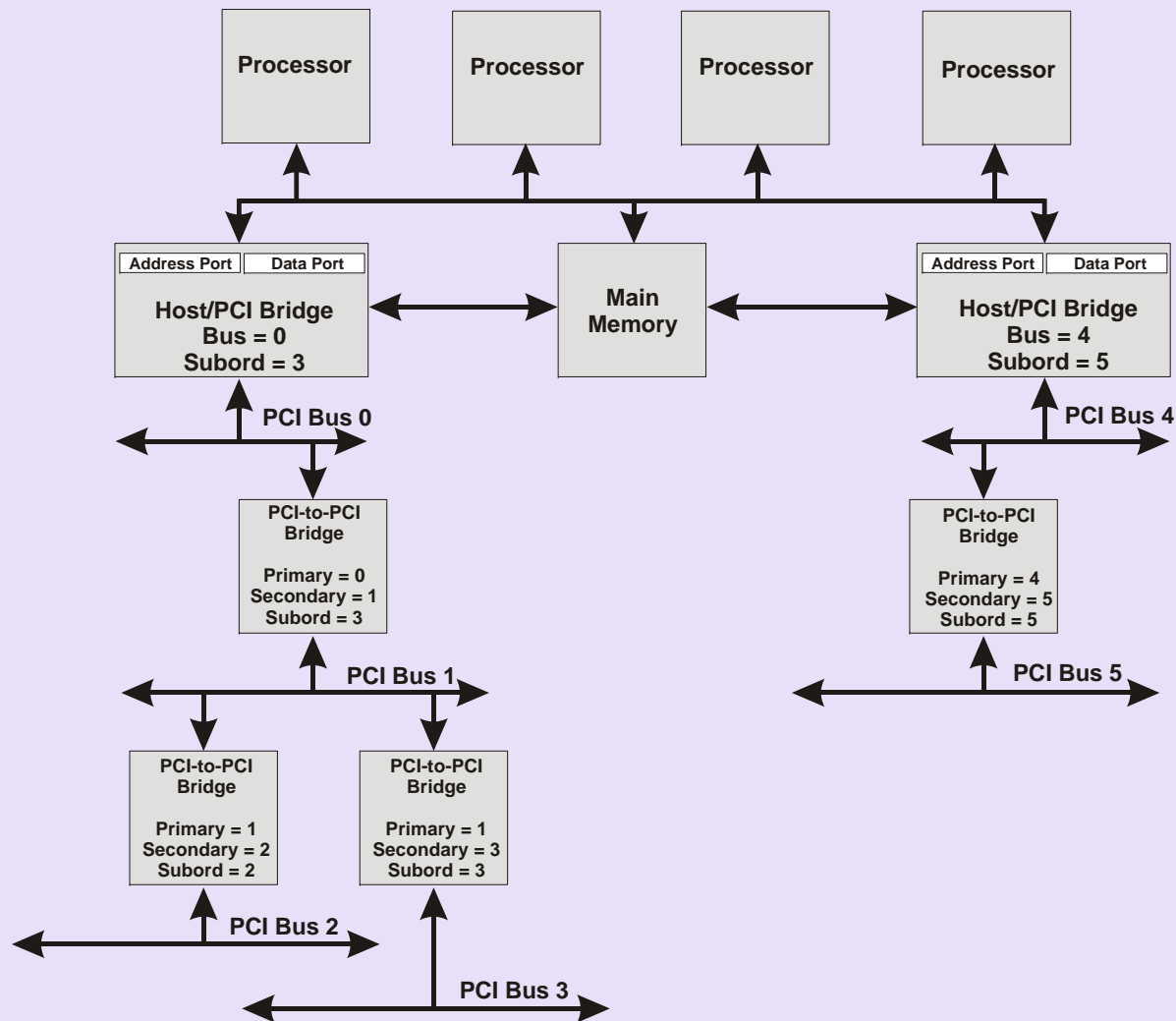
Address Spaces – Memory & I/O

- Memory space mapped cleanly to CPU semantics
 - ✓ 32-bits of address space initially
 - ✓ 64-bits introduced via Dual-Address Cycles (DAC)
 - Extra clock of address time on PCI/PCI-X
 - 4DWORD header in PCI Express
 - ✓ Burstable
- I/O space mapped cleanly to CPU semantics
 - ✓ 32-bits of address space
 - Actually much larger than CPUs of the time
 - ✓ Non-burstable
 - Most PCI implementations didn't support
 - PCI-X codified
 - Carries forward to PCI Express

Address Spaces – Configuration

- Configuration space???
 - ✓ Allows control of devices' address decodes without conflict
 - ✓ No conceptual mapping to CPU address space
 - Memory-based access mechanisms introduced with PCI-X and PCIe
 - ✓ Bus / Device / Function (aka BDF) form hierarchy-based address
 - “Functions” allow multiple, logically independent agents in one physical device.
 - E.g. combination SCSI + Ethernet device
 - 256 bytes or 4K bytes of configuration space per device
 - PCI/PCI-X bridges form hierarchy
 - PCIe switches form hierarchy
 - Look like PCI-PCI bridges to software
 - ✓ “Type 0” and “Type 1” configuration cycles
 - Type 0: to same bus segment
 - Type 1: to another bus segment

Configuration Space (cont'd)





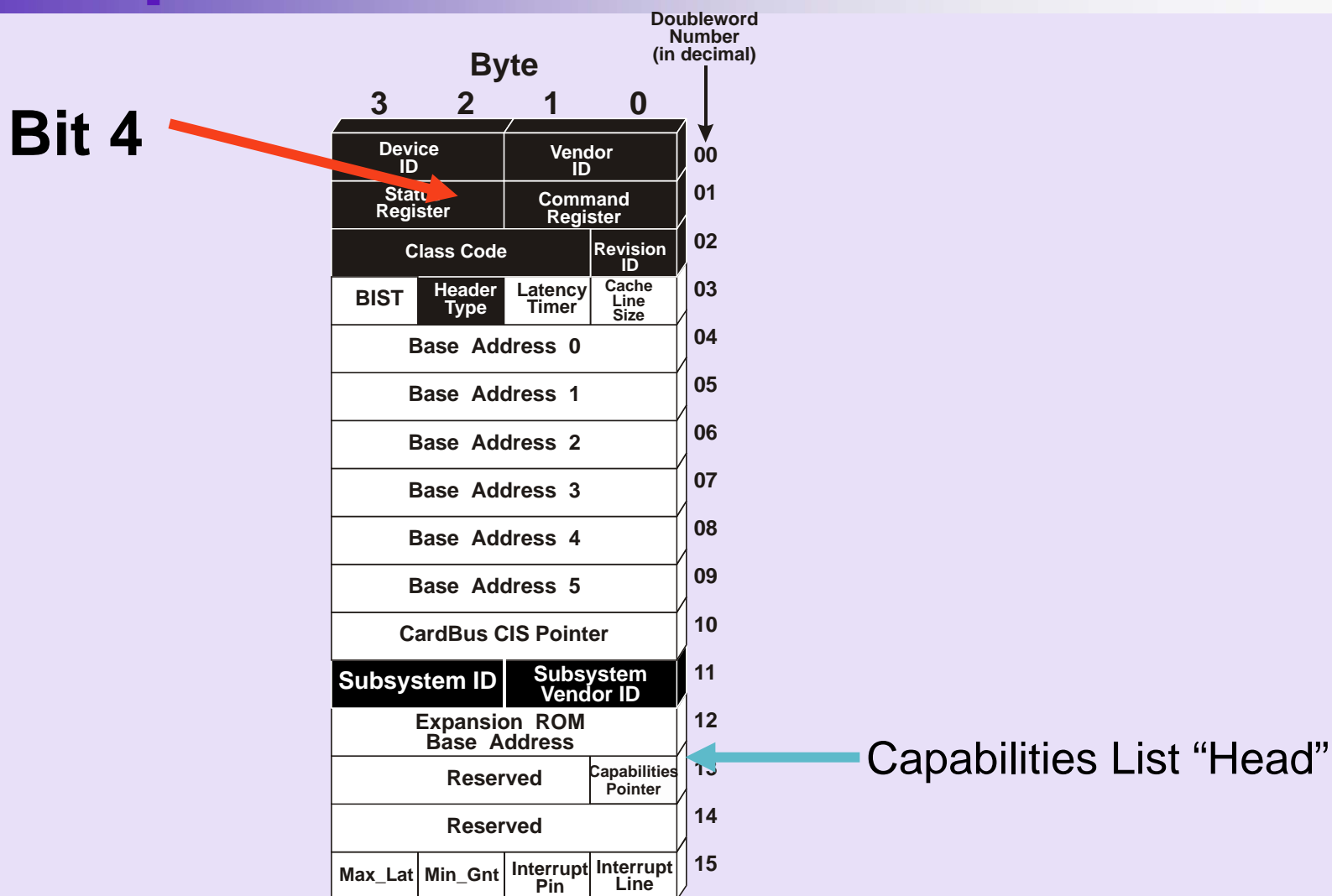
Using Configuration Space

- Device Identification
 - ✓ VendorID: PCI-SIG assigned
 - ✓ DeviceID: Vendor self-assigned
 - ✓ Subsystem VendorID: PCI-SIG
 - ✓ Subsystem DeviceID: Vendor
- Address Decode controls
 - ✓ Software reads/writes BARs to determine required size and maps appropriately
 - ✓ Memory, I/O, and bus-master enables
- Other bus-oriented controls

