CS4410

Operating Systems

Where's the puck going?

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Announcements

- **Final: 12/11 @ 9AM, Barton Hall, 100 west**
- Review session: 12/08, 2PM, zoom (post on Ed discussions)
- Lost sessions: thanks for using; makes me happy about my experiments
- **Please fill out the course evaluations**
  - Easy way to get 5%
  - **Please be constructive** (evaluations are for many eyes, not just me)

Taking 25 steps back!

What is an operating system, and what does it do?

A **software layer** designed with three goals:

- Enable applications to **conveniently access hardware**
- **Manage** all hardware resources
- **Implement common services** for applications

What does an OS do?

- Enables **convenient "abstractions"** for applications to access hardware
  - **CPU:** threads
  - **Memory:** virtual memory
  - **Storage devices:** files
  - **Network:** sockets
  - **Server:** collection of resources needed by an application
    - processes, VM, containers

What does an OS do?

- Enables **convenient "abstractions"** for applications to access hardware
- **Manages** hardware resources
    - Resource **allocation** to individual applications
    - Resource **sharing** across concurrently running applications
    - Resource **isolation** across concurrently running applications

What does an OS do?

- Enables **convenient "abstractions"** for applications to access hardware
- **Manages** hardware resources
- Implements **common services** for applications
    - Security, protection and authentication
    - Reliability
    - Communication
    - Input/output operations
    - Program execution
    - ….

Four Fundamental OS Concepts

- **Thread: Execution Context**
  - A single, sequential execution context
- **Address space** (with **translation**)
  - Program's view of memory is distinct from physical memory
- **Process: an instance of a running program**
  - Address Space + One or more Threads + …
- **Protection/Isolation**
  - Only the “system” can access certain resources
  - Combined with translation, isolates programs from each other

Threads

- **A single, sequential execution context**

- **A virtual core: provides illusion of infinite cores**
  - Enables efficient multiplexing of physical cores…
    - …across concurrently running applications

- **Challenges in designing virtual cores**
  - Scheduling, synchronization

- **The OS provides protection/isolation at process granularity**
  - Each thread has its own state
  - Can access other threads' state (within the same process)

CPU scheduling

- **Many different possible scheduling mechanisms**
- **FIFO, SJF, EDF, RR, SRTF**
    - Some are preemptive, some are not preemptive
    - No one-size-fits-all solution
- **Our focus: understanding tradeoffs (pros and cons) of each mechanism**
    - And using the insights to build a near-ideal CPU scheduler
    - Very close to the Linux CFS scheduler
- **Some conceptual takeaways that we studied**
    - Priority scheduling can “emulate” most scheduling mechanisms
    - Priorities should be used to define physical core share
        - Rather than strictly preferential job scheduling

Synchronization

- **Coordination between multiple…**
  - …threads within the same protection/isolation domain
  - …processes and threads operating on shared data
- **A hard problem**
  - No "algorithm" to design a correct-by-design program
- **Our focus:**
  - Understanding the core challenges in synchronization
  - A suite of techniques that can be used
    - Locks, semaphores, condition variables, monitors
  - Hardware support for synchronization

Memory management

- **Virtual address space: virtualizing physical memory address space**
    - Enables efficient multiplexing of memory…
        - …across concurrently running applications

- We focused on three aspects in memory management

- **Efficient sharing of physical resources**
    - Paging, and page replacement

- **Space and time efficient address translation**
    - Space efficiency: multi-level page tables
    - Time efficiency: TLB, small #levels in multi-level page tables

- **Protection**
    - Apps use virtual address, kernel handles physical addresses

Memory management

- **Virtual memory: provides illusion of infinite memory**
  - By swapping/paging data to secondary storage
  - Each program gets the illusion of having dedicated, infinite, memory

- **Paging**
  - Page faults
  - Page replacement mechanisms:
    - Optimal (Belady's algorithm)
    - LRU
    - Approximating LRU: The clock algorithm
    - Working set page replacement
  - Local and global page replacement

Beyond threads, processes and memory

- **The OS must handle all IO devices**
    - Storage devices: HDD, SSD
    - Network devices: NIC
    - Peripheral devices: mouse, keyboards, …
    - And all buses: memory bus, I/O bus, peripheral bus

- **Mechanisms:** Interrupt-driven I/O, DMA

- **Devices**: Mostly SSD, brief discussion on HDD

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- **OS support for handling <u>storage</u> devices**
  - File systems
    - contiguous, linked list, tree-based multi-level index file storage
    - consistent updates
  - Block layer
  - Device drivers (minimal discussion)

Beyond threads, processes and memory

- **The OS must handle all IO devices**
  - Storage devices: HDD, SSD
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  - Peripheral devices: mouse, keyboards, …
  - And all buses: memory bus, I/O bus, peripheral bus

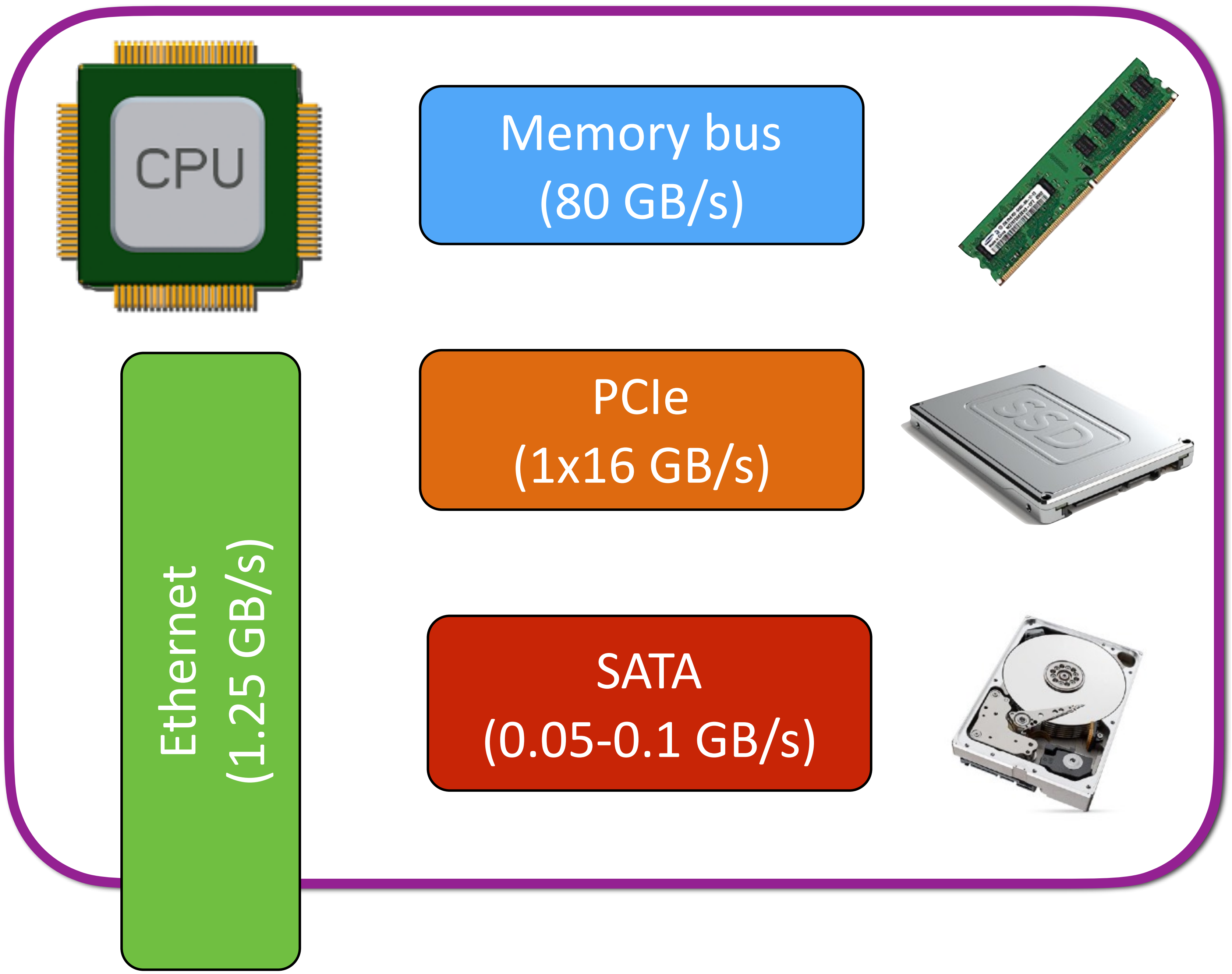
- **OS support for handling <u>network</u> devices**
  - The entire “network stack"
  - End-to-end story
  - Various functionalities that interact with other layers
    - Sockets and ports
    - Packet steering, and tradeoffs
    - Packet aggregation, and tradeoffs

