

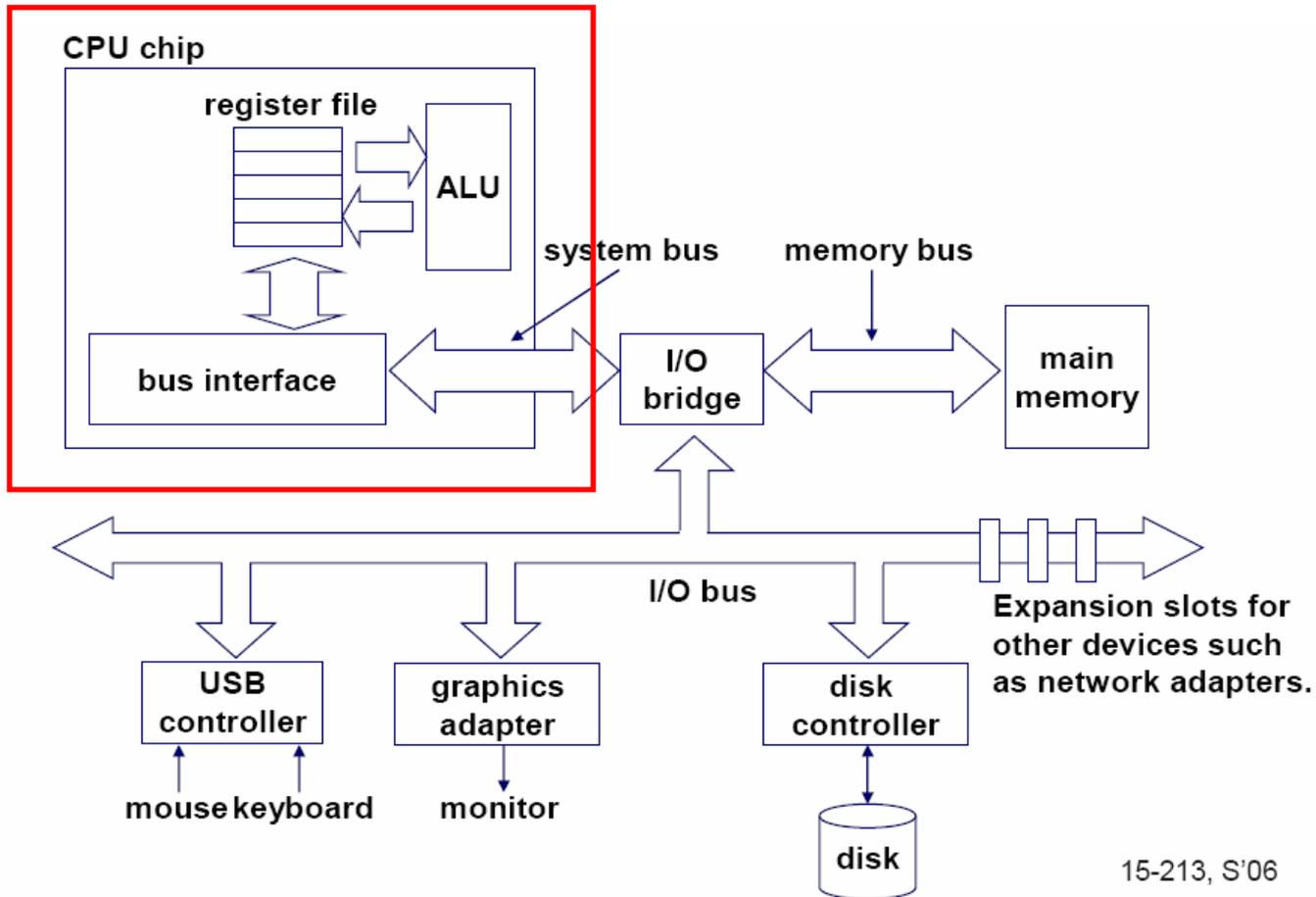
# Multi-core architectures

Jernej Barbic

15-213, Spring 2007