Byte				Doubleword Number (in decimal)
3	2	1	0	↓
Device ID		Vendor ID		00
Status Register		Command Register		01
Class Code			Revision ID	02
BIST	Header Type	Latency Timer	Cache Line Size	03
Base Address 0				04
Base Address 1				05
Base Address 2				06
Base Address 3				07
Base Address 4				08
Base Address 5				09
CardBus CIS Pointer				10
Subsystem ID		Subsystem Vendor ID		11
Expansion ROM Base Address				12
Reserved			Capabilities Pointer	13
Reserved				14
Max_Lat	Min_Gnt	Interrupt Pin	Interrupt Line	15



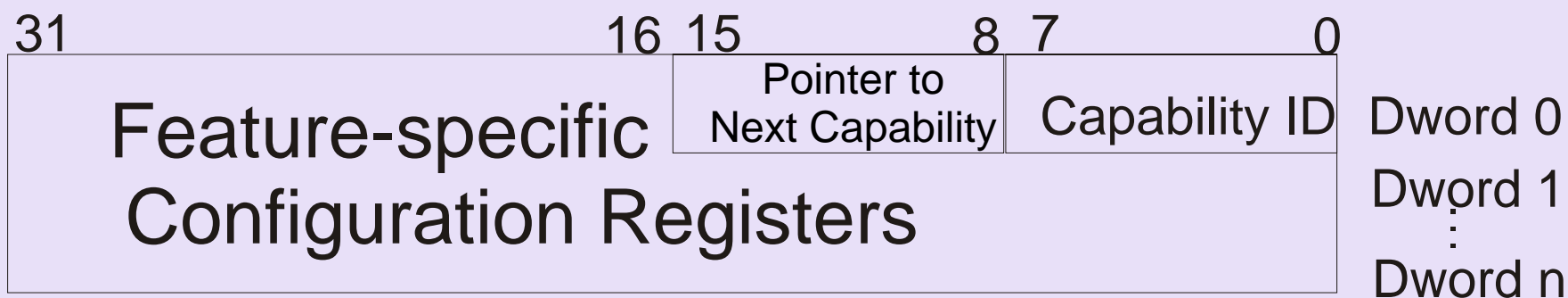
Using Configuration Space – Capabilities List





Using Configuration Space – Capabilities List (cont'd)

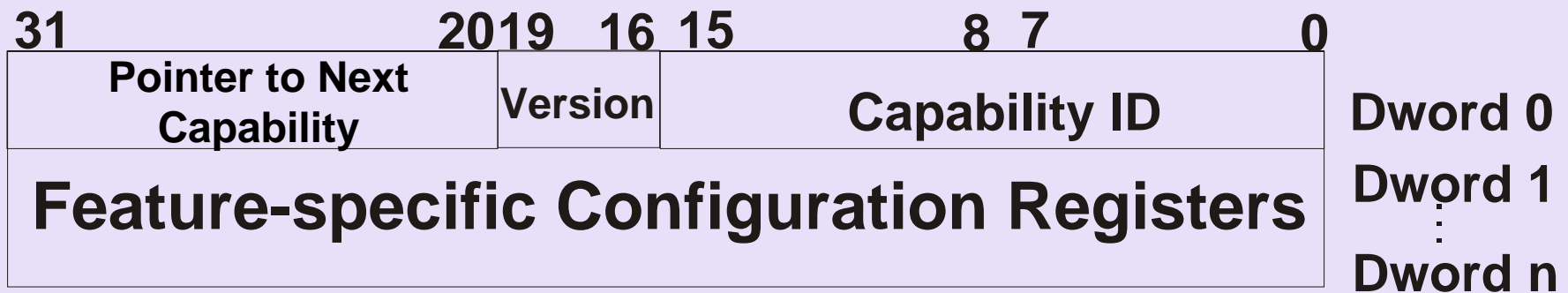
- Linked list
 - ✓ Follow the list! Cannot assume fixed location of any given feature in any given device
 - ✓ Features defined in their related specs:
 - PCI-X
 - PCIe
 - PCI Power Management
 - Etc...





Using Configuration Space – Extended Capabilities List

- PCI Express only
- Linked list
 - ✓ Follow the list! Cannot assume fixed location of any given feature in any given device
 - ✓ First entry in list is *always* at 100h
 - ✓ Features defined in PCI Express specification



Interrupts

- PCI introduced INTA#, INTB#, INTC#, INTD# - collectively referred to as INTx
 - ✓ Level sensitive
 - ✓ Decoupled device from CPU interrupt
 - ✓ System controlled INTx to CPU interrupt mapping
 - ✓ Configuration registers
 - report A/B/C/D
 - programmed with CPU interrupt number
- PCI Express mimics this via “virtual wire” messages
 - ✓ Assert_INTx and Deassert_INTx



What are MSI and MSI-X?

- Memory Write replaces previous interrupt semantics
 - ✓ PCI and PCI-X devices stop asserting INTA, INTB, INTC, INTD once MSI or MSI-X mode is enabled
 - ✓ PCI Express devices stop sending Assert_INTx and Deassert_INTx TLPs once MSI or MSI-X mode is enabled
- NOTE: *Boot devices* and any device intended for a non-MSI operating system generally must still support the appropriate INTx signaling!

MSI vs MSI-X

- MSI uses one address with a variable data value indicating which “vector” is asserting
- MSI-X uses a table of independent address and data pairs for each “vector”
 - ✓ Allows software to control aliasing (when fewer vectors are allocated than requested)
 - ✓ Table size supports more vectors than MSI structure allowed

PCI-X Explained



What is PCI-X?

- “PCI-X is high-performance backward compatible PCI”
 - ✓ PCI-X uses the same PCI architecture
 - ✓ PCI-X leverages the same base protocols as PCI
 - ✓ PCI-X leverages the same BIOS as PCI
 - ✓ PCI-X uses the same connector as PCI.
 - ✓ PCI-X and PCI products are interoperable
 - ✓ PCI-X uses same software driver models as PCI
- PCI-X is faster PCI
 - ✓ PCI-X 533 is up to 32 times faster than the original version of PCI
 - ✓ PCI-X protocol is more efficient than conventional PCI



