# Overview of advanced storage technologies and storage virtualization

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# SCSI Interface

# (SCSI-3 specification)

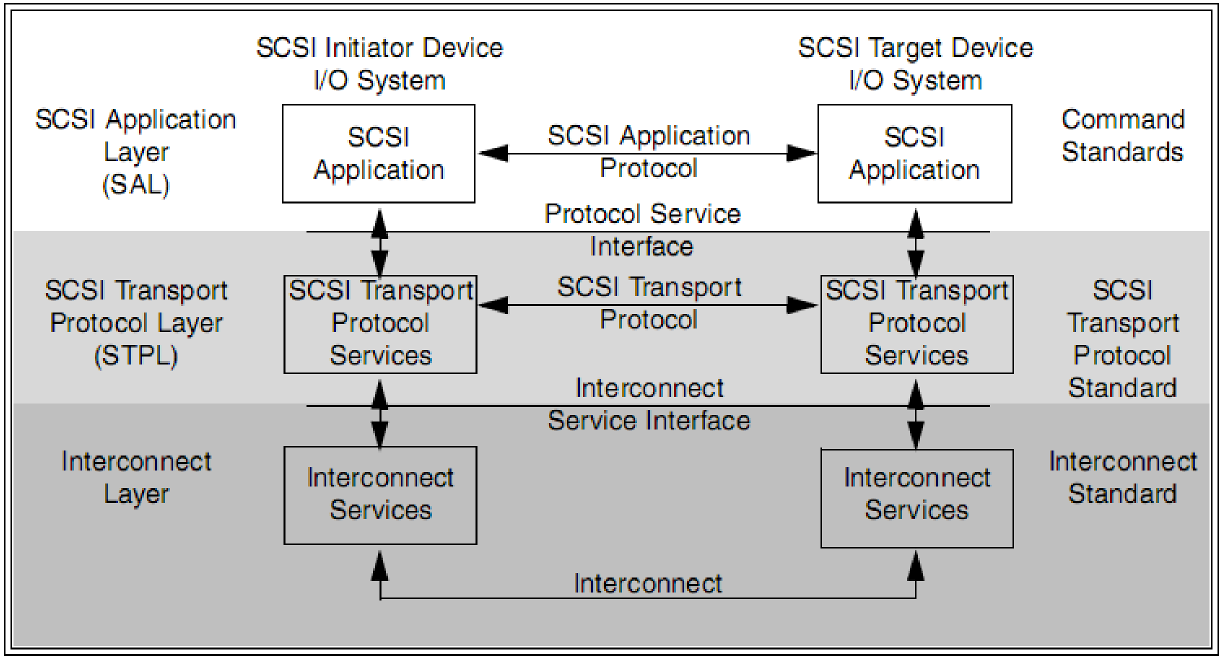
# What will we learn?

- SCSI interface structure and basic operation
- How the computer can, through its SCSI HBA (card), request a disk to perform a read or write operation
- How the SCSI interface allows the disk controller to hide what's going under the hood
- The concept of target, logic unit and LUN
- A detailed description of how a SCSI command is performed at the interface level
- How the SCSI interface is the *lingua franca* of all storage systems

# SCSI-3 History

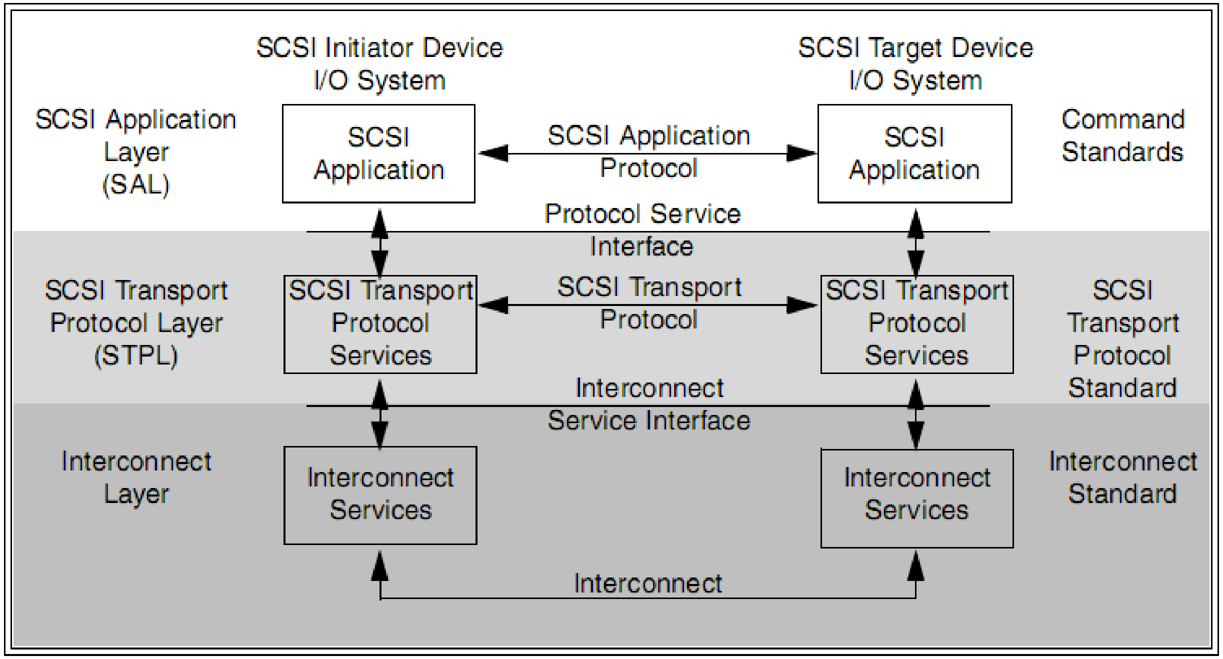
- SCSI interface created in 1978 by Shugart Associates, first standarized 1981
  - **SCSI** = *Small Computers System Interface*
- Developed as logical interface to drive high-performance disks over 8-bit SCSI parallel bus
- Very successful and widely accepted
  - Extended to control all kinds of storage peripherals
- Around 1995 begins development of SCSI-3 standard, published in 2003
- SCSI-3 is no longer a single standard, but a “standards family” (set of interrelated standards)
  - Suffix “-3” has been dropped, so nowadays “SCSI” means “SCSI-3”

# SCSI layered protocol stack



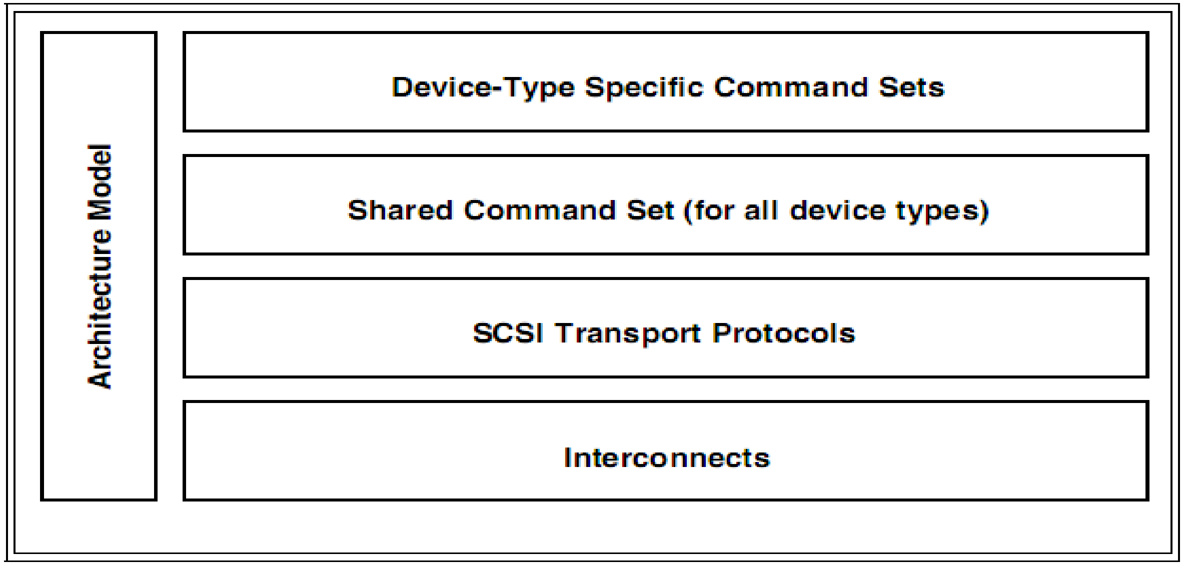

- SCSI-3 models SCSI interface as objects, protocol layers and service interfaces
  - Concept very similar to OSI computer networks reference model
- SCSI objects (protocol entities) exchange frames between peers
  - Frames get encapsulated when travelling downwards through protocol stack and de-encapsulated when travelling upwards