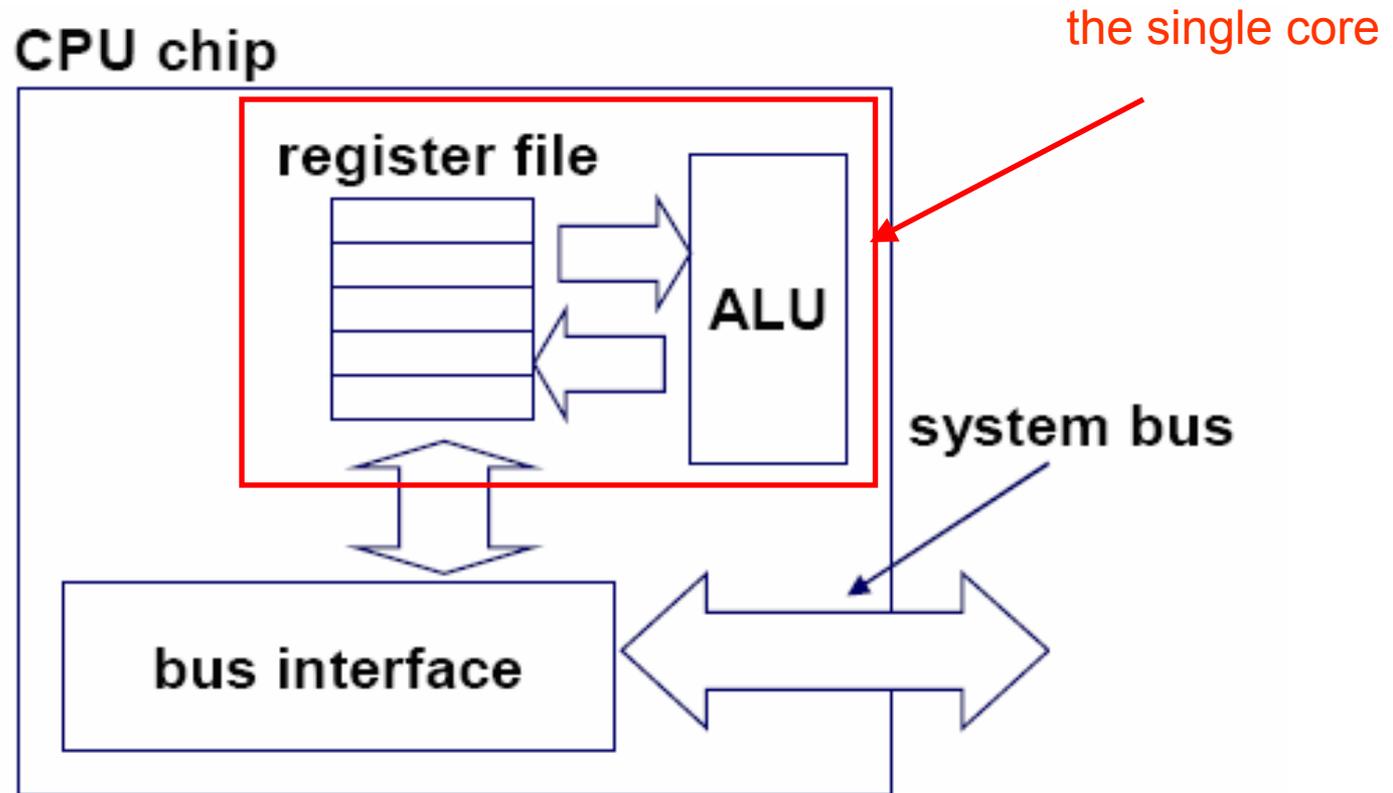
May 3, 2007

# Single-core computer



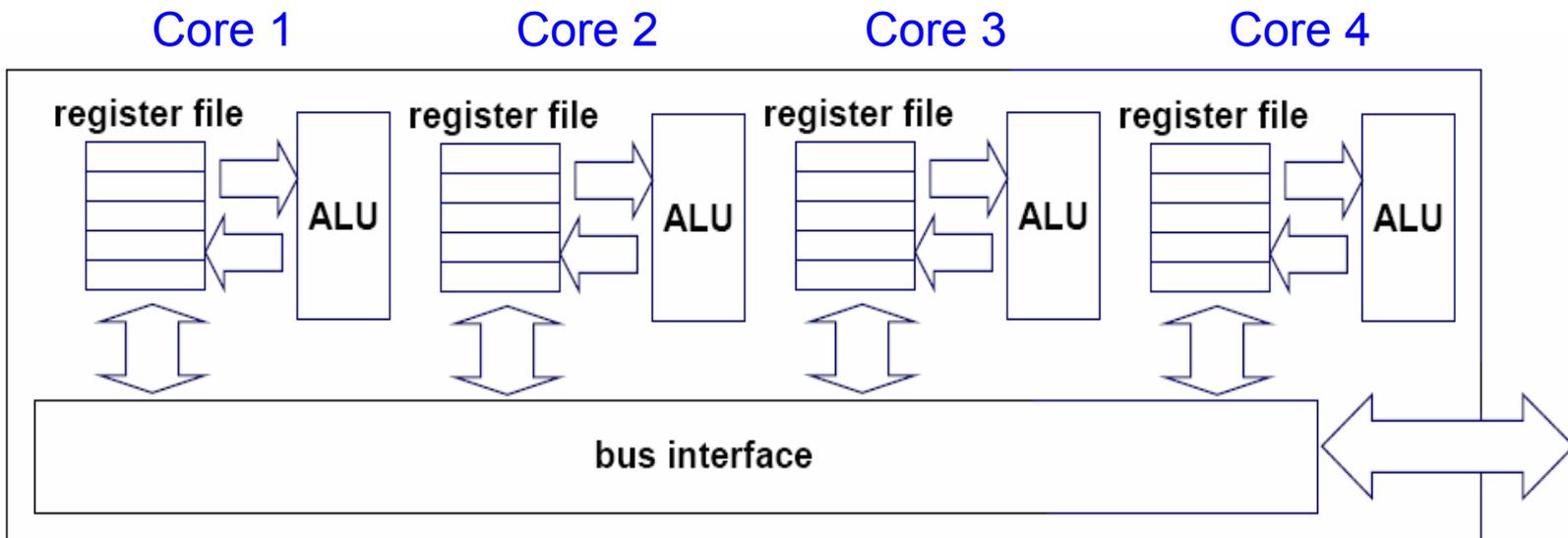