PCI-X Modes and Speeds



Mode 1



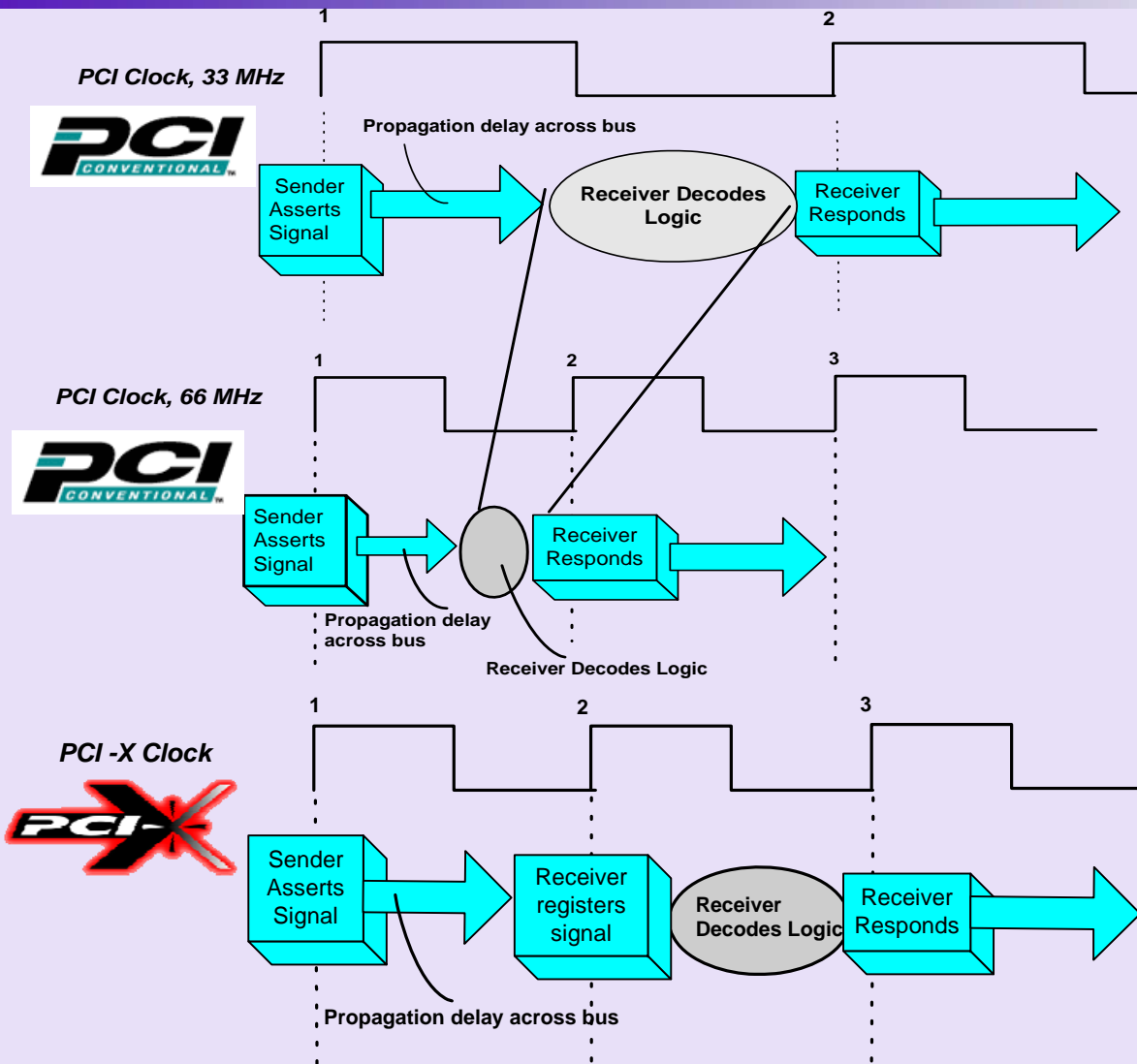
Mode 2

Mode	V _{I/O}	64-Bit		32-Bit		16-Bit	Error Prot	Conf Bytes	DIM
		Slots*	MB/s	Slots*	MB/s				
PCI 33	5V/3.3V		266		133	N/A	par	256	N/A
PCI 66	3.3V		533		266	N/A	par	256	N/A
PCI-X 66	3.3V		533		266	N/A	par or ECC	256	yes
PCI-X 133 (operating at 100 MHz)	3.3V		800		400	N/A	par or ECC	256	yes
PCI-X 133	3.3V		1066		533	N/A	par or ECC	256	yes
PCI-X 266	1.5V		2133		1066	533	ECC	4K	yes
PCI-X 533	1.5V		4266		2133	1066	ECC	4K	yes

* For lower bus speeds, # slots / bus is implementation choice to share bandwidth



Registered Bus Protocol



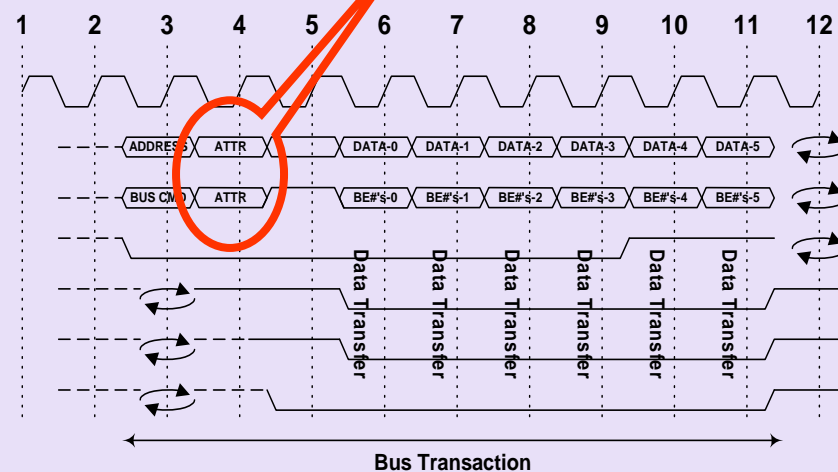
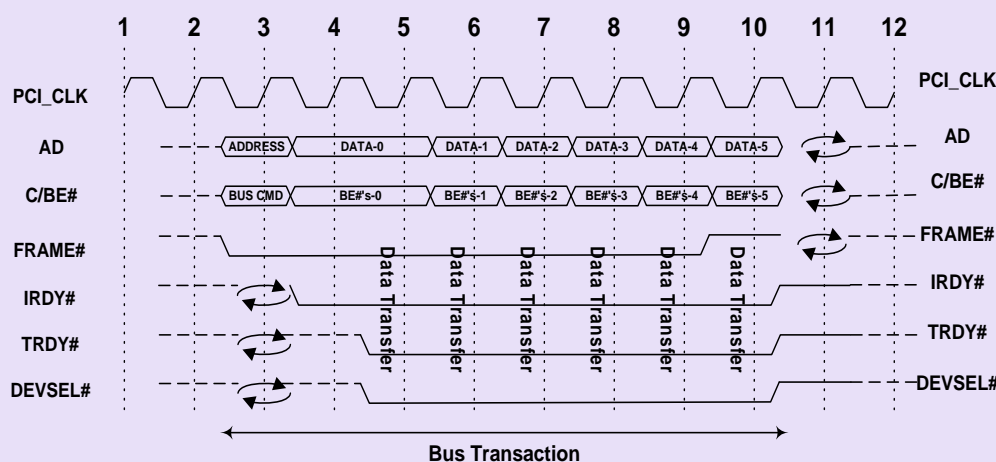
- PCI @ 33MHz
 - ✓ 30 ns period
 - ✓ 7 ns setup time
- PCI @ 66MHz
 - ✓ 15 ns period
 - ✓ 3ns setup time
- PCI-X registered protocol allocates a full clock period for logic decision
 - ✓ @ 66MHz - 15ns
 - ✓ @ 133MHz - 7.5ns



PCI 2.x/3.0 vs. PCI-X Mode 1

- Same bus and control signals
- Evolutionary protocol changes
- Clock frequency up to 133 MHz

New “Attribute”
phase for
enhanced features

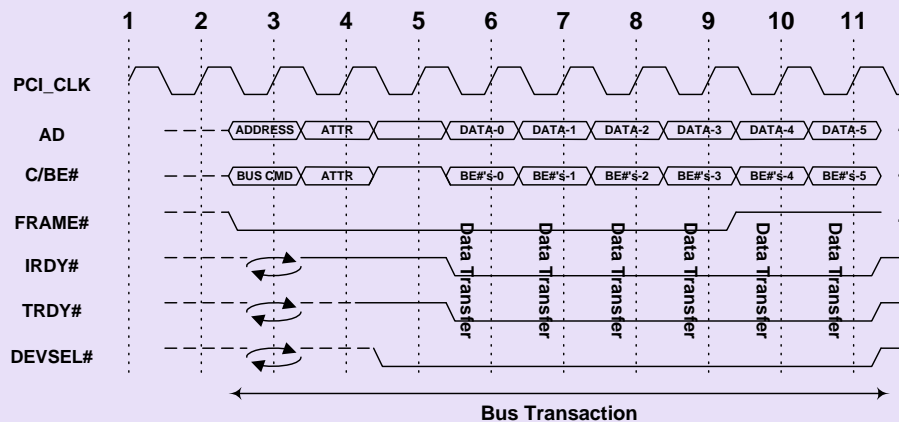


(Common clock)

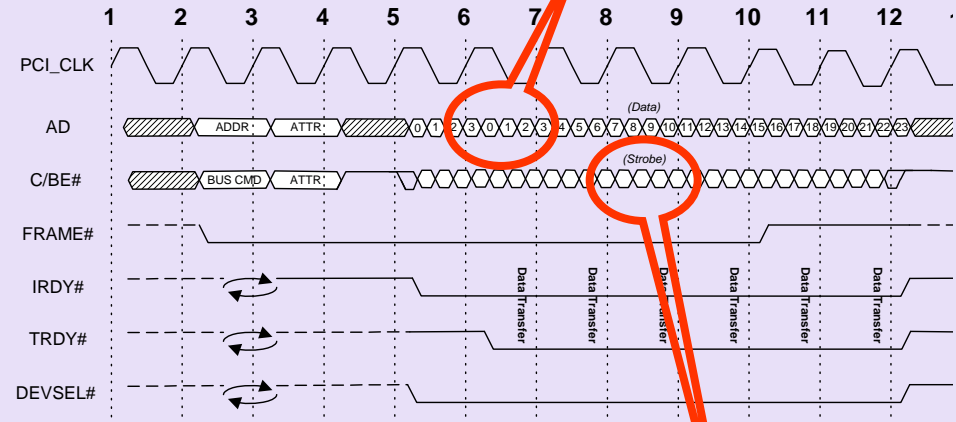


PCI-X 66/133 (Mode 1) vs. PCI-X 266/533 (Mode 2)

- Same bus and control signals
- PCI-X 266 moves 2x the data
PCI-X 533 moves 4x the data
- Clock frequency up to 133 MHz



PCI-X 66/133 (Mode 1)



PCI-X 533 (Mode 2)