# SCSI layered protocol stack



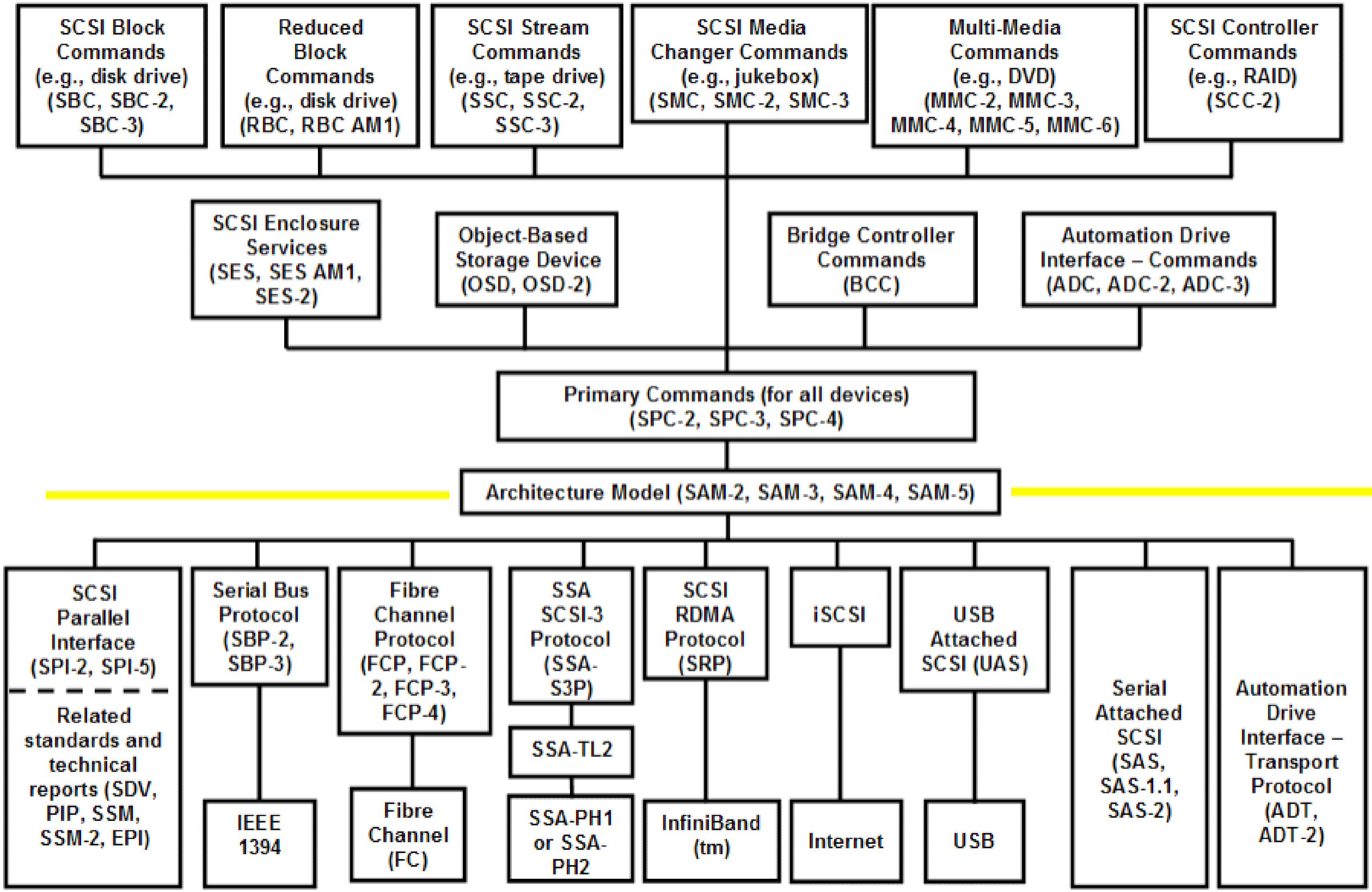

- Model has three layers:
  - Application layer: Commands sent from initiator to target, answers from initiator with data and status info
  - Transport layer: Protocols to wrap SCSI payload within link-level frames
  - Interconnect layer: Essentially, equivalent to link and physical layers of OSI model

# SCSI standards family

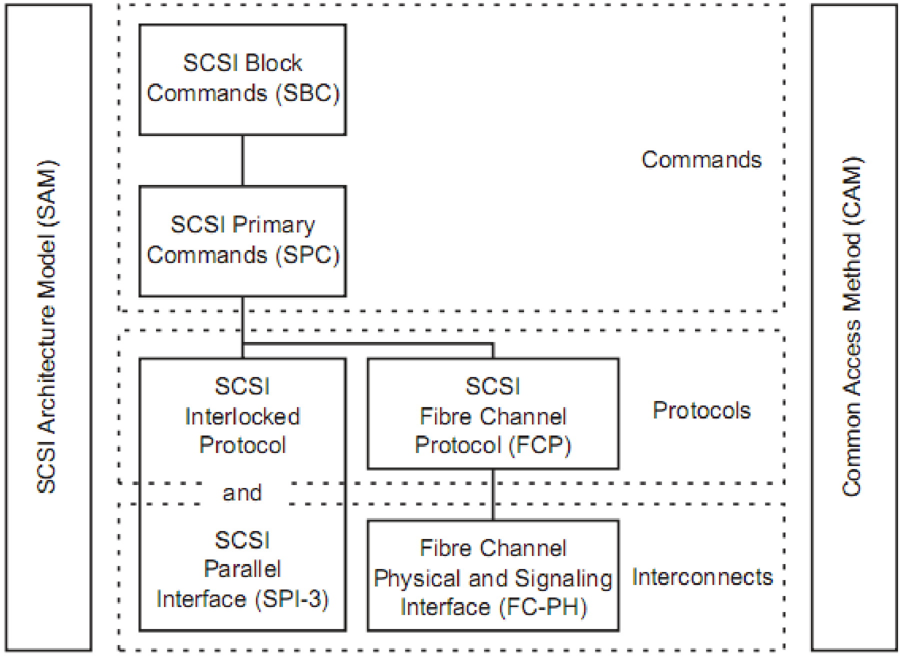



- SCSI-3 standards family defines:
  - A common architecture model, standardizing concepts and behaviors in all layers
  - Set of commands for the application layer
- Commands organized in two different subsets:
  - Primary commands: MUST be implemented by any SCSI device
    - Basic device identification and management
  - Device-specific sets of commands

# SCSI standards family

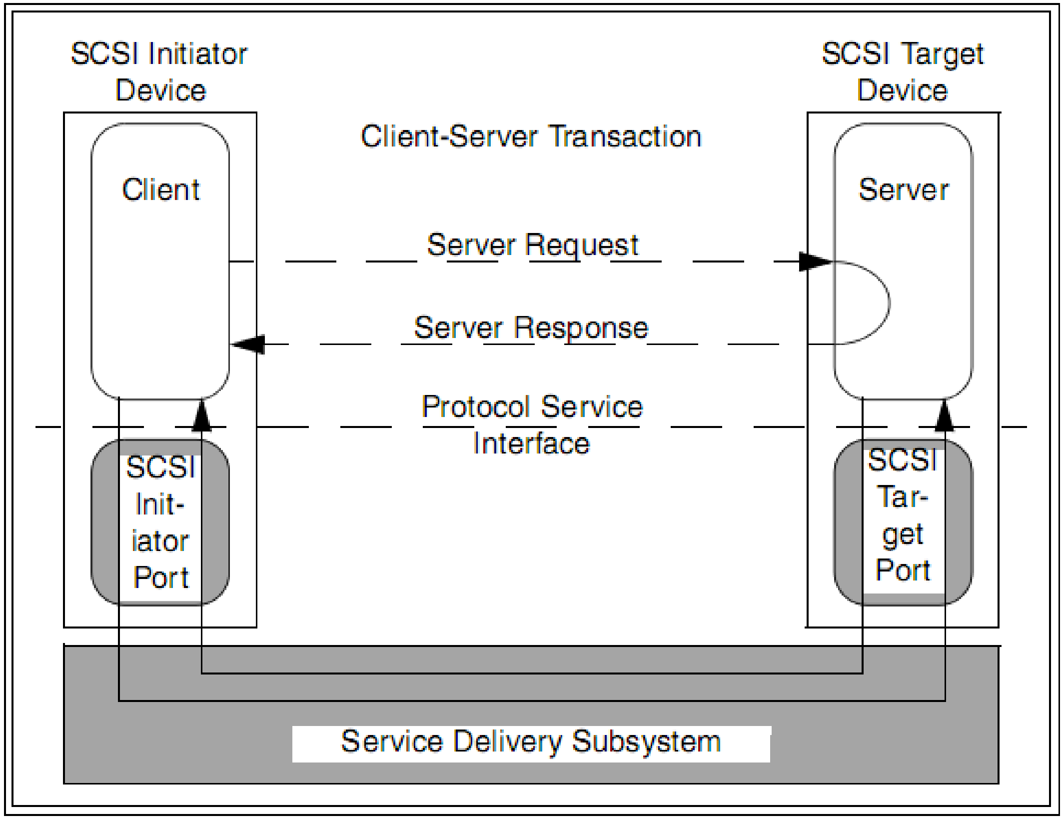


# SCSI standards family



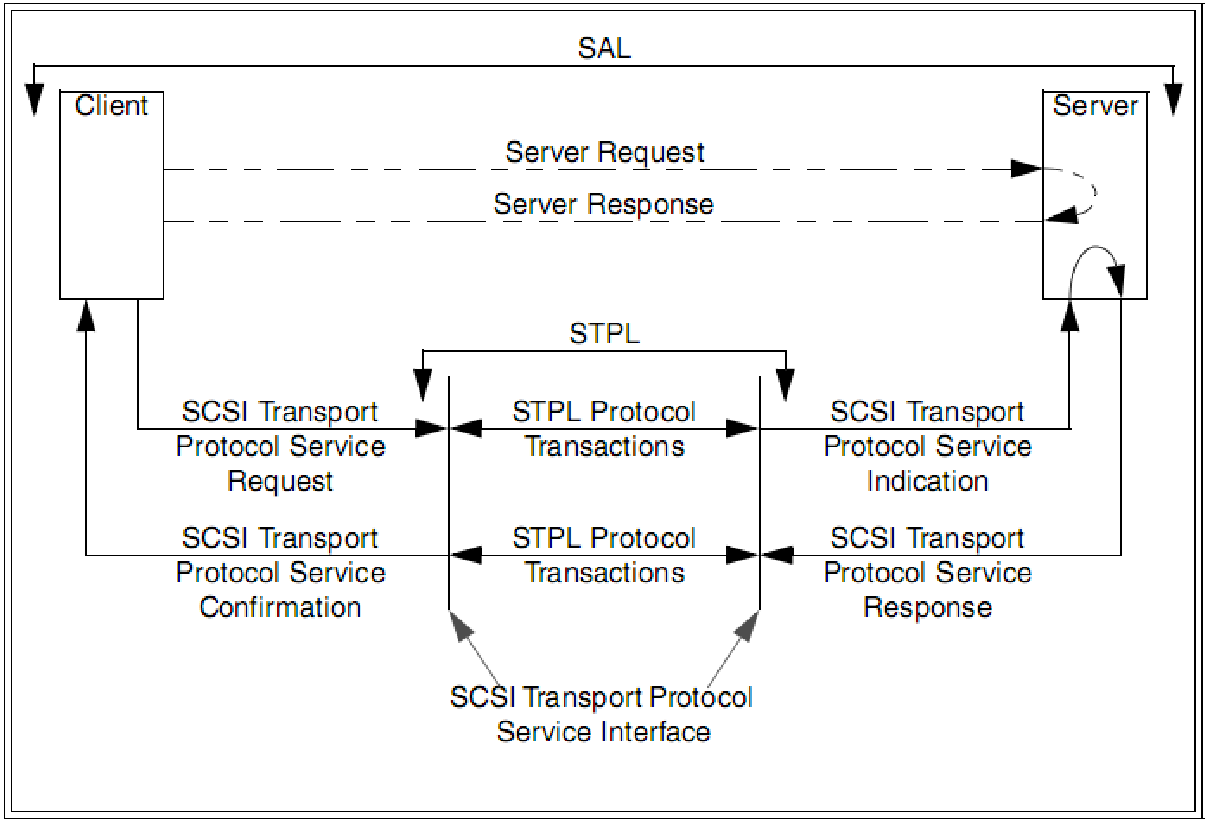

- SCSI-3 protocol stack model allows sending exactly the same commands over different buses or storage networking interconnects
  - Just transport-level wrapping of commands/answers, and link-level behavior, need to be changed
  - Allows also bidirectional payload transfer through two or more different transports between initiator and target