Taking 1 step forward!

Skate where the puck's going, not where it's been!

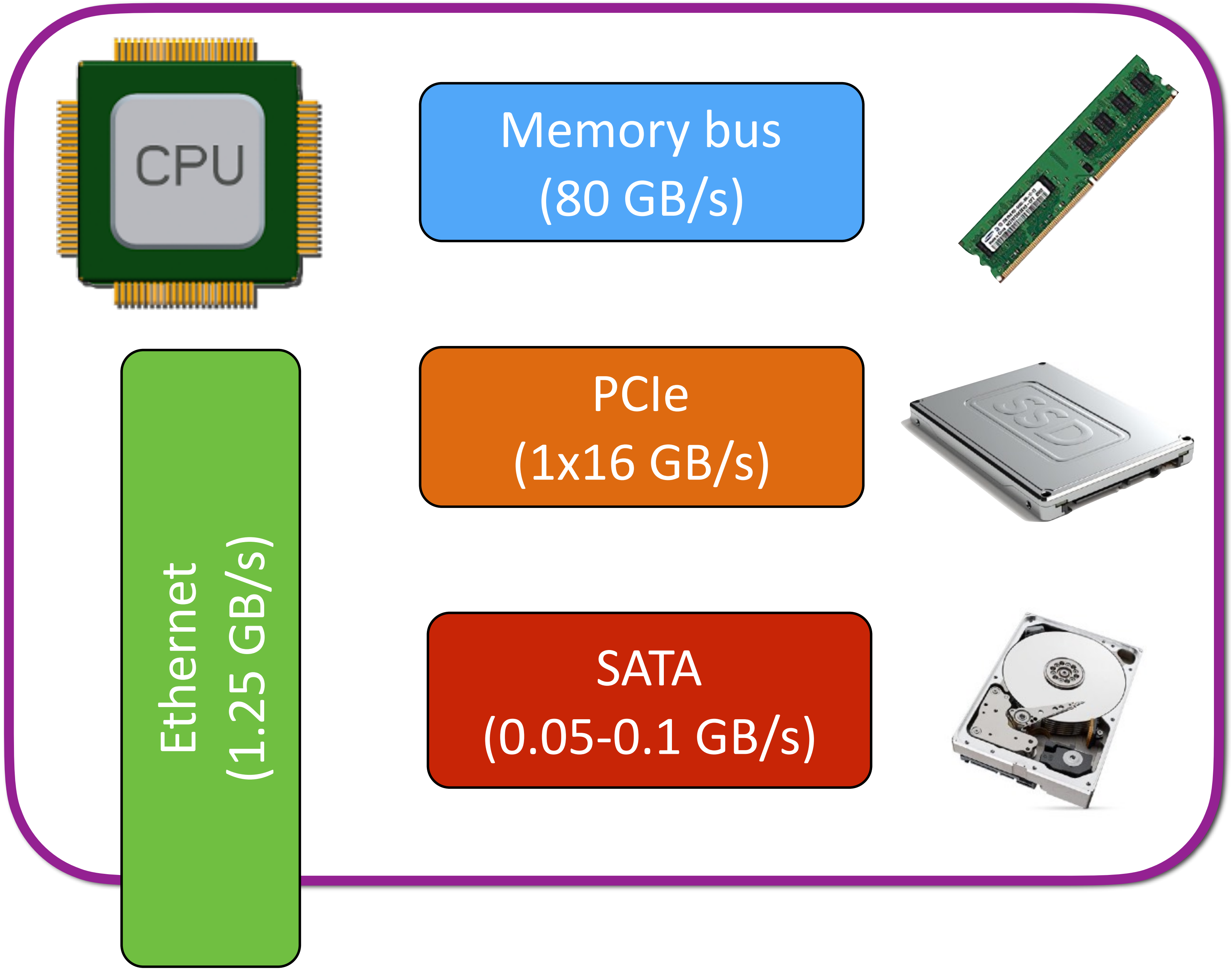
- Walter Gretzky

Where is the puck right now?