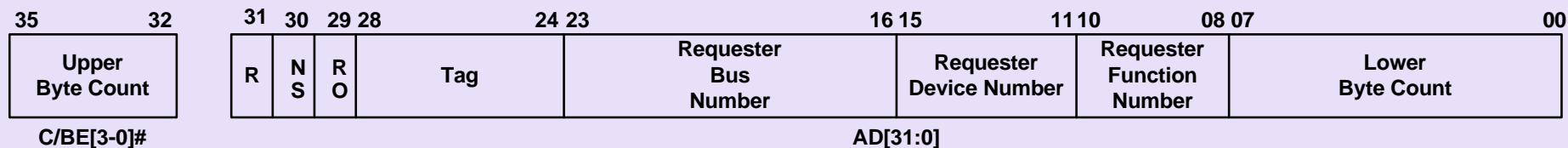
4 transfers per
clock cycle

source-
synchronous
data strobes
share C/BE pins

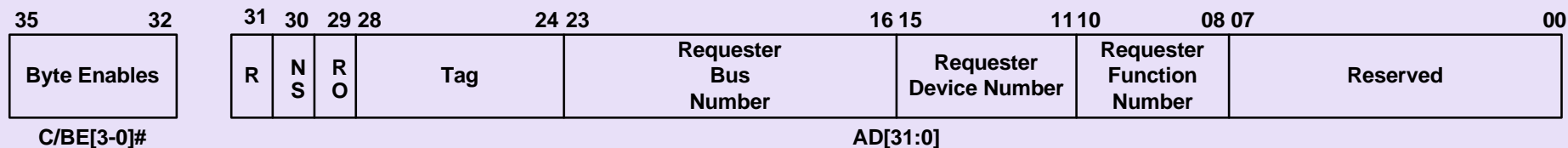


Transaction Attributes

Requester Attributes for Burst Transactions



Requester Attributes for DWORD Transactions



RO -- Relax ordering

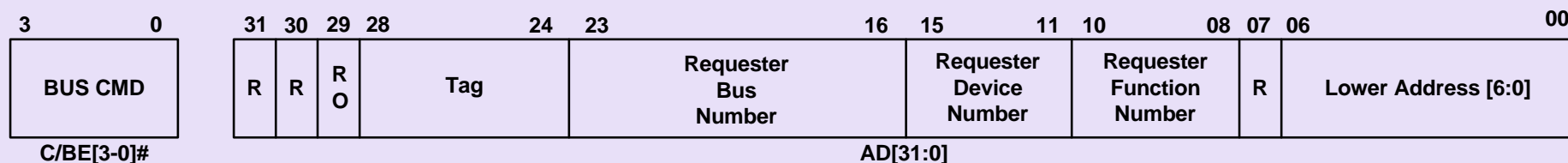
NS -- No Snoop

R -- Reserved



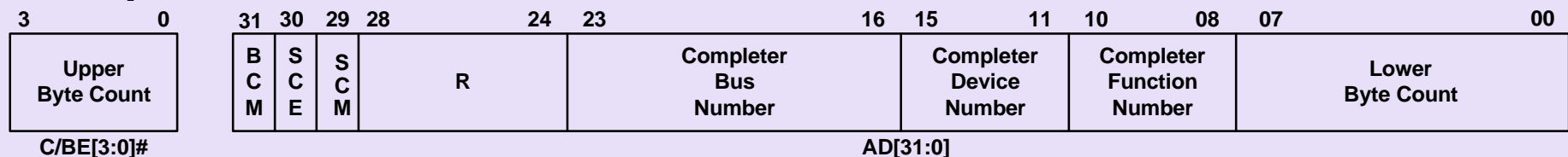
Transaction Attributes

Split Completion Address



RO -- Relaxed ordering

Completer Attributes



SCM -- Split Completion Message

SCE -- Split Completion Error

BCM -- Byte Count Modified

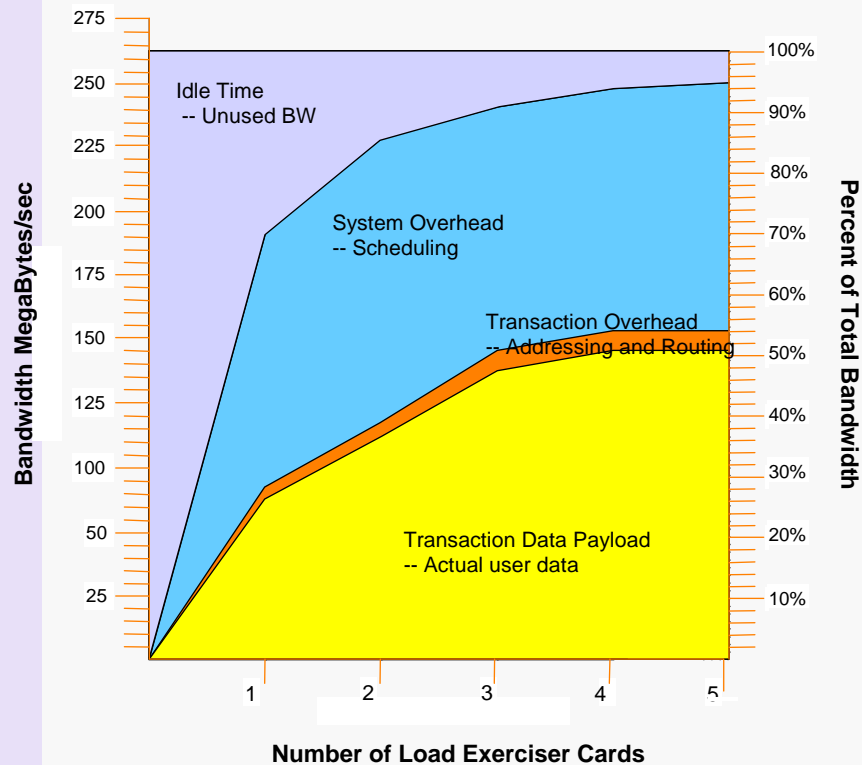
R -- Reserved

Split Transactions

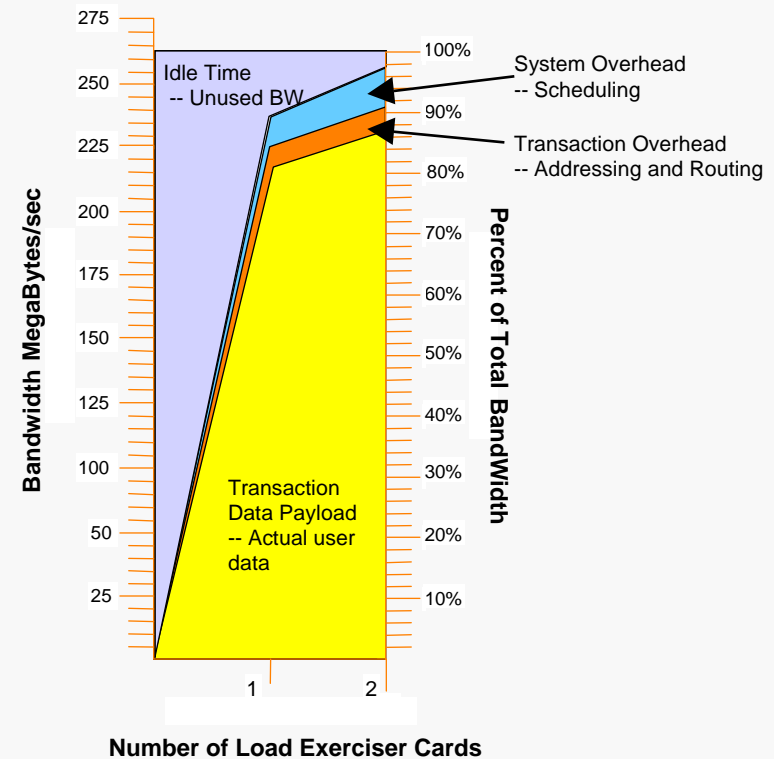
- Bus efficiency of Read almost as good as Write
- Split Completion routed back to requester across bridges using initiator's number and bus number
- Split Transaction components
 - ✓ Step 1. Requester requests bus and arbiter grants bus
 - ✓ Step 2. Requester initiates transaction
 - ✓ Step 3. Target (completer) communicates intent with new target termination, Split Response
 - ✓ Step 4. Completer executes transaction internally
 - ✓ Step 5. Completer requests bus and arbiter grants bus
 - ✓ Step 6. Completer initiates Split Completion

Efficient PCI-X Protocol

Bandwidth Usage with Conventional PCI Protocols



Bandwidth Usage with PCI-X Protocols, included in PCI-X 2.0



The PCI-X protocol is more efficient than traditional PCI.