# SCSI client-server model



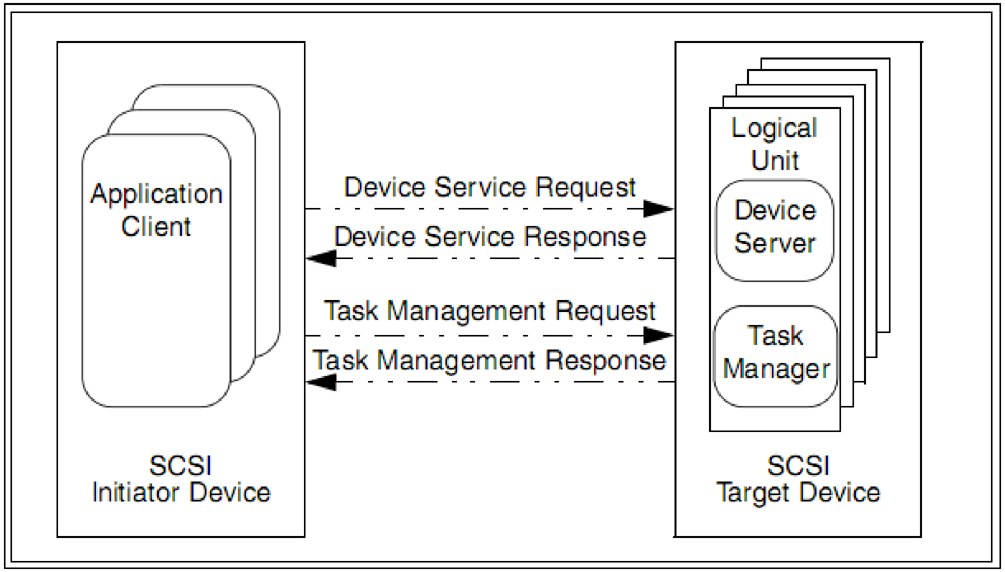

- SCSI I/O transaction between initiator and target is modelled as a client-server transaction
  - Server (= target = storage device) offers service to client (= initiator = HBA)
  - Service = access to write or retrieve data, get status or manage device

# SCSI client-server model




- SCSI command is request from service sent from client (initiator) to server (target)
- Transport and interconnect layer perform physical transport of request and response

# LUNs and tasks




- SCSI target (server) exposes services (functionality) through Logical Units
  - Logical Unit = object that processes commands (ex: read from media)
- Application client (driver in initiator) issues request (command) to Logical Unit
  - Command defines unit of work to be performed by Logical Unit
  - This unit of work is named *task* in SCSI parlance
  - Thus, initiator issues tasks (= commands) to Logical Unit, which processes them

# Command Descriptor Block (CDB)

**Typical CDB for 6-byte commands**

| Bit / Byte | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|
| 0 | OPERATION CODE | | | | | | | |
| 1 | Miscellaneous CDB information | | | (MSB) | | | | |
| 2 | LOGICAL BLOCK ADDRESS (if required) | | | | | | | |
| 3 | | | | | | | | (LSB) |
| 4 | TRANSFER LENGTH (if required)<br>PARAMETER LIST LENGTH (if required)<br>ALLOCATION LENGTH (if required) | | | | | | | |
| 5 | CONTROL | | | | | | | |

- Initiator sends command to Logical Unit issuing a CDB (*Command Descriptor Block*)
  - Structured set of bytes, typically of 6, 10, 12 or 16 bytes
  - Interpreted by target as request to execute a given command, and parameters to it

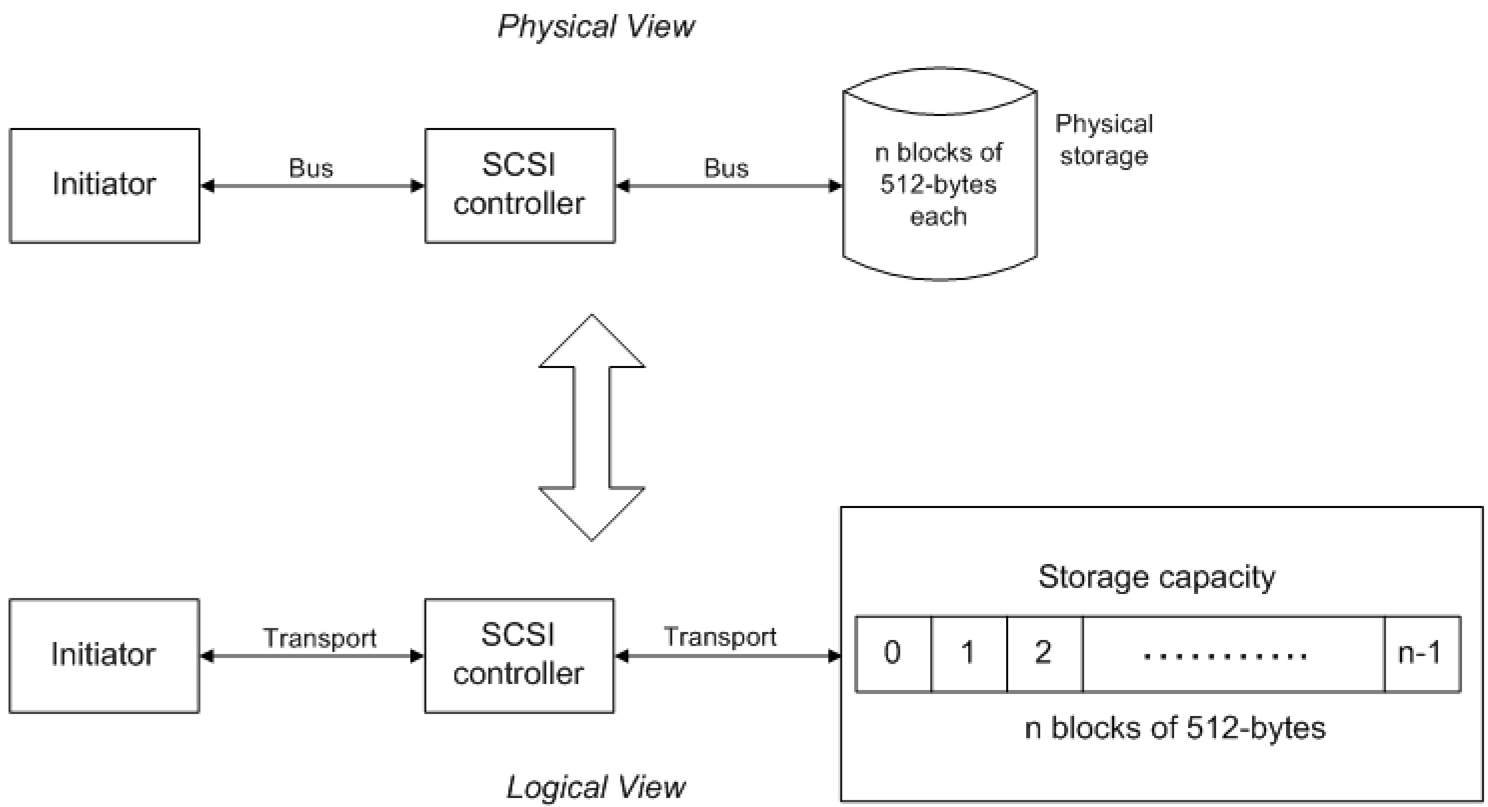
# Command Descriptor Block (CDB)

**Typical CDB for 10-byte commands**

| Bit / Byte | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|
| 0 | OPERATION CODE | | | | | | | |
| 1 | Miscellaneous CDB information | | | | SERVICE ACTION (if required) | | | |
| 2 | (MSB) | LOGICAL BLOCK ADDRESS (if required) | | | | | | |
| 3 | | | | | | | | |
| 4 | | | | | | | | |
| 5 | | | | | | | | (LSB) |
| 6 | Miscellaneous CDB information | | | | | | | |
| 7 | (MSB) | TRANSFER LENGTH (if required)<br>PARAMETER LIST LENGTH (if required)<br>ALLOCATION LENGTH (if required) | | | | | | |
| 8 | | | | | | | | (LSB) |
| 9 | CONTROL | | | | | | | |

- Different size CDBs for same command differ in length of parameters
  - Larger address allows addressing larger storage volumes

# Logical Block Addressing




- SCSI controller hides physical details of storage organization
  - Storage capacity is shown just as a linear array of individually-addressable blocks

# Logical Block Addressing

**Typical CDB for 6-byte commands**

| Bit / Byte | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|
| 0 | OPERATION CODE | | | | | | | |
| 1 | Miscellaneous CDB information | | | (MSB) | | | | |
| 2 | LOGICAL BLOCK ADDRESS (if required) | | | | | | | |
| 3 | | | | | | | | (LSB) |
| 4 | TRANSFER LENGTH (if required)<br>PARAMETER LIST LENGTH (if required)<br>ALLOCATION LENGTH (if required) | | | | | | | |
| 5 | CONTROL | | | | | | | |

- Blocks to be accessed are addressed through 2 parameters in CDB:
  - Address of first logical block of transfer
  - Length, in blocks, of transfer
    - Typical block size = 512 bytes