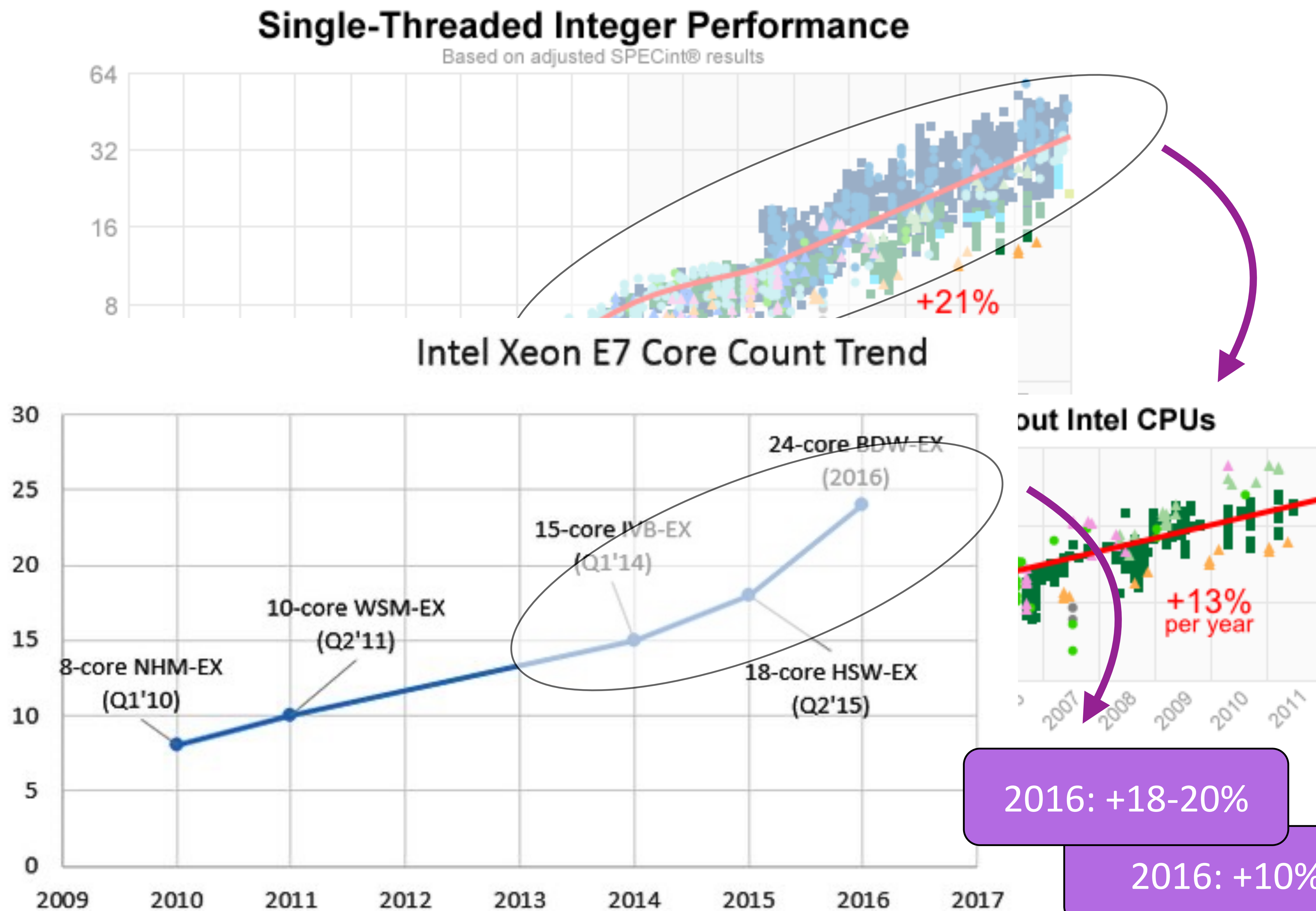


Size (TB)	Random Access (us)	Seq. Access (GB/s)
0.1	0.1	80
1	25	1x
10	4000	0.1x

Where is the puck going?



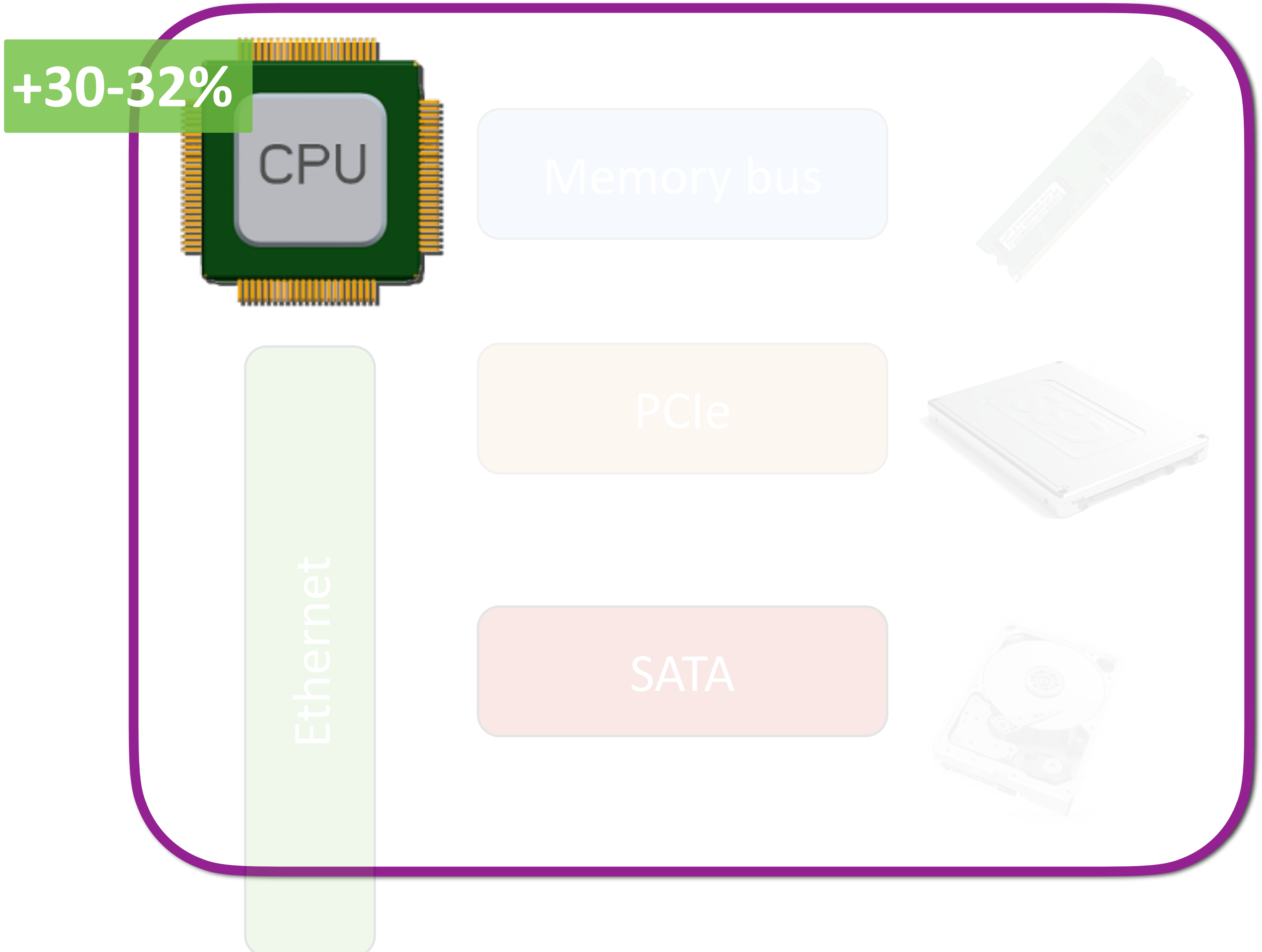
Where is the puck going? (CPU performance)