PCI Express Overview



PCIe Architecture Features

■ PCI Compatibility

- ✓ Configuration and PCI software driver model
- ✓ PCI power management software compatible

■ Performance

- ✓ Scalable frequency (2.5-5GT/s)
- ✓ Scalable width (x1, x4, x8, x16)
- ✓ Low latency and highest utilization (Bandwidth/pin)

■ Physical Interface

- ✓ Point-to-point, dual-simplex
- ✓ Differential low voltage signaling
- ✓ Embedded clocking
- ✓ Supports connectors, modules, cables

■ Protocol

- ✓ Fully packetized split-transaction
- ✓ Credit-based flow control
- ✓ Hierarchical topology support
- ✓ Virtual channel mechanism

■ Advanced Capabilities

- ✓ CRC-based data integrity, hot plug, error logging

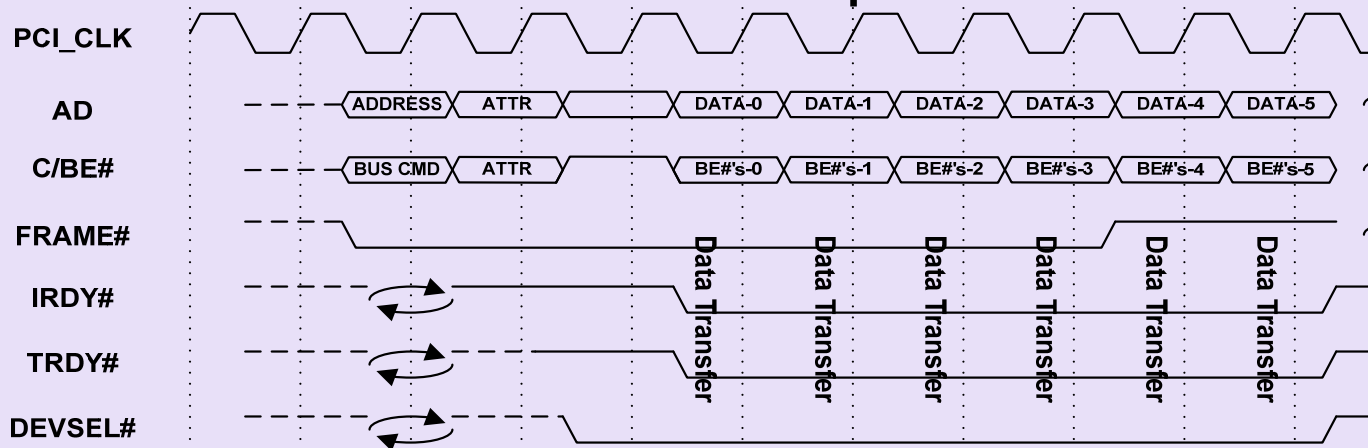
■ Enhanced Configuration Space

- ✓ Extensions and bridges into other architectures



PCIe Protocol Overview

- PCI-X Address/Attribute phases:

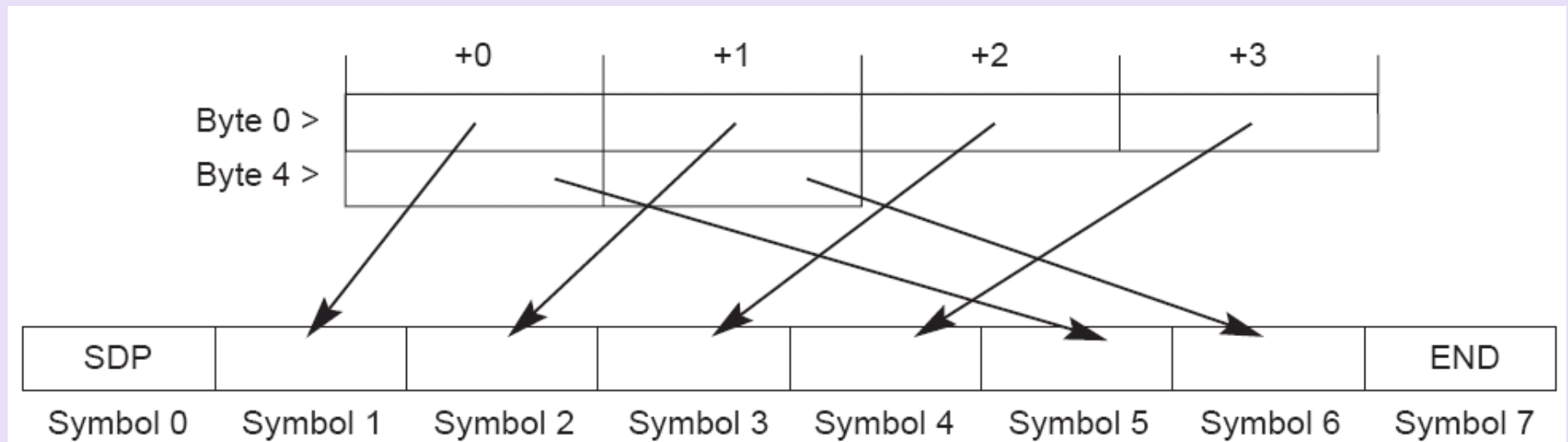


- Evolved into the PCIe Packet Header:

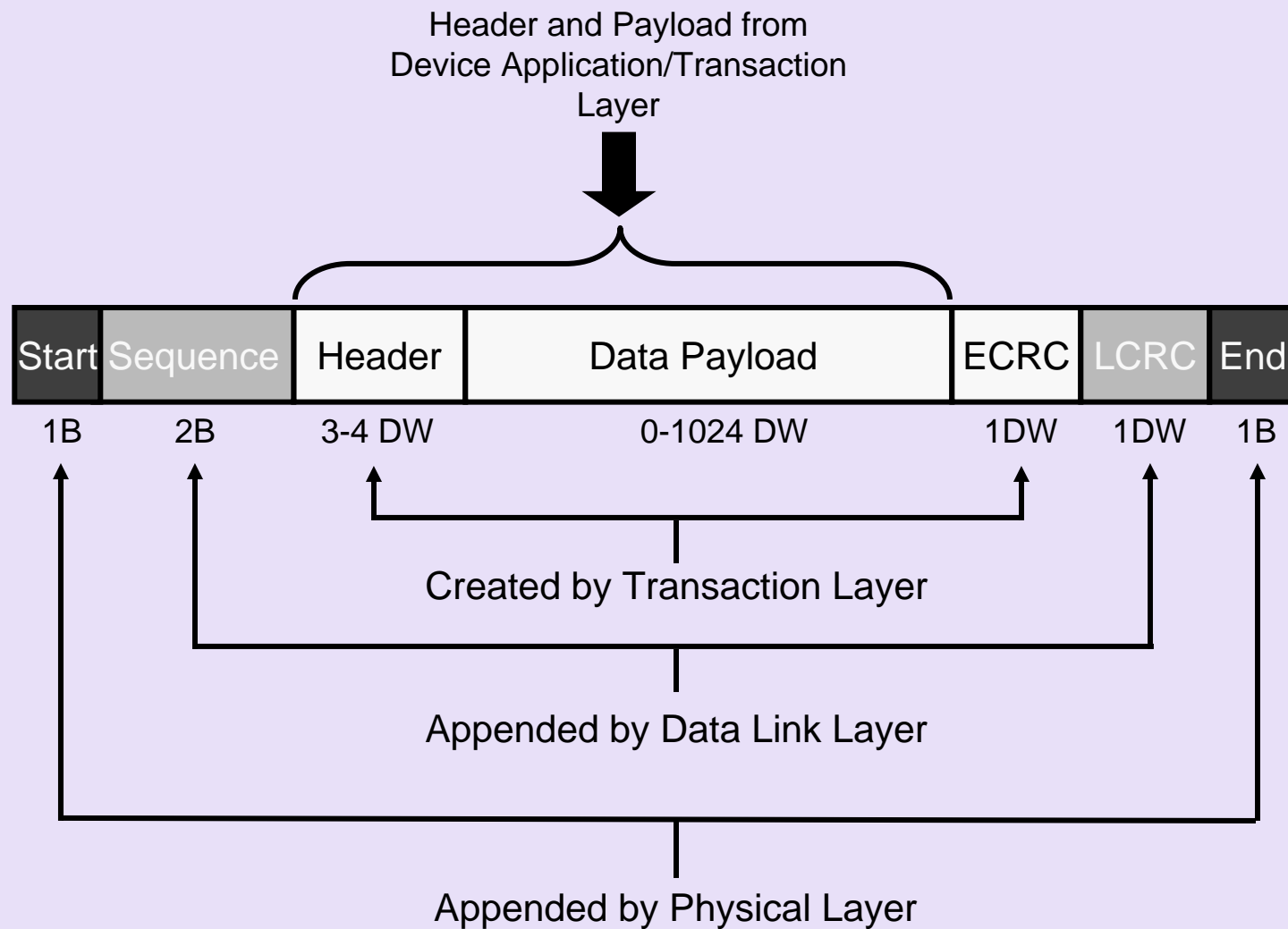
	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0
Byte 0 >	R	Fmt x	1	Type				R	TC		Reserved				T D	E P	Attr		R	Length												
Byte 4 >	Requester ID																Tag						Last DW BE				1st DW BE					
Byte 8 >	Address[63:32]																															
Byte 12 >	Address[31:2]																														R	