15-213, S'06

# Single-core CPU chip



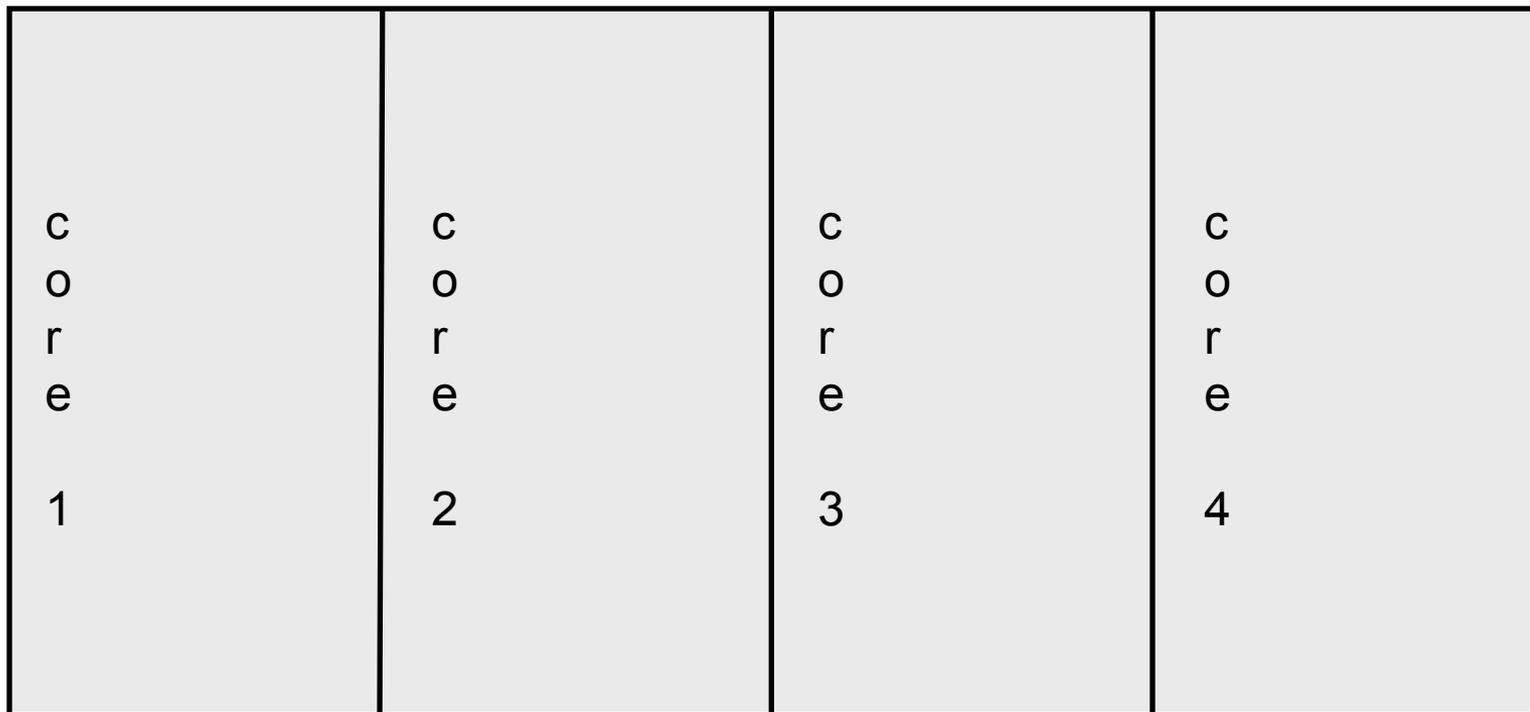
# Multi-core architectures

- This lecture is about a new trend in computer architecture:  
Replicate multiple processor cores on a single die.