2016: +18-20%

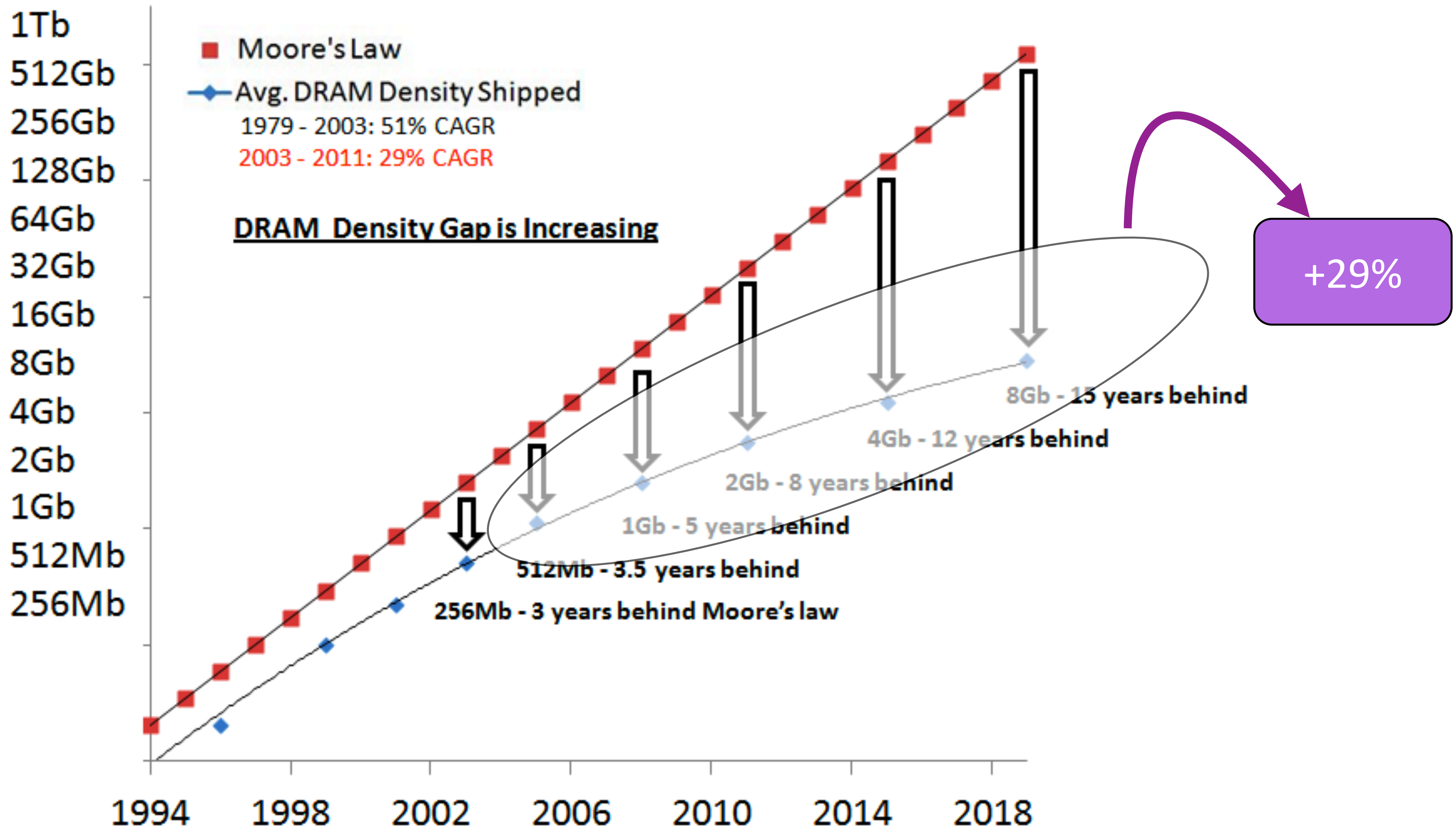
2016: +10%

Where is the puck going?

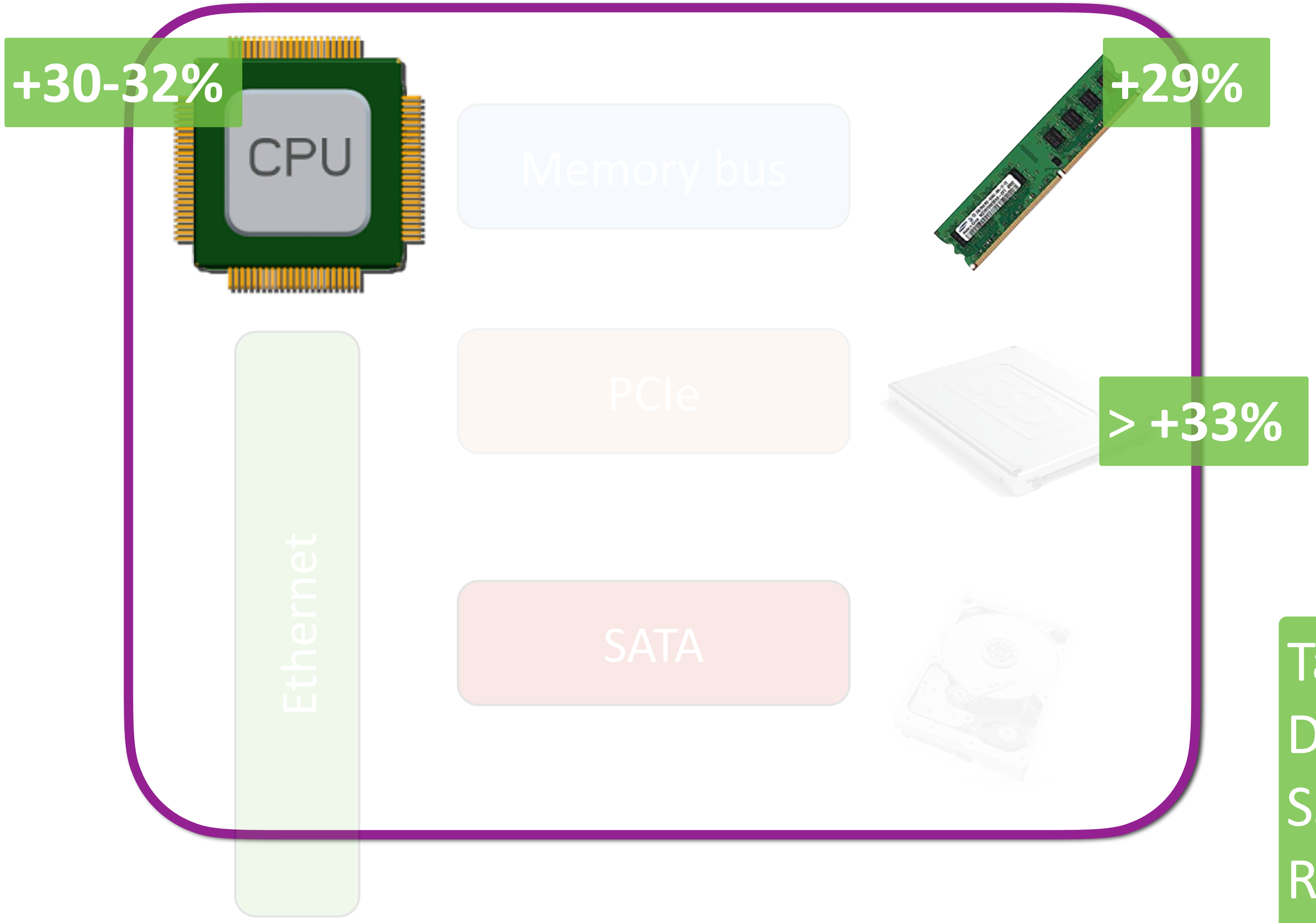


- **#Cores: +18-20%**
- **Per core: +10%**

Where is the puck going? (DRAM capacity)