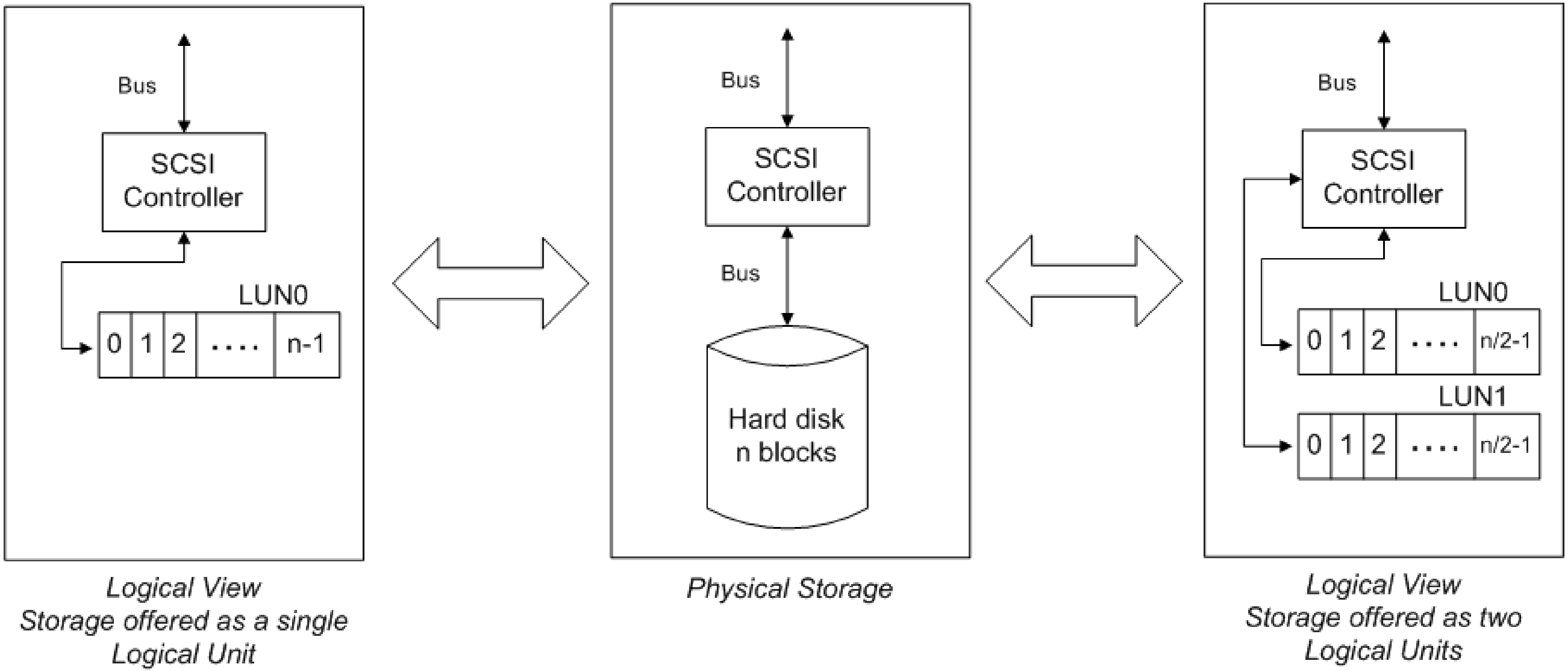
# Logical Block Addressing

Typical CDB for long LBA 16-byte commands

| Bit / Byte | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|
| 0 | OPERATION CODE | | | | | | | |
| 1 | Miscellaneous CDB information | | | | | | | |
| 2 | (MSB) | LOGICAL BLOCK ADDRESS | | | | | | |
| 3 | | | | | | | | |
| 4 | | | | | | | | |
| 5 | | | | | | | | |
| 6 | | | | | | | | |
| 7 | | | | | | | | |
| 8 | | | | | | | | |
| 9 | | | | | | | | (LSB) |
| 10 | (MSB) | TRANSFER LENGTH (If required) PARAMETER LIST LENGTH (if required) ALLOCATION LENGTH (if required) | | | | | | |
| 11 | | | | | | | | |
| 12 | | | | | | | | |
| 13 | | | | | | | | (LSB) |
| 14 | Miscellaneous CDB information | | | | | | | |
| 15 | Control | | | | | | | |

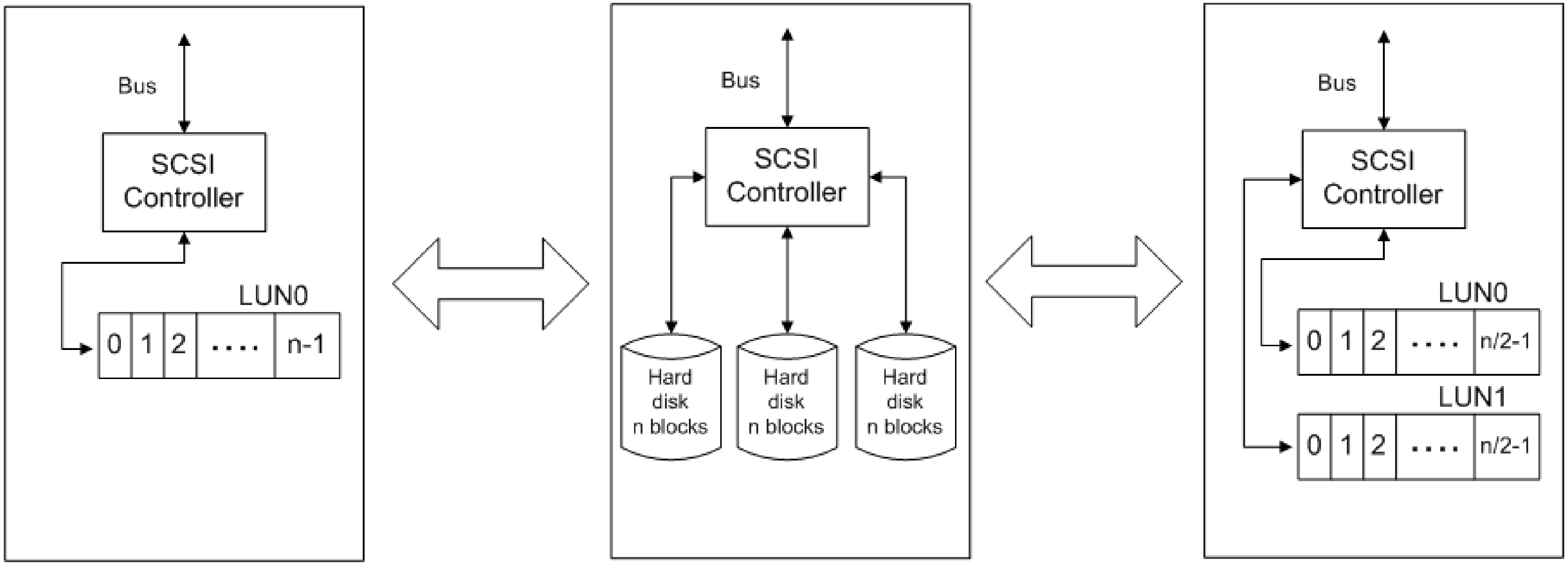
- Allowing larger address fields, SCSI interface copes with increasingly larger storage volumes:
  - CDB-6: $2^{21}$ blocks = 1 GByte
  - CDB-10: $2^{32}$ blocks = 2 TBytes
    - Typical LUN size limit for many SCSI controllers and virtualization software
  - CDB-16: $2^{24}$ blocks = 9 x $10^{18}$ bytes ~ 9 ExaBytes

# LUNs and LBA give flexibility




- Logical Units allow greater flexibility to organize storage
  - Controller just needs to map physical blocks to logical addresses
  - Required unique numerical identifier for each Logical Unit
    - **LUN** = *Logic Unit Number*