PCIe Protocol Overview

- The packet bytes get converted to 8b/10b and serialized



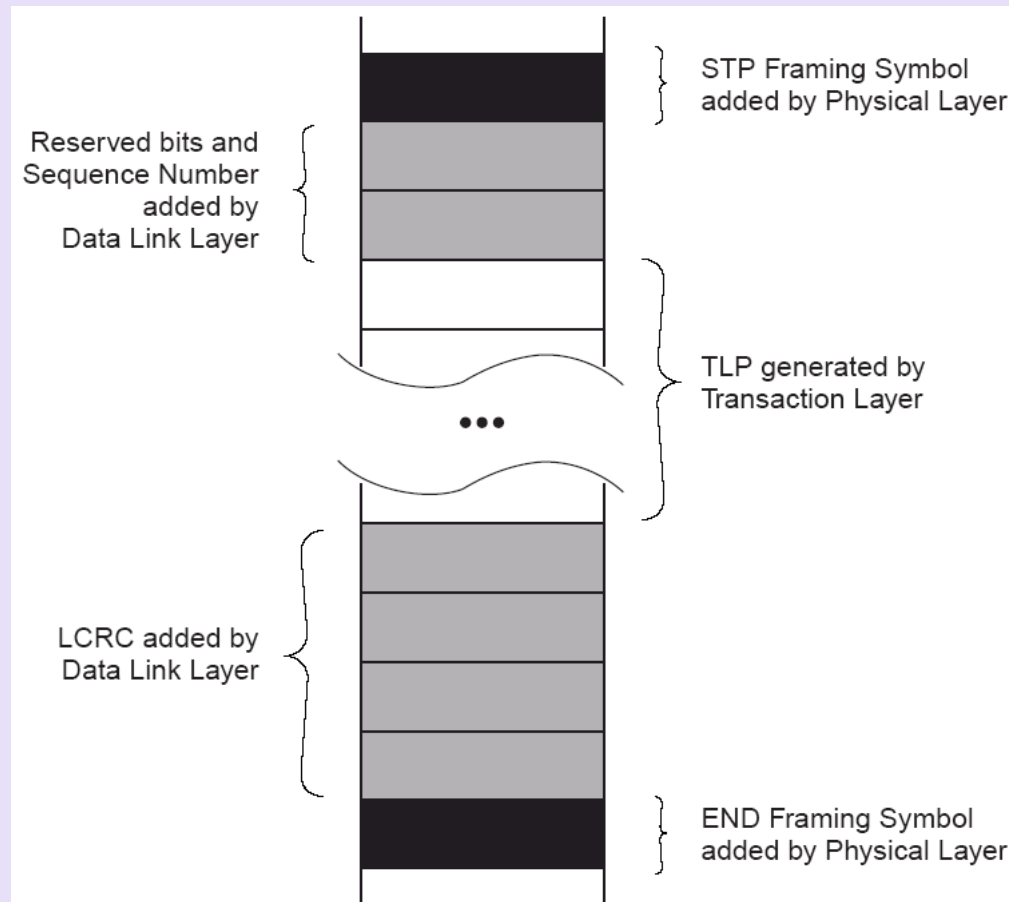
PCIe Protocol Overview



PCIe Protocol Overview

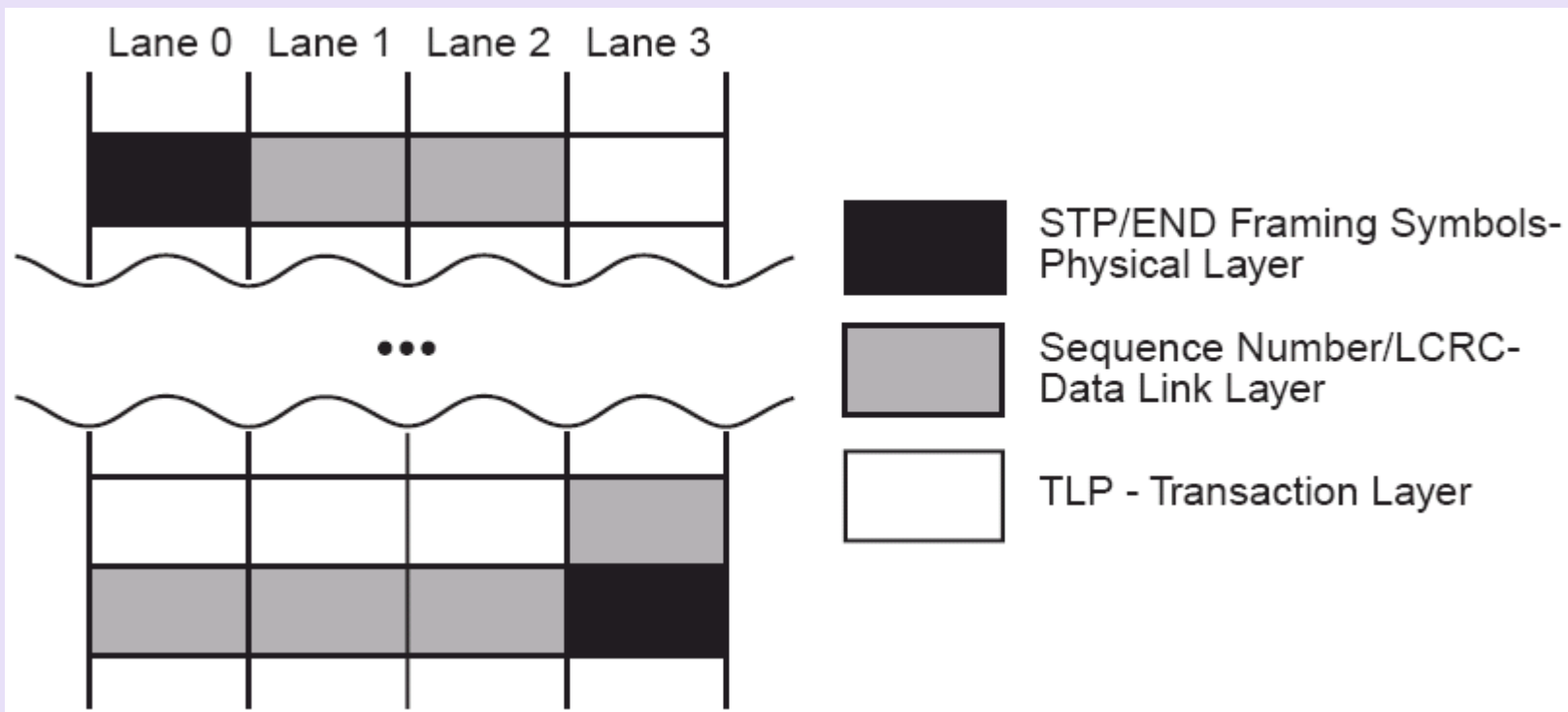
- Framing varies depending on link width

✓ x1



PCIe Protocol Overview

- Framing varies depending on link width
 - ✓ x4





PCIe Power Management

- PCI Power Management – Device Layer
 - ✓ Introduced with Conventional PCI
 - ✓ Software-driven, addresses ***devices not in use***
 - ✓ D0 – operating normally
 - ✓ D1 – reduced power
 - ✓ D2 – reduced power
 - In both D1/D2, the device can't *do* anything on the bus except respond to configuration cycles
 - ✓ D3_{cold} – device powered off
 - ✓ D3_{hot} – device all but powered off