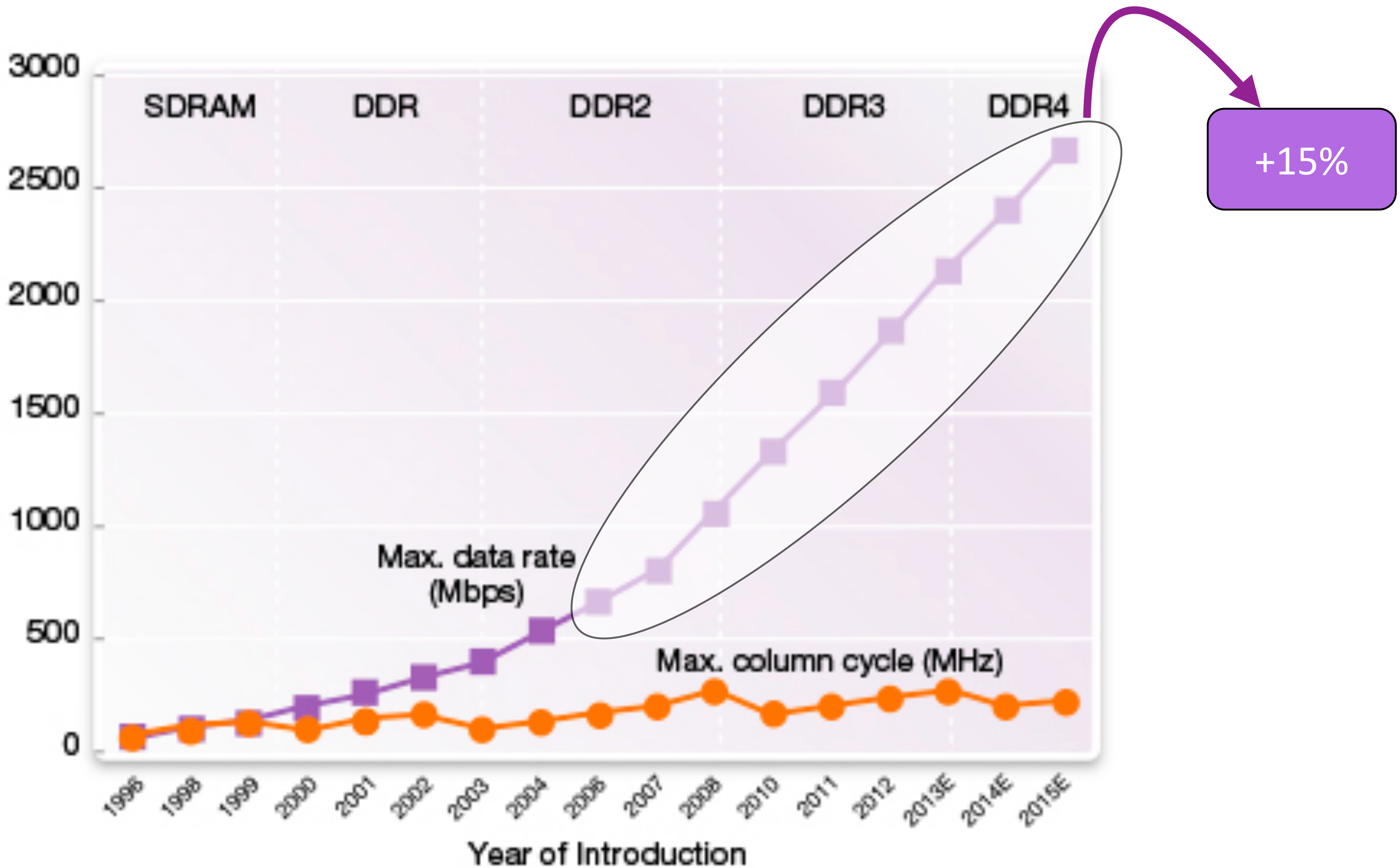
Where is the puck going?



Tape is dead,
Disk is tape,
SSD is disk,
RAM is the king!

- Jim Gray

Where is the puck going? (Memory bus)



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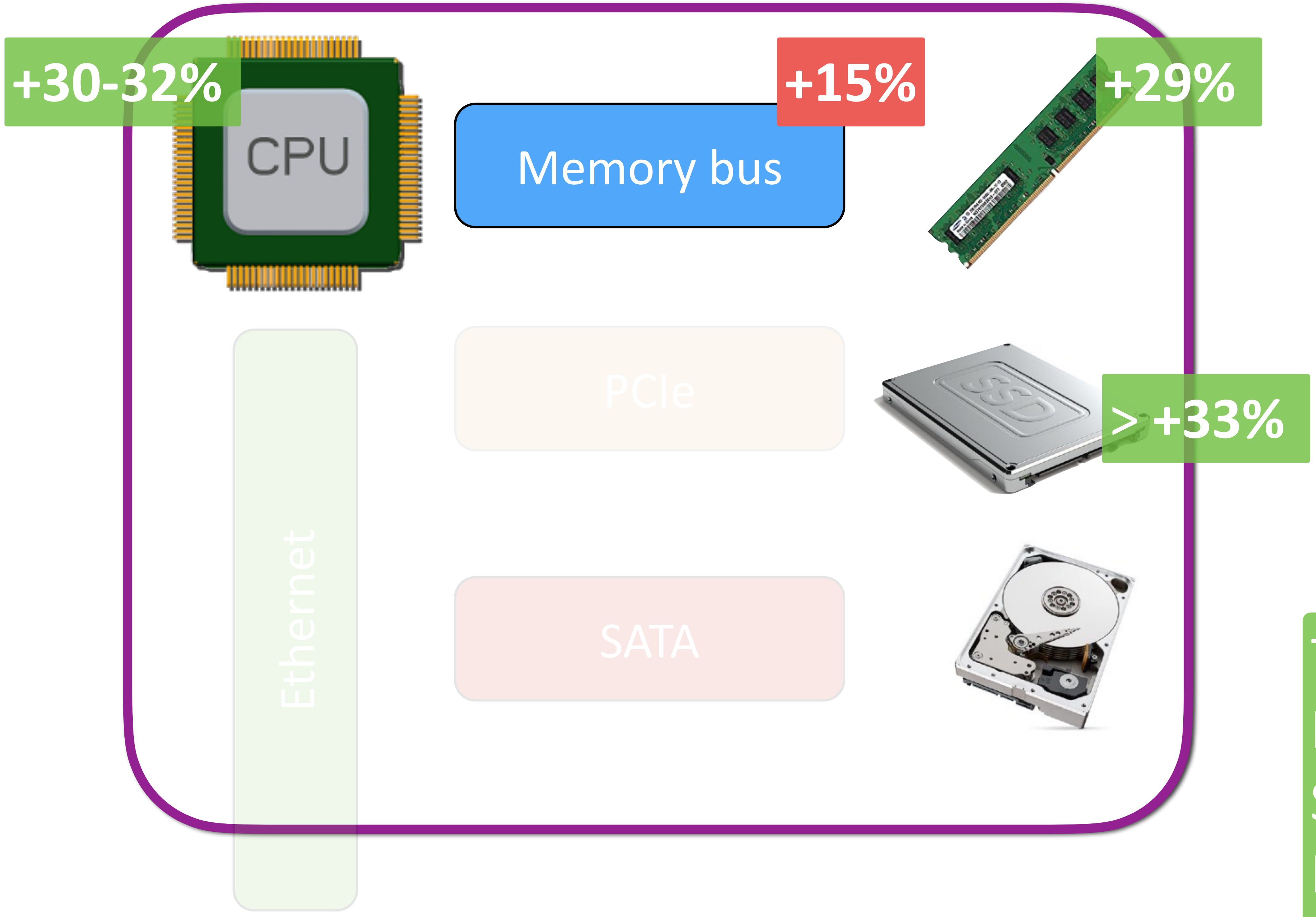