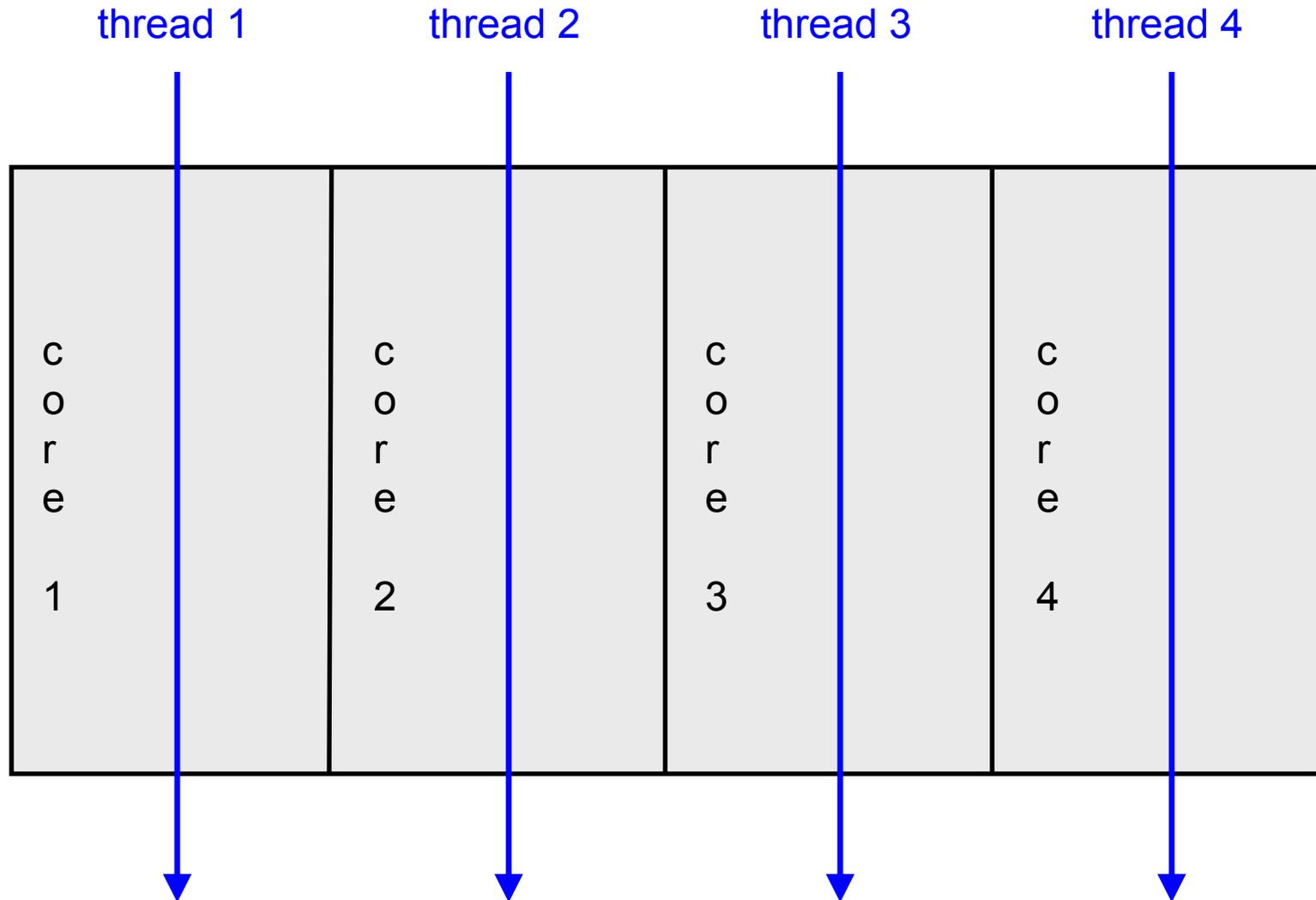


# Multi-core CPU chip

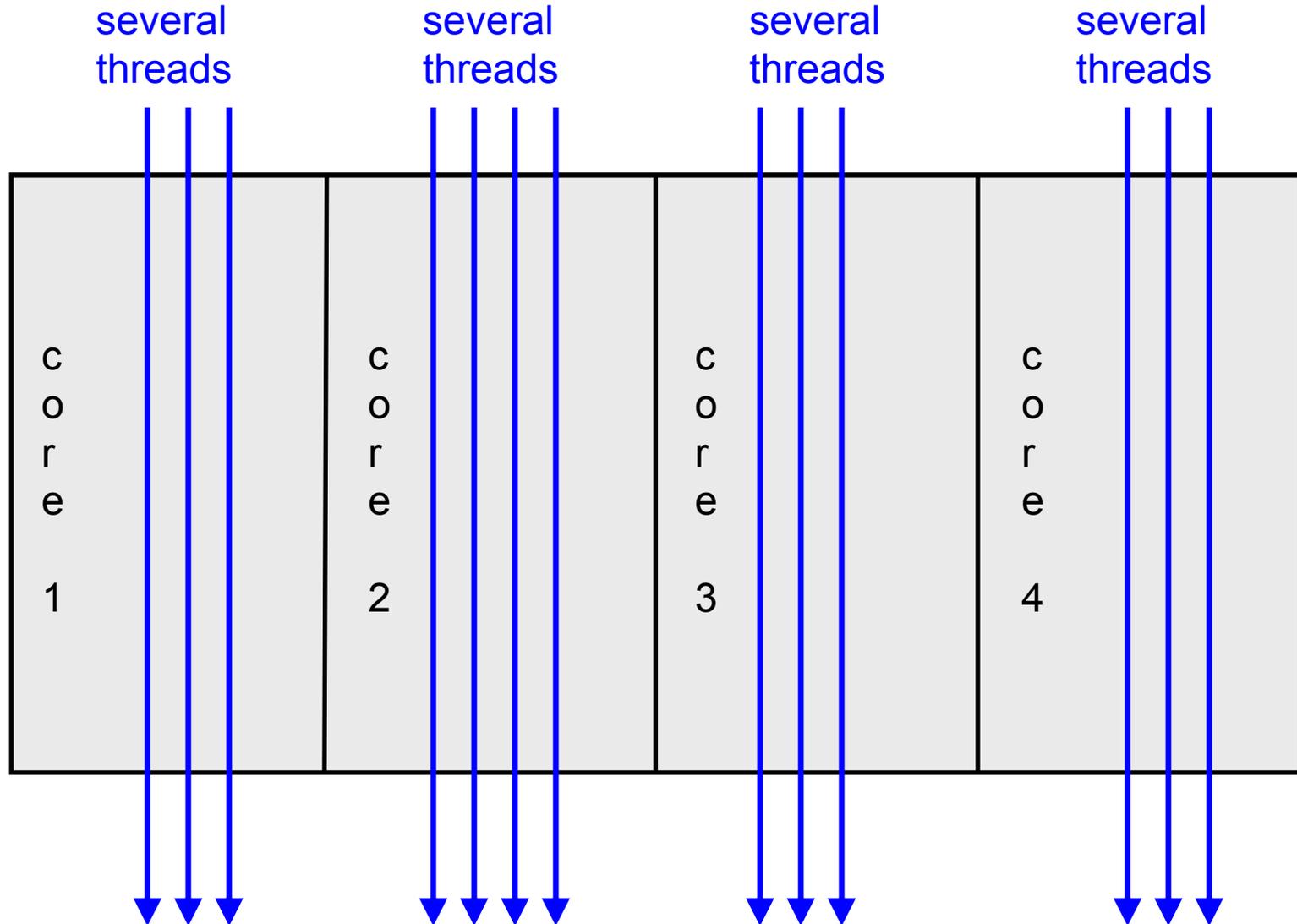
- The cores fit on a single processor socket
- Also called CMP (Chip Multi-Processor)



# The cores run in parallel



# Within each core, threads are time-sliced (just like on a uniprocessor)



# Interaction with the Operating System

- OS perceives each core as a separate processor
- OS scheduler maps threads/processes to different cores
- Most major OS support multi-core today: Windows, Linux, Mac OS X, ...

# Why multi-core ?

- Difficult to make single-core clock frequencies even higher
- Deeply pipelined circuits:
  - heat problems
  - speed of light problems
  - difficult design and verification
  - large design teams necessary
  - server farms need expensive air-conditioning
- Many new applications are multithreaded
- General trend in computer architecture (shift towards more parallelism)



# Instruction-level parallelism

- Parallelism at the machine-instruction level
- The processor can re-order, pipeline instructions, split them into microinstructions, do aggressive branch prediction, etc.
- Instruction-level parallelism enabled rapid increases in processor speeds over the last 15 years

# Thread-level parallelism (TLP)

- This is parallelism on a more coarser scale
- Server can serve each client in a separate thread (Web server, database server)
- A computer game can do AI, graphics, and physics in three separate threads
- Single-core superscalar processors cannot fully exploit TLP
- Multi-core architectures are the next step in processor evolution: explicitly exploiting TLP

# General context: Multiprocessors

- Multiprocessor is any computer with several processors
- SIMD
  - Single instruction, multiple data
  - Modern graphics cards
- MIMD
  - Multiple instructions, multiple data