# LUNs and LBA hide complexity



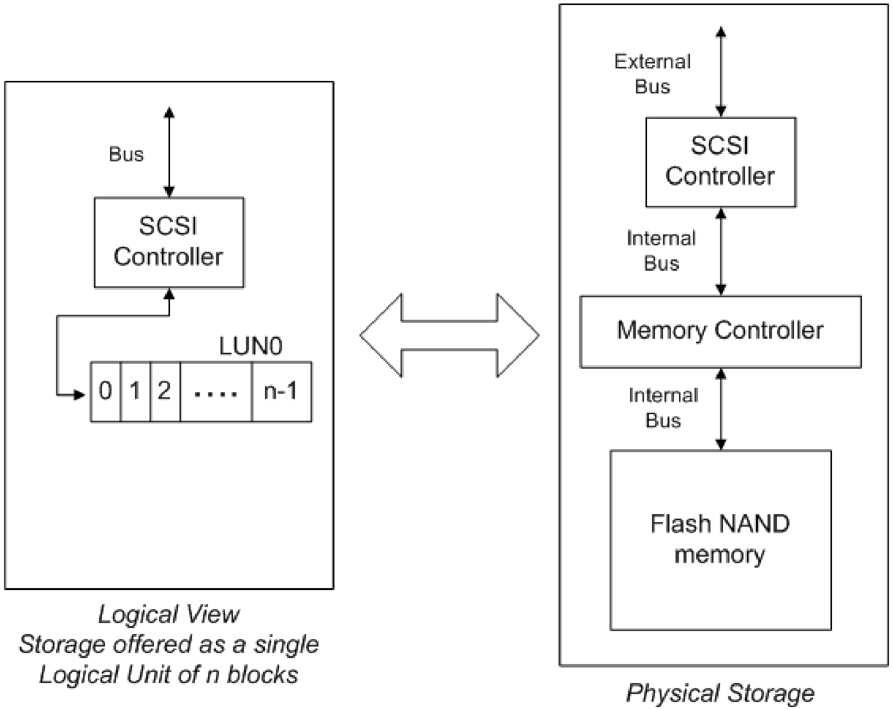

*Logical View*
*Storage offered as a single Logical Unit*

*Physical Storage*

*Logical View*
*Storage offered as two Logical Units*

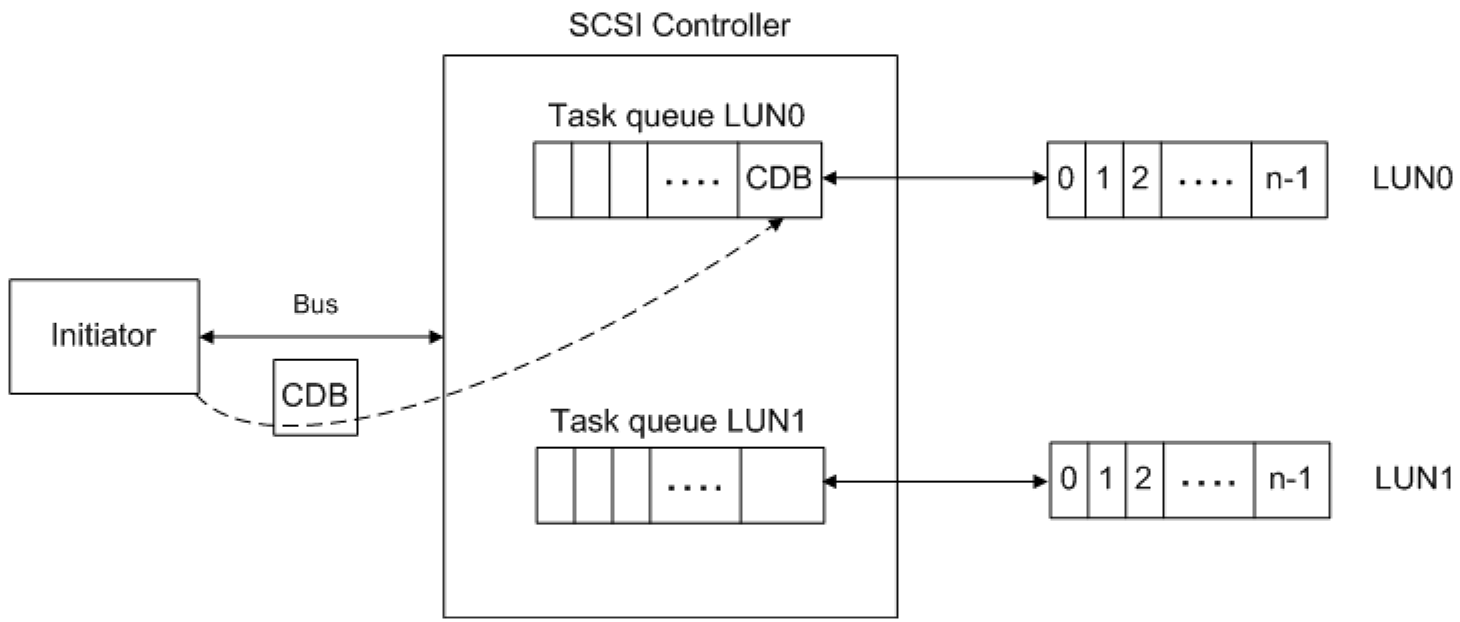
- Logical Units hide complexity of hardware setup
  - Left: controller shows several physical disks as single, larger disk
    - LBA hides physical placement of data
    - Controller free to transparently optimize placement
  - Right: controller sums total storage as split in several LUNs
    - Allow transparency of complex placement strategies (RAID, replication)

# LUNs and LBA hide complexity



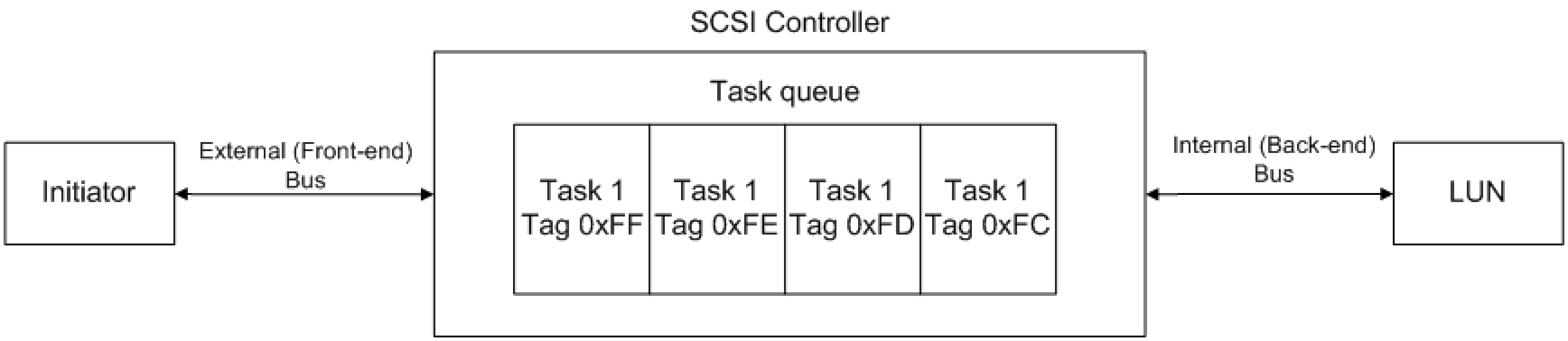

- Logical Units also hide nature of storage
  - Example: Flash storage (SSD, USB drives) has a complex internal architecture
    - Blocks are dynamically migrated for wear-leveling
    - Simple external view as a single LUN of n blocks
    - Memory controller manages mapping between logical LBA address and physical memory page

# LUNs and task queues



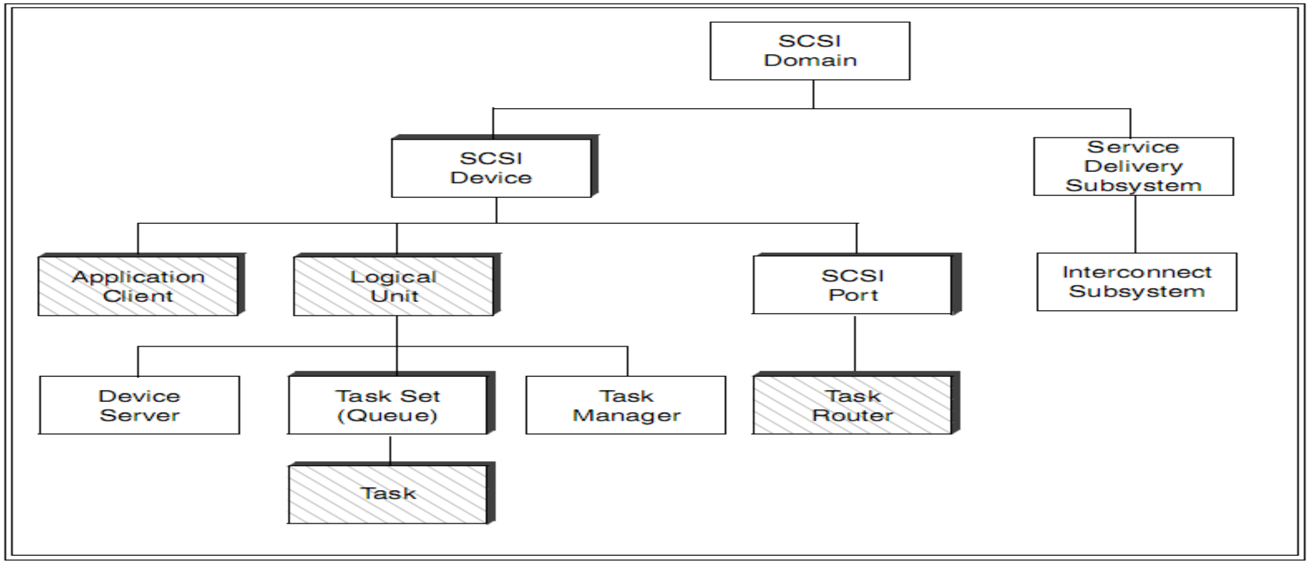

- SCSI controller can offer for each LUN none, one or several task queues to manage pending commands (*tasks*)
  - CDB inserted into queue, and can be executed asynchronously
  - If several commands in queue, can be reordered before execution, if hardware supports it
- If no queue, commands must execute using synchronous I/O (only a single command pending at any time)

# LUNs and task queues




- Use of task queue requires identifying each individual task
  - Each task is assigned numerical identifier, unique within queue
  - Tag provides context reference for task when executing
- Tags are not required in synchronous I/O ("*untagged commands*")

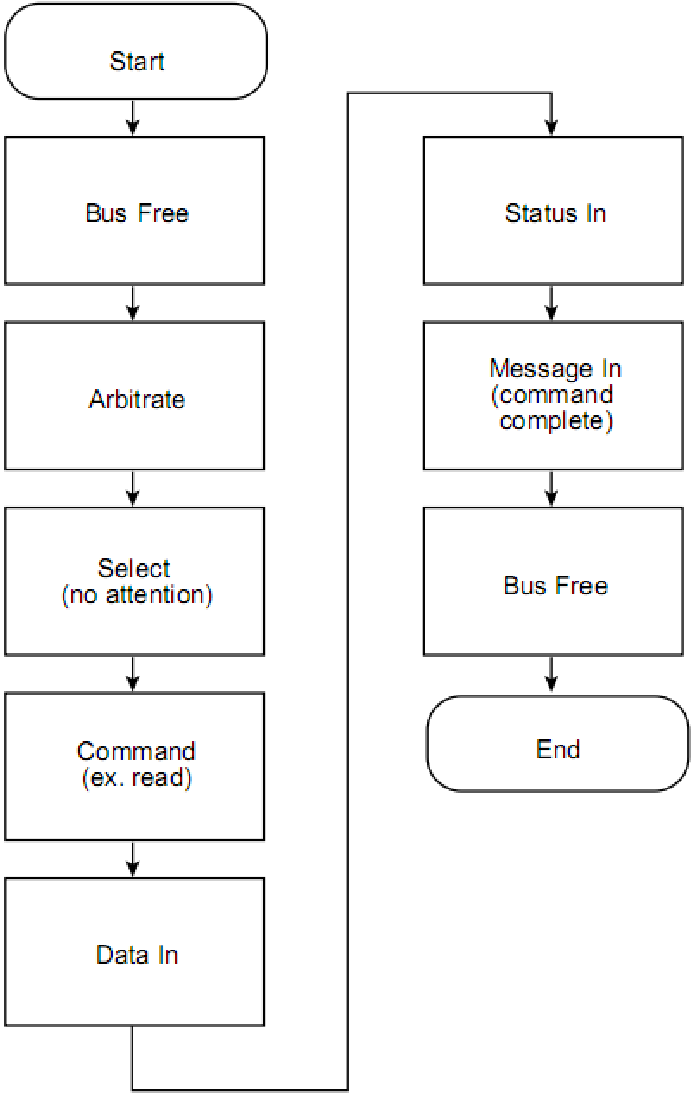
# SCSI task addressing




- Issuing or answering SCSI task requires use of several numerical identifiers:
  - Initiator ID and Target ID = Identifiers of physical devices involved
  - Logical Unit Number (LUN) = Identifier or logical unit, of target device, which must process this command
  - Task queue = Identifier of queue, within LU, in which command is inserted
  - Task tag = unique identifier for this task within queue