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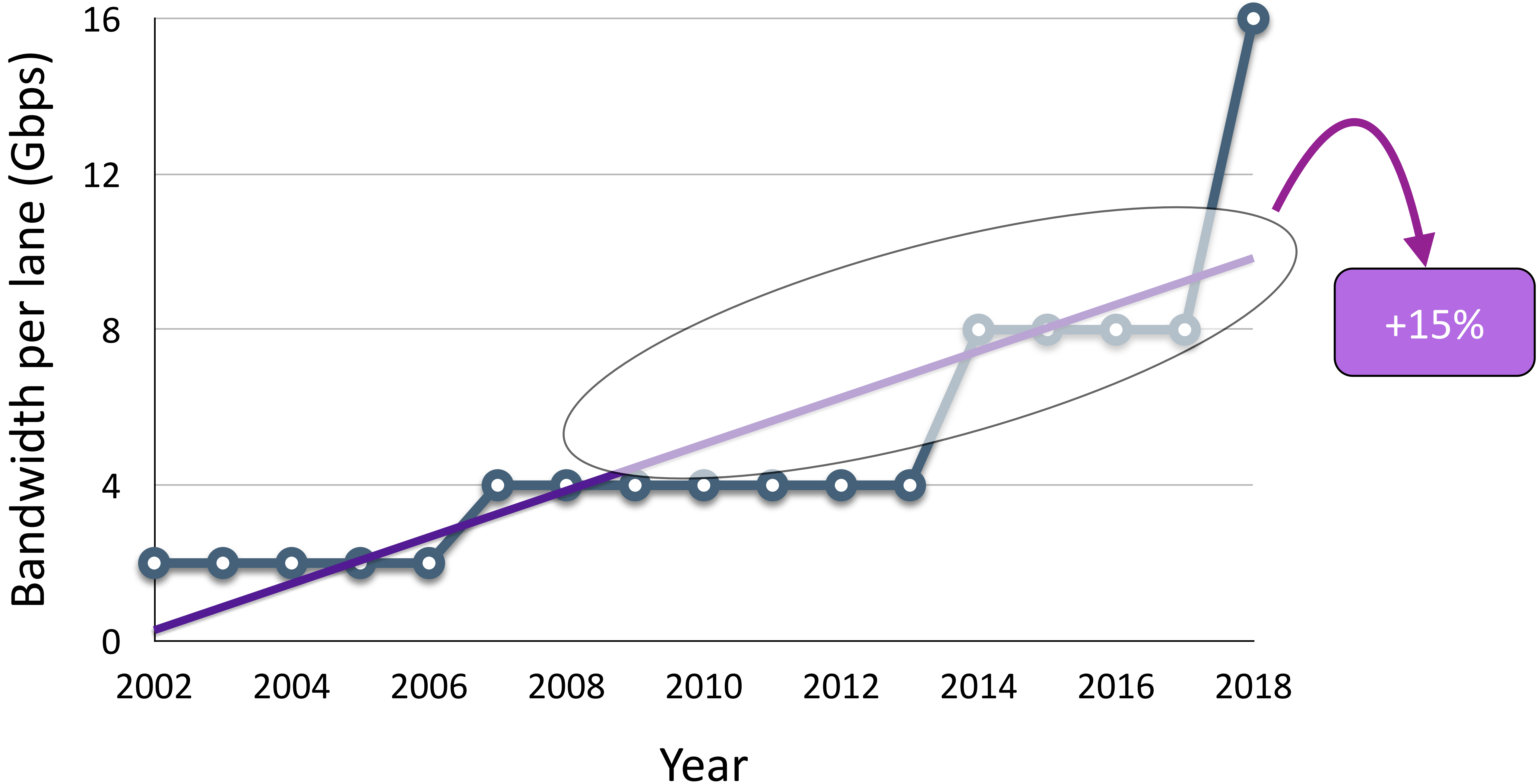
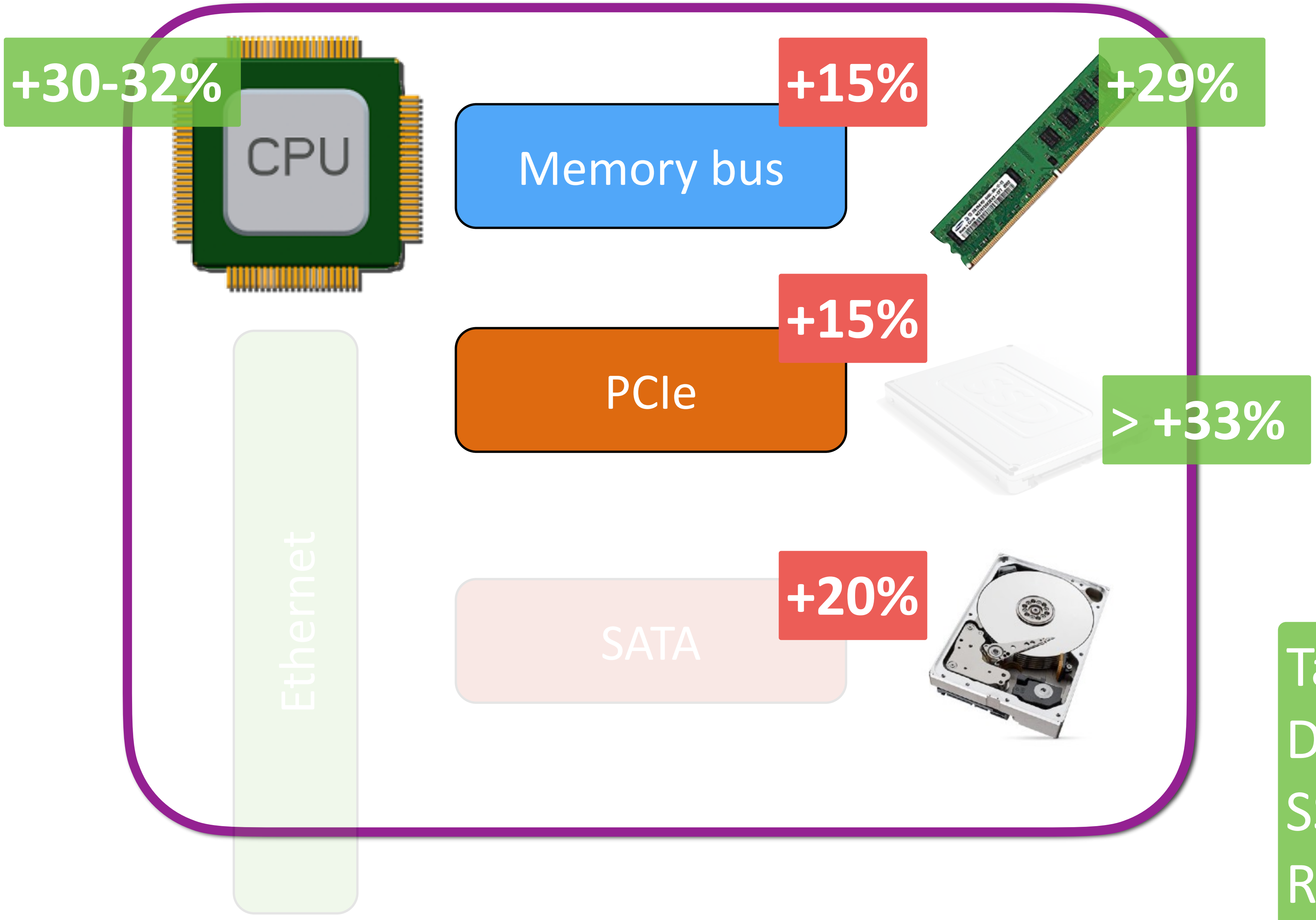
Where is the puck going? (PCIe)



Where is the puck going?