PCIe Power Management

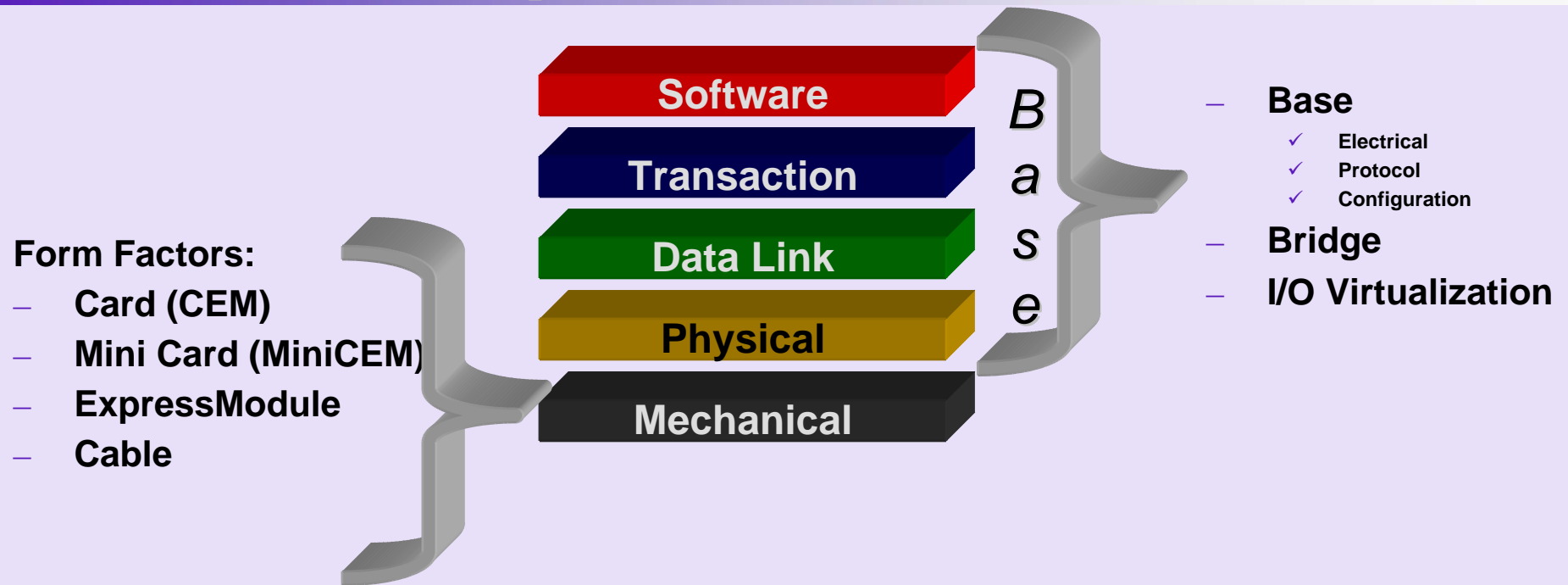
- Link Layer
 - ✓ L0 – operating normally
 - ✓ L0s – one or both sides in low power mode
 - ✓ L1 – lower powered mode
 - ✓ L2 – deep power save mode but Vaux provided
 - ✓ L3 – powered off
- Active State Power Management (ASPM)
 - ✓ Software-invisible, addresses ***idle devices***
 - ✓ L0s required – enter on timer, exit on activity
 - ✓ L1 optional – enter on timer or other conditions, exit on activity



PCIe Power Management

- Dynamic Power Allocation (DPA)
 - ✓ New configuration space reporting and selecting different power “envelopes” for each device function
 - ECN against PCIe 2.0 (appears in PCIe 2.1 and 3.0)
 - Endpoint-only
 - ✓ Addresses ***fully functioning*** devices
 - ✓ Software-set
 - Allows trading off performance for power
 - Exact “cost” of reduced power is device-dependent

PCIe Specifications



- Layered, scalable architecture
- Performance matched to applications
- Innovative form factors

I/O Virtualization Overview

I/O Virtualization – What?

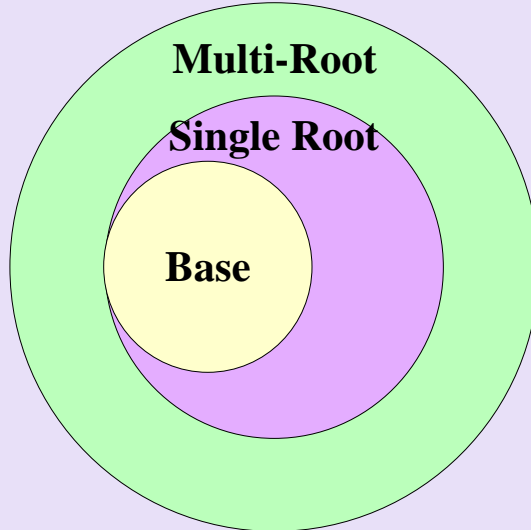
From an adapter point of view:

- One physical device looks like multiple devices
- Virtual devices appear completely independent
 - ✓ May occupy different PCI memory ranges
 - ✓ May have different settings for PCI Configuration registers

From a system point of view:

- “System Image” is a real or virtual system of CPU(s), Memory, O/S, I/O, etc
 - ✓ Multiples may run on one or more sets of hardware
- Each “System Image” (SI) needs to “see” it’s own PCI hierarchy
 - ✓ Even if NO end devices are actually shared
 - ✓ Only its “portion” of shared end devices

I/O Virtualization – How?



“Concentric Circles” model

- Attachment of existing PCIe 1.x Base components
 - ✓ Root Complexes, Switches, Endpoints, and Bridges.
- A solution to use a combination of existing base and IOV-aware components:
 - ✓ Single Root capabilities are a superset of the PCIe 1.x Base specification.
 - ✓ Multi-Root capabilities build upon the Base and Single Root capabilities.
- IOV-capable components are backwards compatible with existing software.
 - ✓ Although some or all of the new IOV capabilities may not be supported in these circumstances.

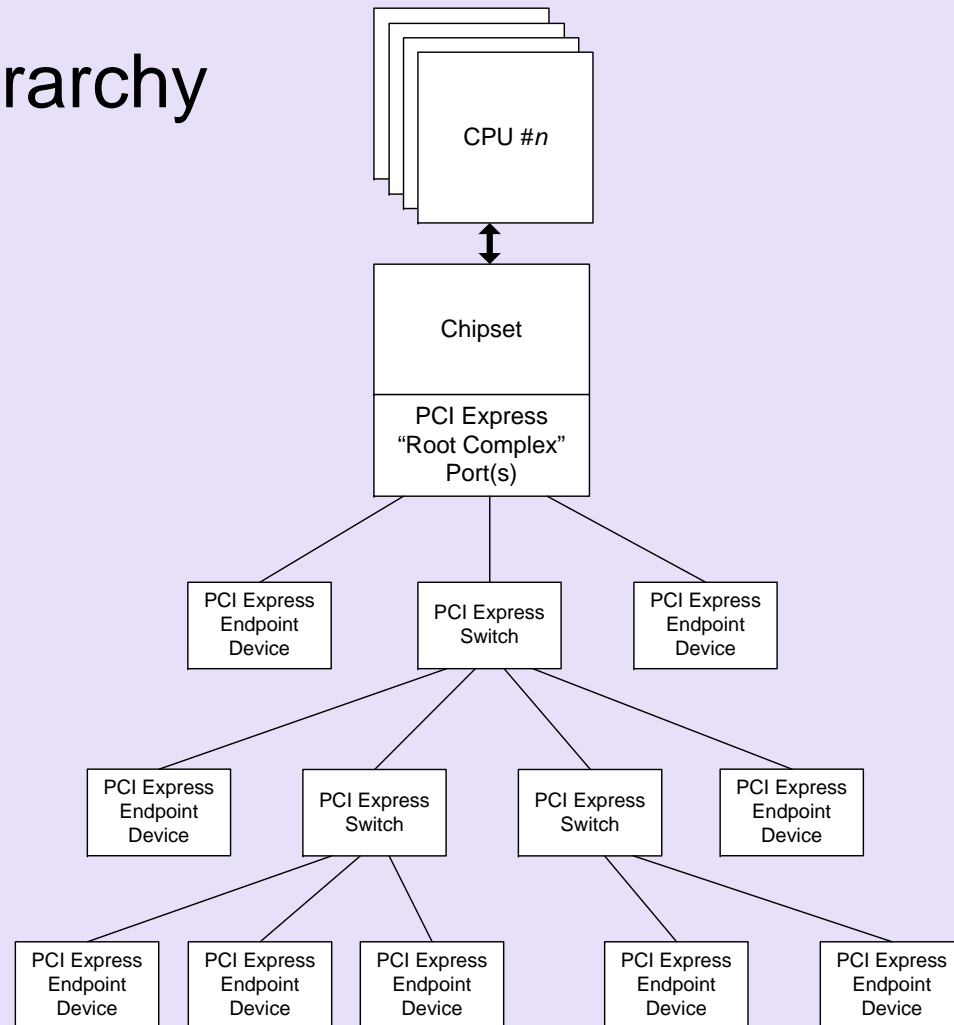


I/O Virtualization “Flavors”

- Single Root (SR IOV)
 - ✓ Fits into existing PCI hierarchies today, with address space partitioned/allocated “above” the Root Complex
 - Uses RoutingID (formerly the Bus/Device/Function field) in packets to track back to appropriate System Image
 - ✓ Existing or absolutely minimally changed Root Complex silicon
 - ✓ Existing or minimally changed Switch silicon
 - ✓ New Endpoint silicon
 - ✓ Presumes existence of a Virtualization Intermediary
 - Opens market to lots of existing or simply-derived systems
 - Shifts substantial burden to software

I/O Virtualization “Flavors”