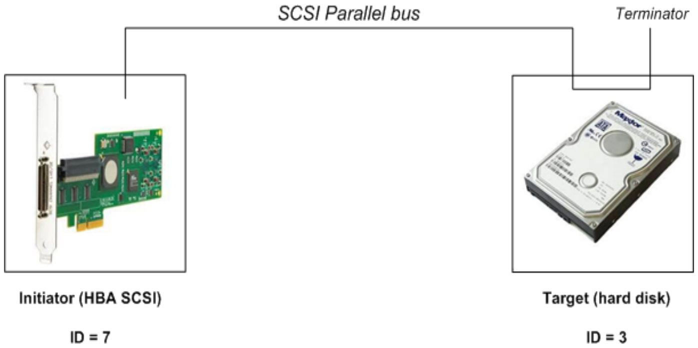
# Example: simple WRITE command on SPI

- Simplest way to understand operation of SCSI interface
- SCSI interface executes command as an ordered sequence of phases
  - Task will end with sending of status info on outcome of command



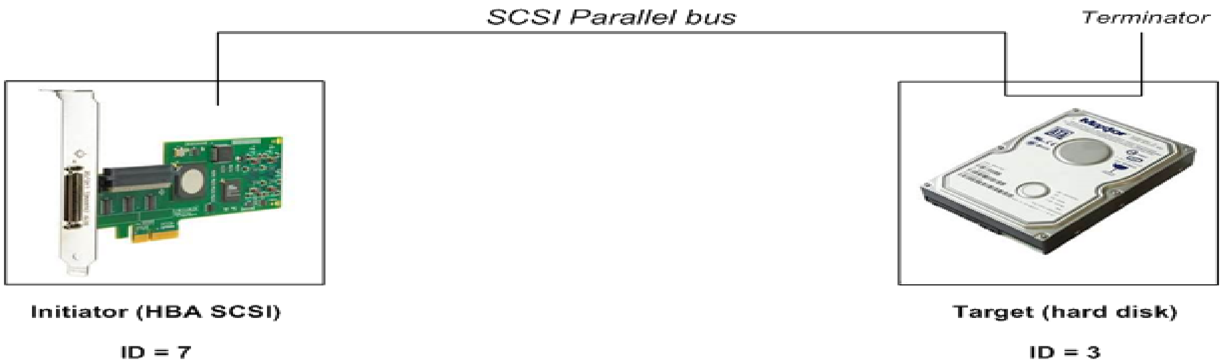
# Example: simple WRITE command on SPI

- Figure contains decoding of real traffic capture (with logic analyzer) for SCSI WRITE(10) command between initiator and target shown above
  - Write: data goes from initiator to disk




| Time | Time | STAT | DATA-8 |
|---|---|---|---|
| 4554214772 ns | 151.61 us | ARBITRATION | 80 |
| 4554215356 ns | 0.584 us | SELECT | 88 |
| 4554218924 ns | 3.568 us | MSG OUT | C0 |
| 4554220922 ns | 1.998 us | MSG OUT | 20 |
| 4554223122 ns | 2.2 us | MSG OUT | FE |
| 4554228472 ns | 5.35 us | COMMAND | 2A |
| 4554228896 ns | 0.424 us | COMMAND | 00 |
| 4554229172 ns | 0.276 us | COMMAND | 00 |
| 4554229448 ns | 0.276 us | COMMAND | 03 |
| 4554229722 ns | 0.274 us | COMMAND | 22 |
| 4554229998 ns | 0.276 us | COMMAND | FF |
| 4554230272 ns | 0.274 us | COMMAND | 00 |
| 4554230548 ns | 0.276 us | COMMAND | 00 |
| 4554230822 ns | 0.274 us | COMMAND | 80 |
| 4554231096 ns | 0.274 us | COMMAND | 00 |
| 4554236148 ns | 5.052 us | DATA OUT | 00 |
| 4554236248 ns | 0.1 us | DATA OUT | 00 |
| 4554236350 ns | 0.102 us | DATA OUT | 20 |
| 4560918946 ns | 6682.596 us | STATUS | 00 |
| 4560920940 ns | 1.994 us | MSG IN | 00 |

# Example: simple WRITE command on SPI




| | | | | |
|---|---|---|---|---|
| 4554214772 ns | 151.61 us | ARBITRATION | 80 | = 1000 0000 |
| 4554215356 ns | 0.584 us | SELECT | 88 | = 1000 1000 |

- SCSI transaction starts addressing physical devices involved
  - For parallel SCSI, addressing done in ARBITRATION stage
  - Parallel SCSI is multi-drop, so bus-master and bus-slave must be chosen
  - HBA (ID = 7) wins arbitration and becomes bus master
  - HBA selects then hard disk (ID = 3) as bus slave (peer for this transfer)

# Example: simple WRITE command on SPI

**IDENTIFY message format**

| Bit / Byte | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|
| 0 | IDENTIFY | DISCPRIV | LUN | | | | | |

**Task attribute message codes**

| Code | Support | | | | Message name |
|---|---|---|---|---|---|
| | IU Transfers Disabled | | IU Transfers Enabled | | |
| | Iniator | Target | Initiator | Target | |
| 24h | O | O | N/A | N/A | ACA |
| 21h | Q | Q | N/A | N/A | Head of Queue |
| 22h | Q | Q | N/A | N/A | Ordered |
| 20h | Q | Q | N/A | N/A | Simple |

| | | | | |
|---|---|---|---|---|
| 4554218924 ns | 3.568 us | MSG OUT | C0 | LUN = 0 |
| 4554220922 ns | 1.998 us | MSG OUT | 20 | Simple queue |
| 4554223122 ns | 2.2 us | MSG OUT | FE | TAG |

- SCSI transaction needs now address LU, queue and command tag
  - Initiator addresses LUN0 of target device (hard disk)
  - Command is inserted into “Simple” queue
  - Command is uniquely identified within simple queue by tag 0xFE

# Example: simple WRITE command on SPI

**WRITE (10) command**

| Byte \ Bit | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|
| 0 | OPERATION CODE (2Ah) | | | | | | | |
| 1 | WRPROTECT | | | DPO | FUA | Reserved | FUA_NV | Obsolete |
| 2 | (MSB) | LOGICAL BLOCK ADDRESS | | | | | | |
| 5 | | | | | | | | (LSB) |
| 6 | Reserved | | | GROUP NUMBER | | | | |
| 7 | (MSB) | TRANSFER LENGTH | | | | | | |
| 8 | | | | | | | | (LSB) |
| 9 | CONTROL | | | | | | | |

| | | | | |
|---|---|---|---|---|
| 4554228472 ns | 5.35 us | COMMAND | 2A | WRITE(10) codop |
| 4554228896 ns | 0.424 us | COMMAND | 00 | |
| 4554229172 ns | 0.276 us | COMMAND | 00 | LBA (MSB) |
| 4554229448 ns | 0.276 us | COMMAND | 03 | |
| 4554229722 ns | 0.274 us | COMMAND | 22 | |
| 4554229998 ns | 0.276 us | COMMAND | FF | LBA (LSB) |
| 4554230272 ns | 0.274 us | COMMAND | 00 | |
| 4554230548 ns | 0.276 us | COMMAND | 00 | Transfer Length (MSB) |
| 4554230822 ns | 0.274 us | COMMAND | 80 | Transfer Length (LSB) |
| 4554231096 ns | 0.274 us | COMMAND | 00 | |

- Initiator sends now CDB to target
  - Target interprets CDB and gets ready to write 0x80 blocks (64 KB) data in media, starting from specified LBA

# Example: simple WRITE command on SPI

**Status byte code bit values**

| Status byte | Status represented | Task Ended |
|---|---|---|
| **00h** | Good | Yes |

**Message format**

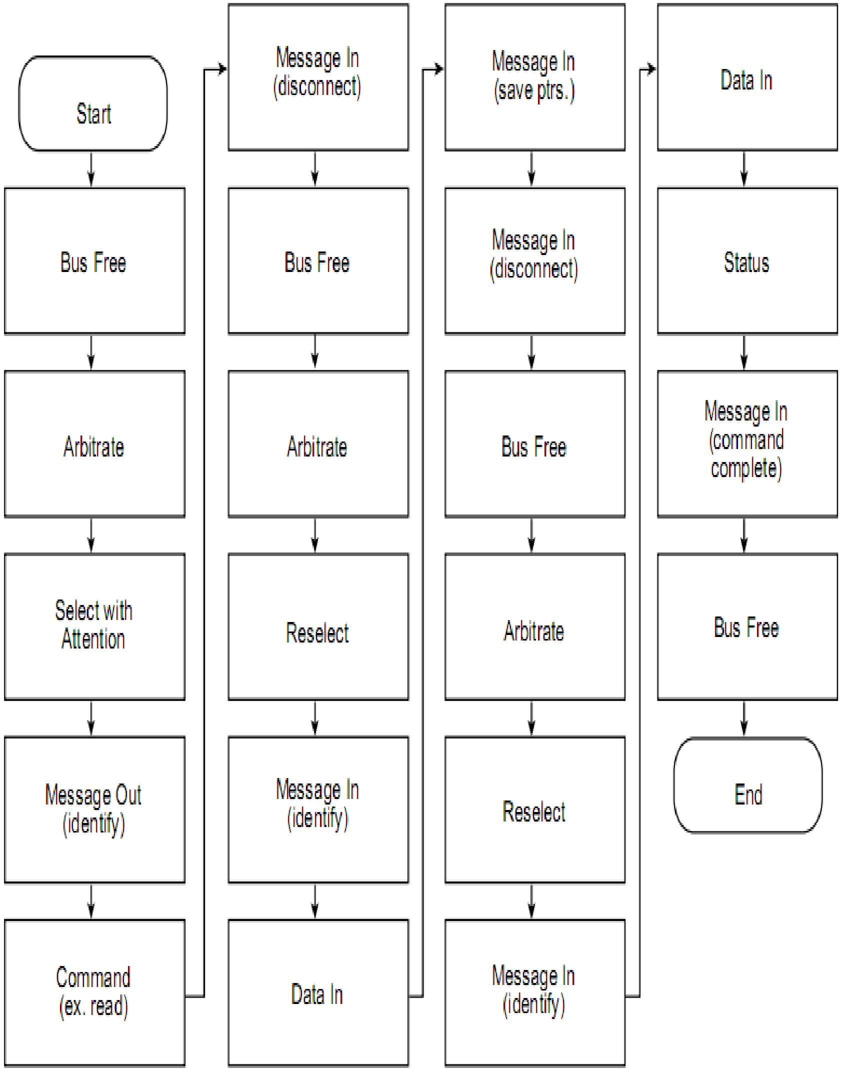
| Message code | Message format |
|---|---|
| **00h** | One-byte message (TASK COMPLETE) |

| | | | | |
|---|---|---|---|---|
| 4554236148 ns | 5.052 us | DATA OUT | 00 | Start of data transfer |
| 4554236248 ns | 0.1 us | DATA OUT | 00 | |
| 4554236350 ns | 0.102 us | DATA OUT | 20 | End of data transfer |
| 4560918946 ns | 6682.596 us | STATUS | 00 | Command ended OK |
| 4560920940 ns | 1.994 us | MSG IN | 00 | Task completed |