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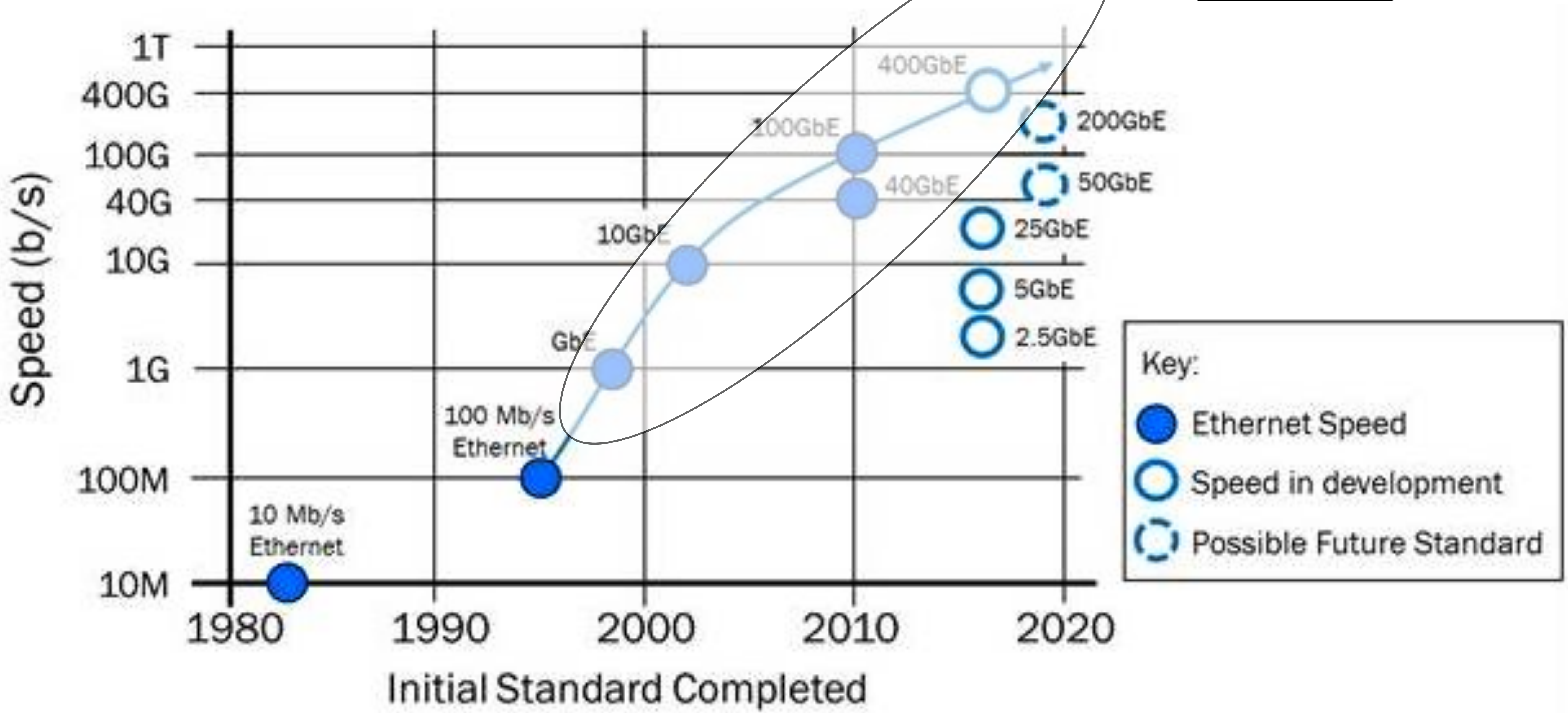
Where is the puck going? (Ethernet)

+33-40%



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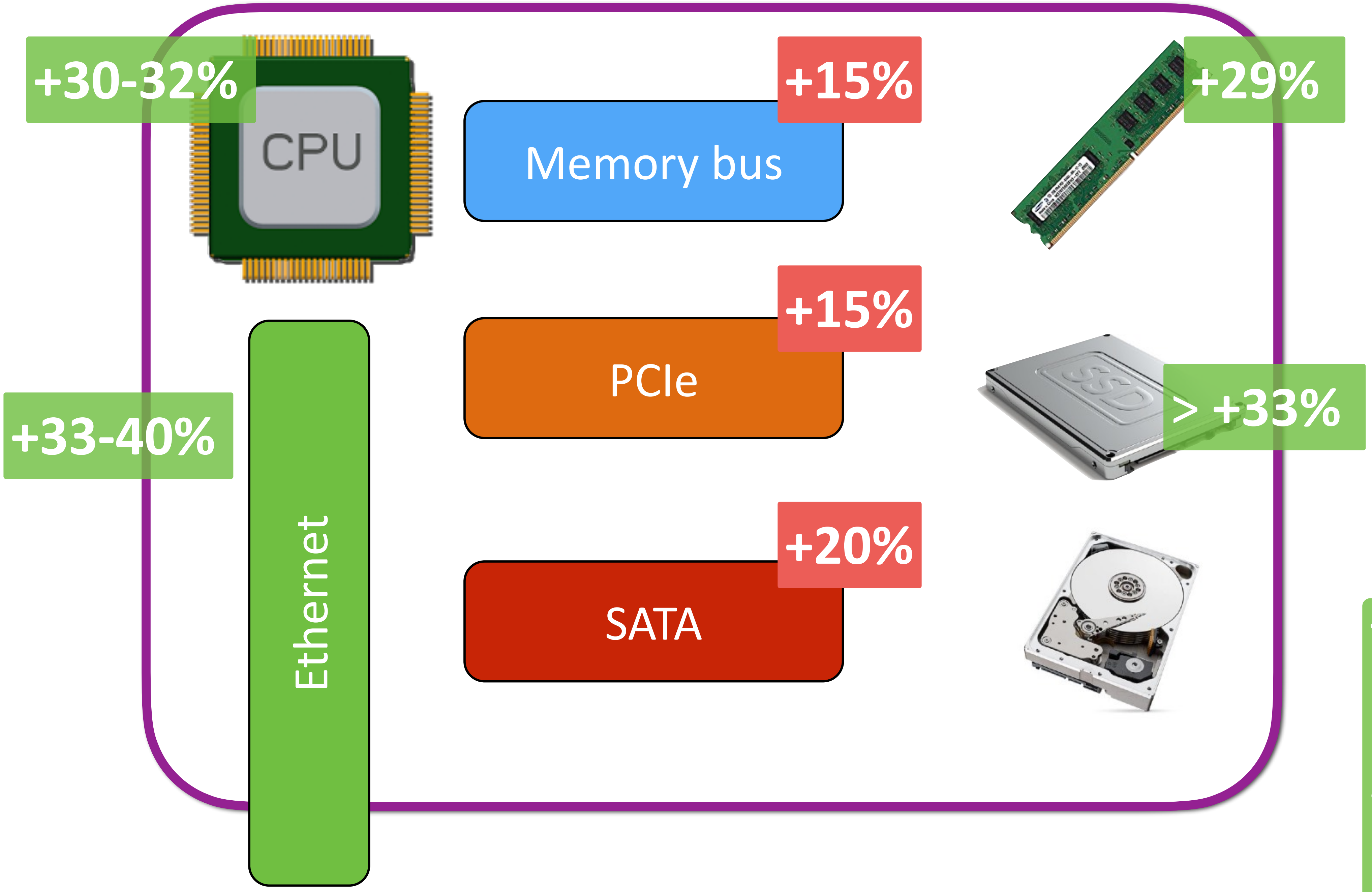