- Single Root Hierarchy



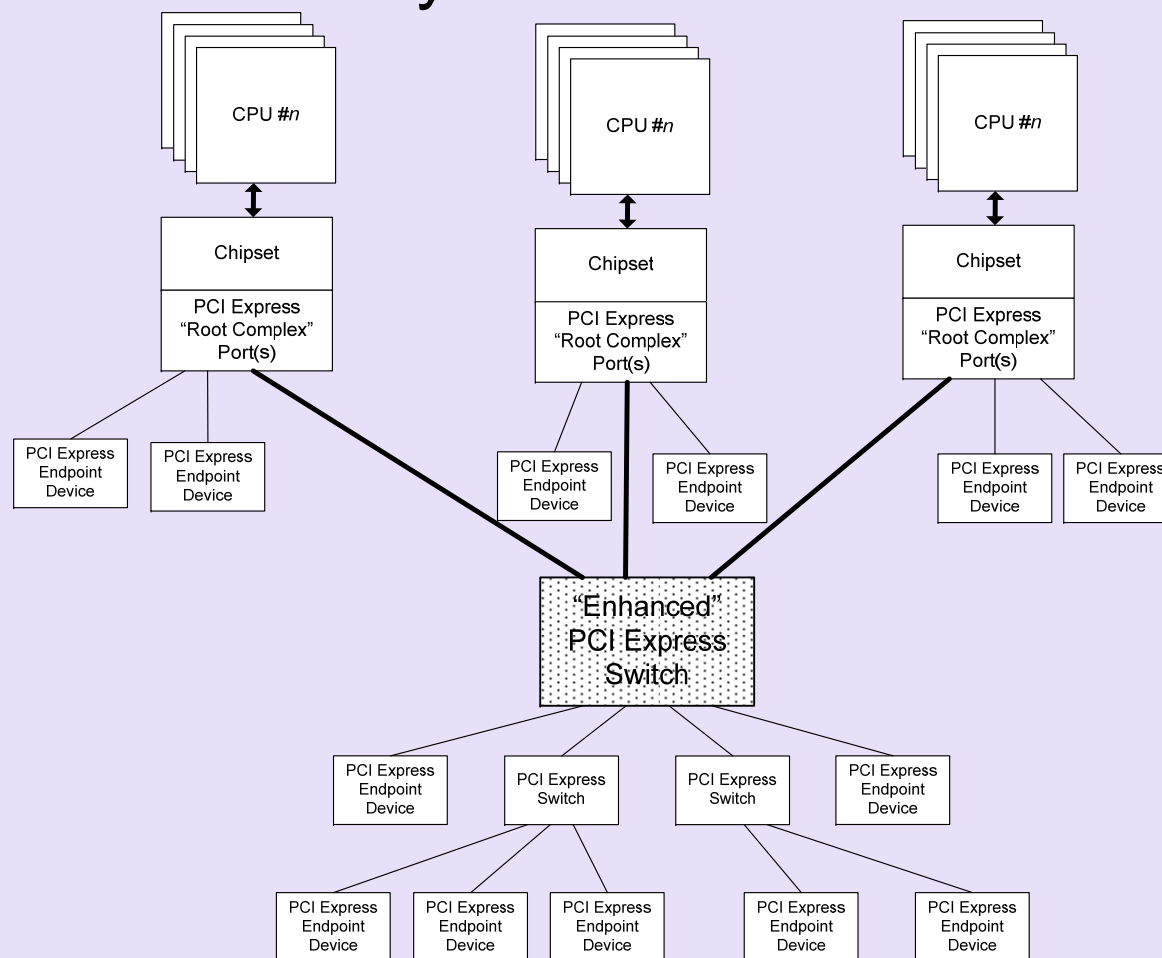


I/O Virtualization “Flavors” (cont’d)

- Multi-Root (MR IOV)
 - ✓ Most obvious example is a blade server with a PCIe “backplane”
 - ✓ New PCIe hierarchy construct
 - Effectively a (mini) fabric
 - Logically partitions the hierarchy into multiple Virtual Planes (VPs) all sharing the same physical hierarchy
 - ✓ Existing or absolutely minimally changed Root Complex (i.e. chipset) silicon
 - ✓ New Switch silicon
 - Allows for use of existing or minimally changed switches in a reduced capacity in certain places
 - ✓ New Endpoint silicon

I/O Virtualization “Flavors” (cont’d)

- Multi-Root Hierarchy



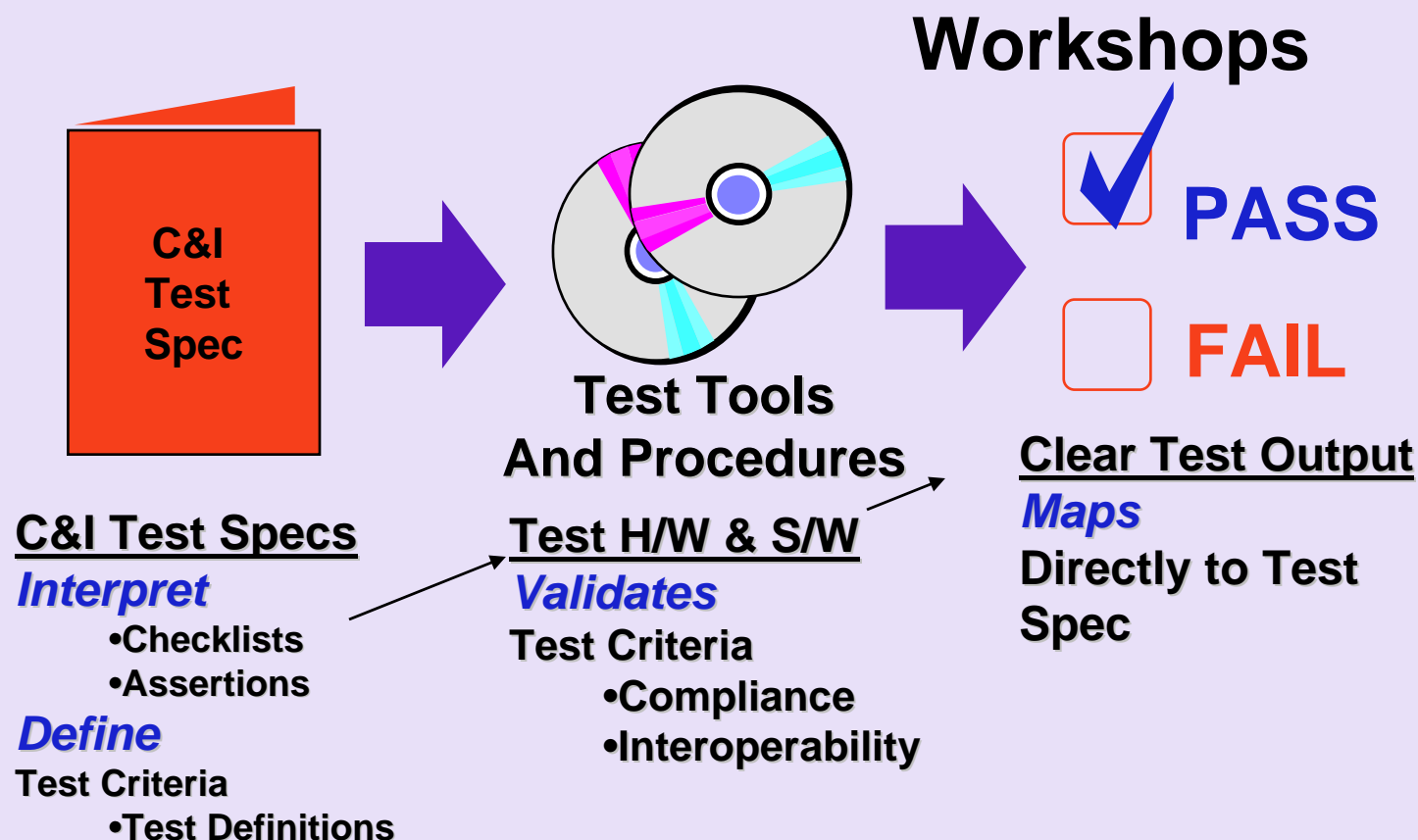


I/O Virtualization “Flavors” (cont’d)

- Address Translation Services (ATS)
 - ✓ Defines a set of transactions PCIe components can use to exchange and share translated addresses
 - With an I/O MMU, bus addresses map to different system addresses based on the “identity” of the agent using them
 - Allows each SI to appear to use the entire address space
 - System’s I/O MMU does translation of “normal” addresses
 - Expensive in performance terms
 - Impossible to size I/O MMU’s TLB or cache for all applications
 - ATS-aware devices can translate an address range and bypass I/O MMU
 - New PCIe commands for translation Requests, Completions, and Invalidations
 - ✓ Implementation is optional even for IOV devices

Compliance Program Overview

PCI-SIG Compliance Process





Compliance Workshop Overview

- Workshops are usually announced 2 months in advance
- System and card vendors register for the compliance workshops
- Systems are set up in suites
- PCI-SIG systems are set up
- Test schedule is developed
 - ✓ Indicates when cards are to be tested in the systems
 - ✓ Each card & system vendor receives a schedule for their product
 - ✓ Test forms are used to record the results of the testing

Thank you for attending the
PCIe Technology Seminar

For more information please go to
www.pcisig.com