- Initiator sends data to target (disk)
- Target ends transaction by:
  - Reporting command executed OK (*Status Good)*
  - Declaring command as finished (*Task Complete)*

# Example: WRITE with split transaction

- SCSI interface allows split transactions
  - Target can disconnect after command, and reconnect to start data transfer
  - Data transfer itself can be interrupted and resumed, if needed
- Coupled with tagged queuing, provides high flexibility for optimizing command execution
  - Allows command reordering
  - Avoids wasting time idling the bus



# Example: WRITE with split transaction

| Time | Time | STAT | DATA-8 |
|---|---|---|---|
| 4547006302 ns | 0.584 us | SELECT | 88 |
| 4547009868 ns | 3.566 us | MSG OUT | C0 |
| 4547011968 ns | 2.1 us | MSG OUT | 20 |
| 4547014268 ns | 2.3 us | MSG OUT | FE |
| 4547019518 ns | 5.25 us | COMMAND | 2A |
| 4547019918 ns | 0.4 us | COMMAND | 00 |
| 4547020194 ns | 0.276 us | COMMAND | 00 |
| 4547020468 ns | 0.274 us | COMMAND | 03 |
| 4547020794 ns | 0.326 us | COMMAND | 22 |
| 4547021118 ns | 0.324 us | COMMAND | 7F |
| 4547021418 ns | 0.3 us | COMMAND | 00 |
| 4547021718 ns | 0.3 us | COMMAND | 00 |
| 4547021994 ns | 0.276 us | COMMAND | 80 |
| 4547022268 ns | 0.274 us | COMMAND | 00 |
| 4547024850 ns | 2.582 us | MSG IN | 04 |
| 4547339692 ns | 314.842 us | ARBITRATION | 08 |
| 4547340602 ns | 0.91 us | RESELECT | 88 |
| 4547342134 ns | 1.532 us | MSG IN | 80 |
| 4547356896 ns | 14.762 us | MSG IN | 20 |
| 4547358492 ns | 1.596 us | MSG IN | FE |
| 4547378766 ns | 20.274 us | DATA OUT | 00 |
| 4547378868 ns | 0.102 us | DATA OUT | 00 |
| 4547378968 ns | 0.1 us | DATA OUT | 00 |
| 4554061068 ns | 6682.1 us | STATUS | 00 |
| 4554063162 ns | 2.094 us | MSG IN | 00 |

**IDENTIFY message format**

| Bit / Byte | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|
| 0 | IDENTIFY | DISCPRIV | LUN | | | | | |

- Figure shows single SCSI task (command), split in two I/O transactions
- Note that LUN addressing from initiator (MSG OUT C0) allows also DISCONNECT privilege
  - Essentially, tells target that initiator can store in RAM CDB, pointers and status info to resume this command, if needed

# Example: WRITE with split transaction

Link Control message codes

| Code | Support | | | | Message name |
|---|---|---|---|---|---|
| | IU transfers disabled | | IU transfers enabled | | |
| | Init | Targ | Init | Targ | |
| 04h | O | O | O | O | DISCONNECT |

| | | | | |
|---|---|---|---|---|
| 4547024850 ns | 2.582 us | MSG IN | 04 | |
| 4547339692 ns | 314.842 us | ARBITRATION | 08 | = 0000 1000 |
| 4547340602 ns | 0.91 us | RESELECT | 88 | = 1000 1000 |
| 4547342134 ns | 1.532 us | MSG IN | 80 | LUN = 0 |
| 4547356896 ns | 14.762 us | MSG IN | 20 | Simple queue |
| 4547358492 ns | 1.596 us | MSG IN | FE | TAG |
| 4547378766 ns | 20.274 us | DATA OUT | 00 | |

- After last byte of CDB, target disconnects from initiator
  - Task still active and pending
- When ready for transfer, target reconnects
  - Wins arbitration and becomes bus-master (!)
  - Re-selects initiator, which becomes bus-slave (!).
    - SPI functional equivalent to raising interrupt
  - Note that only <u>bus role</u> is reversed, NOT interface role

# Example: WRITE with split transaction

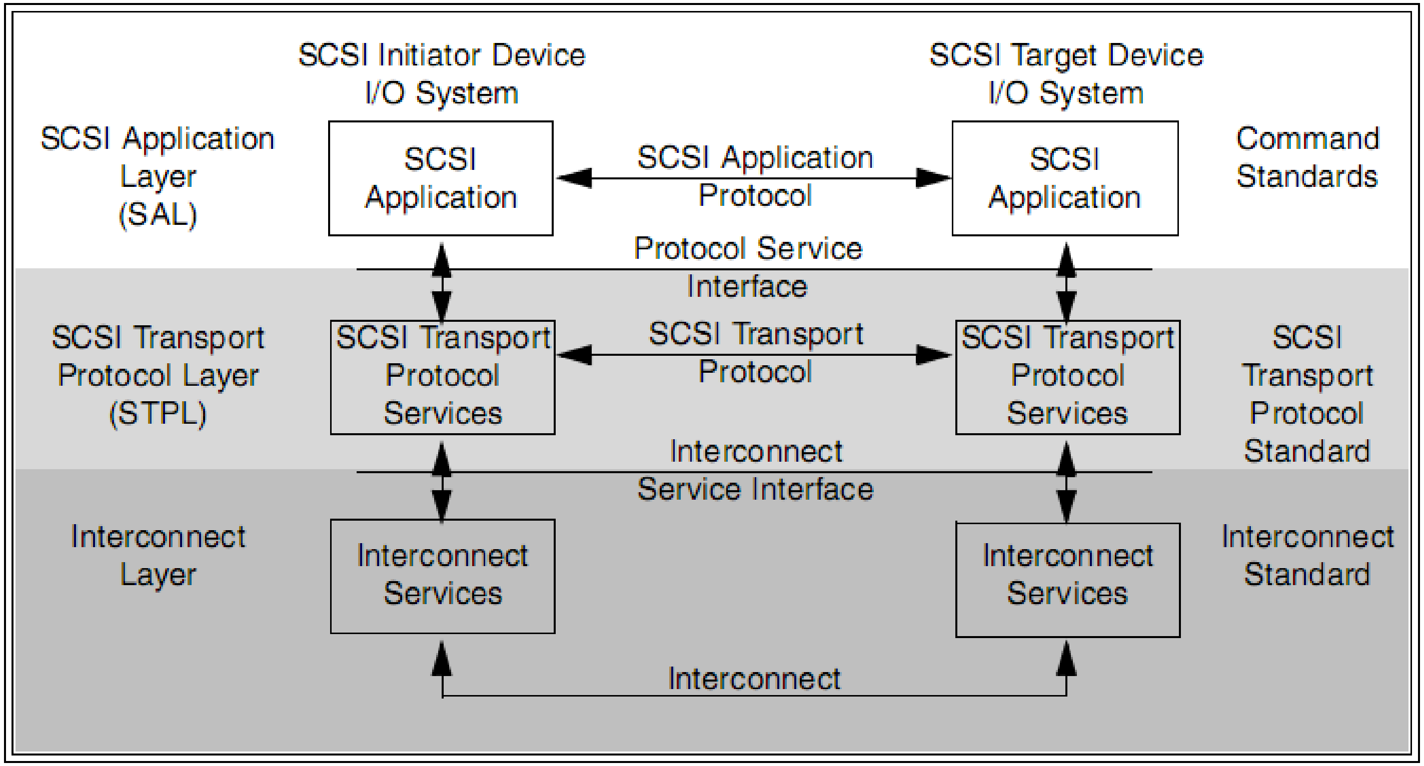
**Link Control message codes**

| Code | Support | | | | Message name |
|---|---|---|---|---|---|
| | IU transfers disabled | | IU transfers enabled | | |
| | Init | Targ | Init | Targ | |
| 04h | O | O | O | O | DISCONNECT |

| | | | | |
|---|---|---|---|---|
| 4547024850 ns | 2.582 us | MSG IN | 04 | |
| 4547339692 ns | 314.842 us | ARBITRATION | 08 | = 0000 1000 |
| 4547340602 ns | 0.91 us | RESELECT | 88 | = 1000 1000 |
| 4547342134 ns | 1.532 us | MSG IN | 80 | LUN = 0 |
| 4547356896 ns | 14.762 us | MSG IN | 20 | Simple queue |
| 4547358492 ns | 1.596 us | MSG IN | FE | TAG |
| 4547378766 ns | 20.274 us | DATA OUT | 00 | |