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Many powerful implications

- **CPU is becoming the core bottleneck**
    - Storage devices can achieve 10-100x higher throughput
    - NIC can transmit/receive 10-100x more packets
    - PCIe can transmit/receive 10-100x more data
    - But CPU capacity is mostly stagnant

- **New devices are emerging**
    - New hardware accelerators: for apps that require more compute
        - FPGAs, TPUs, SmartNICs
    - Non-volatile memory devices
        - byte addressable, but persistent
        - 10x slower than main memory, 10x faster than SSD
    - RDMA NICs
        - Can read/write to memory on other servers without CPU

CPU is becoming the bottleneck

- **Today, CPU involved in all steps**
  - Running applications
  - Kernel processing
  - I/O

- **Many of these are heavy-weight operations**
  - Thread and process state management
  - Context switches
  - Swapping and paging
  - Storage access
  - Network access

- Need to rethink design/optimization of each of these layers

Emergence of new devices [Compute]

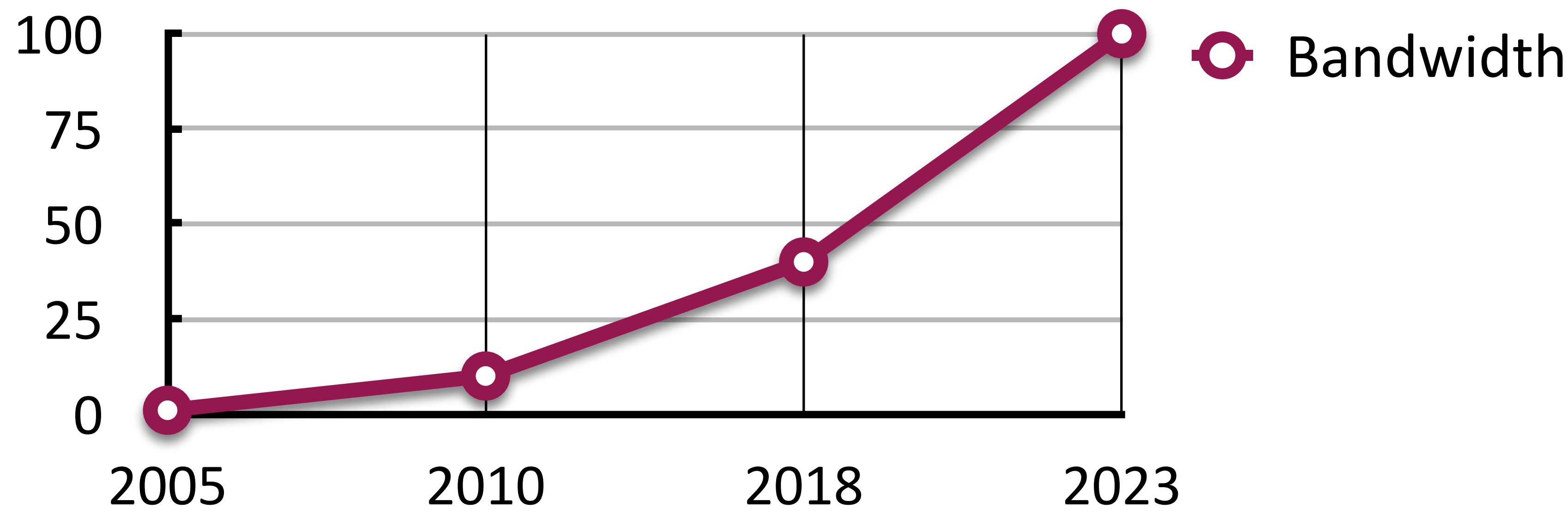
- **New hardware accelerators: for apps that require more compute**
  - How should the OS enable sharing of accelerators?
  - How should the OS orchestrate traditional CPU and accelerator resources?
  - How should CPUs and accelerators share memory?

- **Requires rethinking the abstractions developed over decades**
  - Threads
  - Processes
  - Virtual address space, and virtual memory
  - Sockets

Emergence of new devices [Storage]

- **Non-volatile memory devices**
  - Byte-addressable—like main memory
  - Persistent—like SSDs
  - 10x slower than main memory, 10x faster than SSDs
- **Requires rethinking the abstractions developed over decades**
  - Virtual address space
  - Virtual memory
  - Page replacement

Remote Memory Faster than Local Storage



- **Under zero queueing:**
  - Remote memory access takes less than 6.3us
  - Local SSD access latency today is 25us (hardware, ignoring stack)
  - Remote Direct Memory Access (RDMA) becomes feasible

Emergence of new devices [Network]

- **Remote Direct Memory Access**
    - Enables accessing remote server memory….
        - …without involving remote server CPU
    - “Kernel-bypass”: CPUs can read/write data to NIC without kernel

- **Requires rethinking the abstractions developed over decades**
    - Sockets
    - Protection/isolation
    - Virtual address space, and virtual memory

Operating Systems are the bottleneck again!

- **Lot of research in "user space designs" and kernel-bypass**
  - Minimize kernel involvement
  - Low-overhead CPU scheduling
  - Lots of interesting challenges
- **Lot of research in low-overhead storage stack design**
  - Revisiting File systems, virtual memory, block layer, …
  - To minimize CPU utilization, to achieve low latency and high throughput
  - Extremely interesting challenges
- **Lot of research in low-overhead network stack design**
  - Revisiting the many layers within the network stack
  - To minimize CPU utilization, to achieve low latency and high throughput
  - Requires rethinking host architecture, and host network
  - One of the biggest challenges faced by the OS community

Closing Thoughts

- **These are exciting times for operating systems**
  - The first ever since the invention of SSDs!
  - You are witness to the transformation!!!!
- **And, I am glad I got the chance to introduce you to this world :-)**
  - You have made me a better teacher!!!!
  - Thank you.
- **Wherever you end up:**
  - Please remember me
  - Say hello if you see me
  - Remember, there is nothing more important than
    - **Knowing the fundamentals!!!!**
    - **Being happy!!!!**