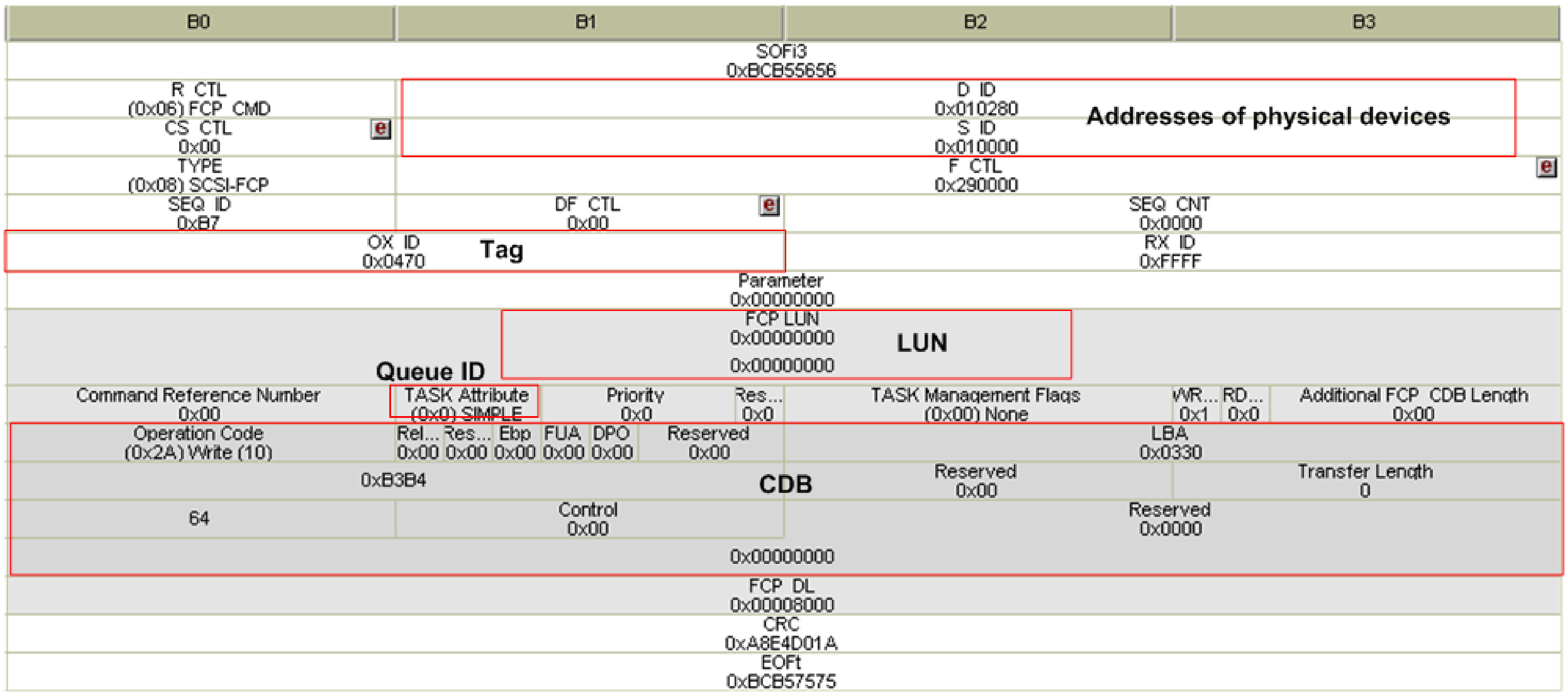
- Target sends now messages to identify task being resumed
  - Addresses LUN, queue and tag
- Disk accepts now data from initiator
- Command ends with Status Good (see end of complete transaction)

# Example: WRITE over other transports



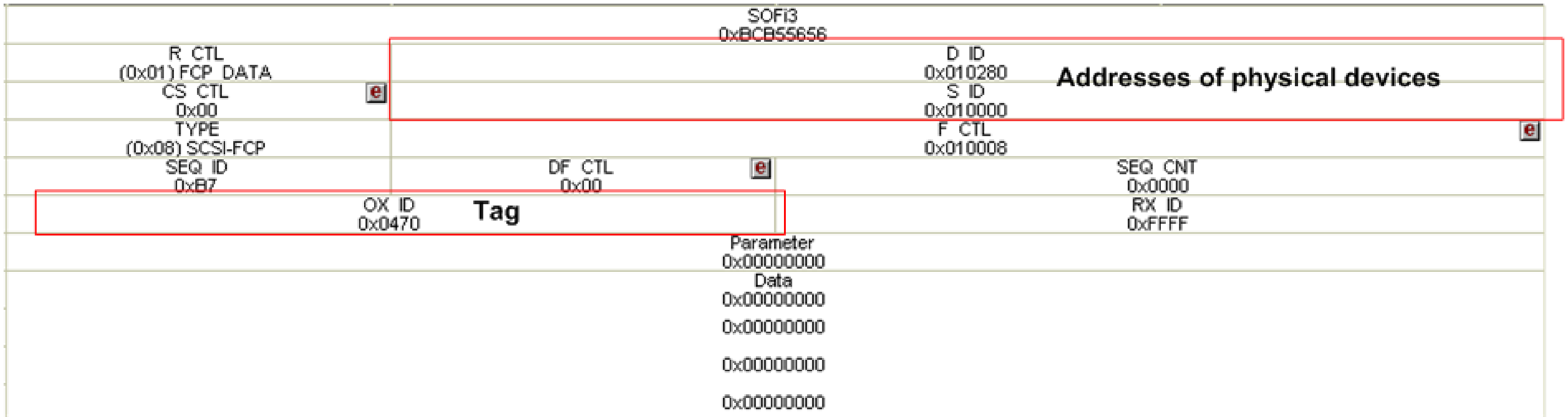

- Layered stack model means that SCSI protocol works the same way over any transport
  - Once understood over parallel SCSI (SPI), it is easy to understand its operation over any other bus

# Example: WRITE over Fibre Channel



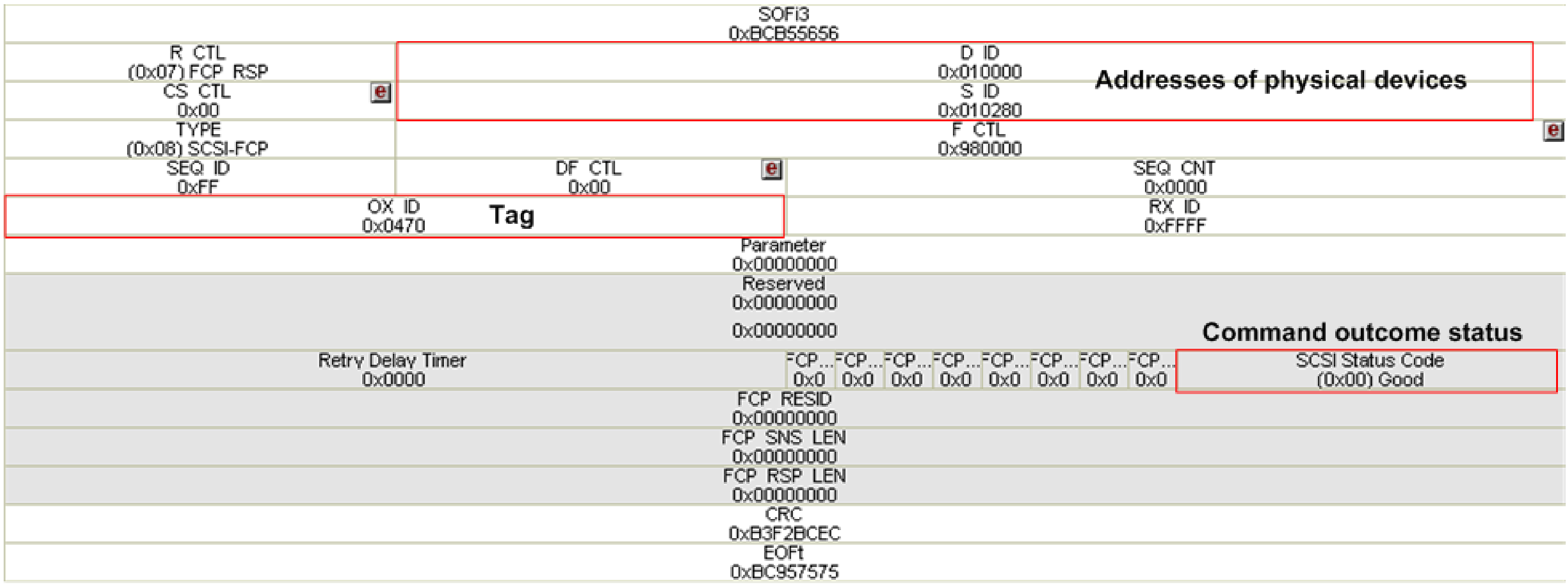

- Figure shows SCSI WRITE(10) command encapsulated within a Fibre Channel frame
  - SCSI protocol payload is straightforward to identify and interpret

# Example: WRITE over Fibre Channel



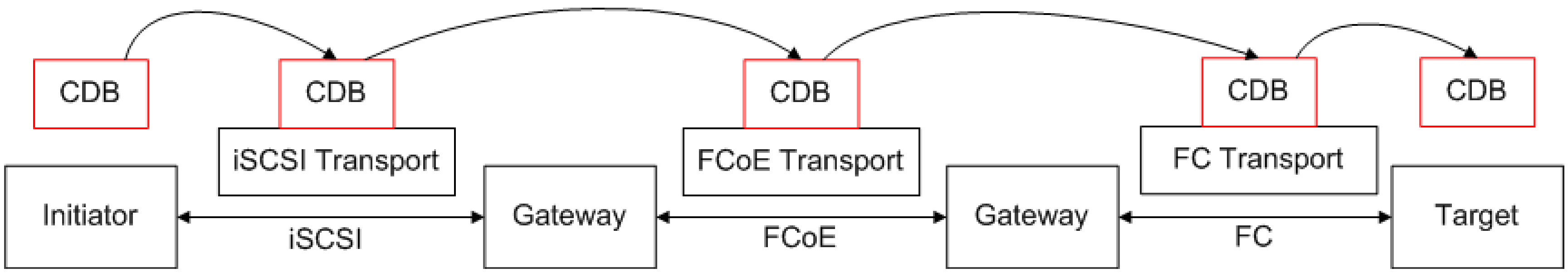

- Figure shows data transfer belonging to that same split transaction
  - Physical identifiers plus tag are enough to recover context of current task

# Example: WRITE over Fibre Channel




- Figure shows frame that completes SCSI protocol for WRITE command
    - Again, physical identifiers plus tag allow to recover context of current task
    - Status code is same as in parallel SCSI

# Summary: SCSI gives great flexibility




- SCSI protocol payload can be hopped from transport to transport with no changes
  - Encapsulation/De-encapsulation is straightforward and reasonably fast
- SCSI allows transaction between initiator and target while traversing several different buses/storage networking infrastructures
  - Ideal for accessing real storage from virtual machines, or for virtualizing storage

# What’s next?

- We’ve seen that most I/O transactions can today be described as the exchange of SCSI payload over various transport layers

- Now we will see how servers and storage devices can be interconnected in storage-specific networks, over which these SCSI exchanges are performed, and how these networks allow for redundant and/or high-performance storage configurations