Lemieux cluster,  
Pittsburgh  
supercomputing  
center

# Multiprocessor memory types

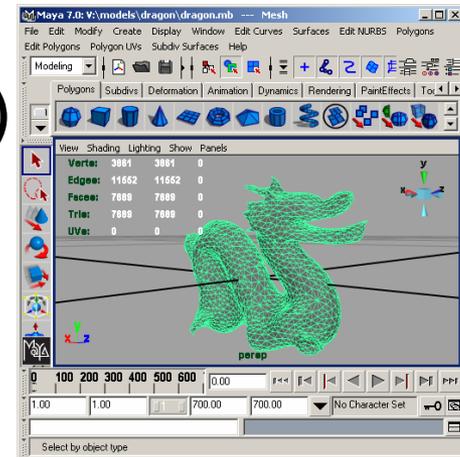
- Shared memory:  
In this model, there is one (large) common shared memory for all processors
- Distributed memory:  
In this model, each processor has its own (small) local memory, and its content is not replicated anywhere else

Multi-core processor is a special kind of a multiprocessor:  
All processors are on the same chip

- Multi-core processors are MIMD: Different cores execute different threads (Multiple Instructions), operating on different parts of memory (Multiple Data).
- Multi-core is a shared memory multiprocessor: All cores share the same memory

# What applications benefit from multi-core?

- Database servers
- Web servers (Web commerce)
- Compilers
- Multimedia applications
- Scientific applications, CAD/CAM
- In general, applications with *Thread-level parallelism* (as opposed to instruction-level parallelism)



Each can run on its own core



# More examples

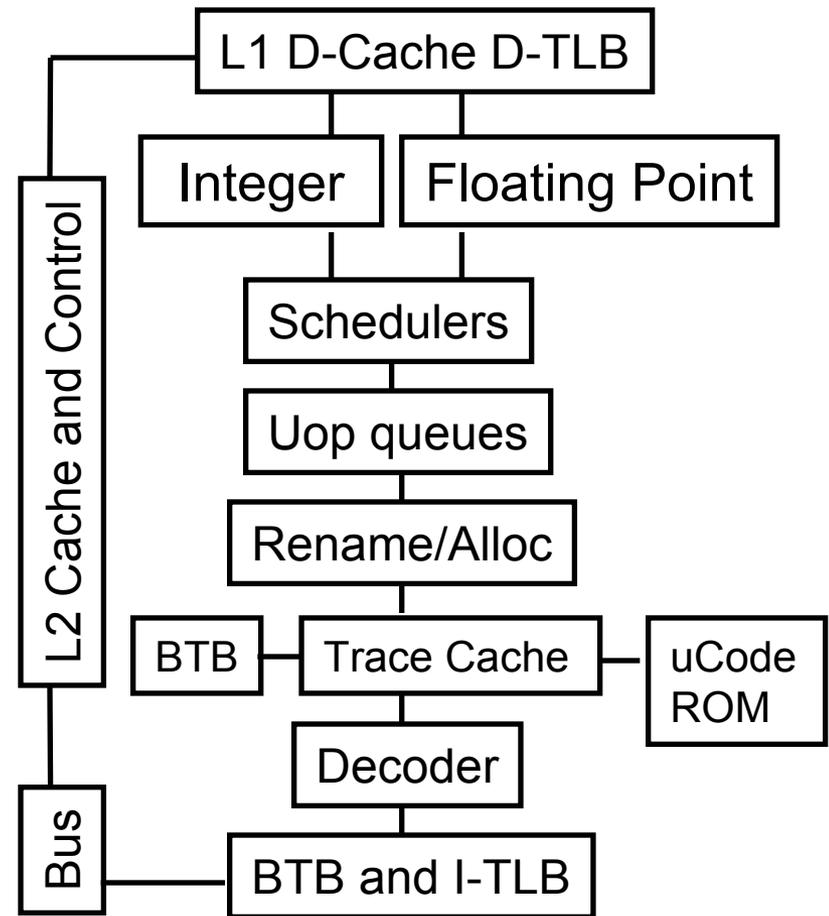
- Editing a photo while recording a TV show through a digital video recorder
- Downloading software while running an anti-virus program
- “Anything that can be threaded today will map efficiently to multi-core”
- BUT: some applications difficult to parallelize

# A technique complementary to multi-core: Simultaneous multithreading

- Problem addressed:  
The processor pipeline can get stalled:

- Waiting for the result of a long floating point (or integer) operation
- Waiting for data to arrive from memory

Other execution units wait unused

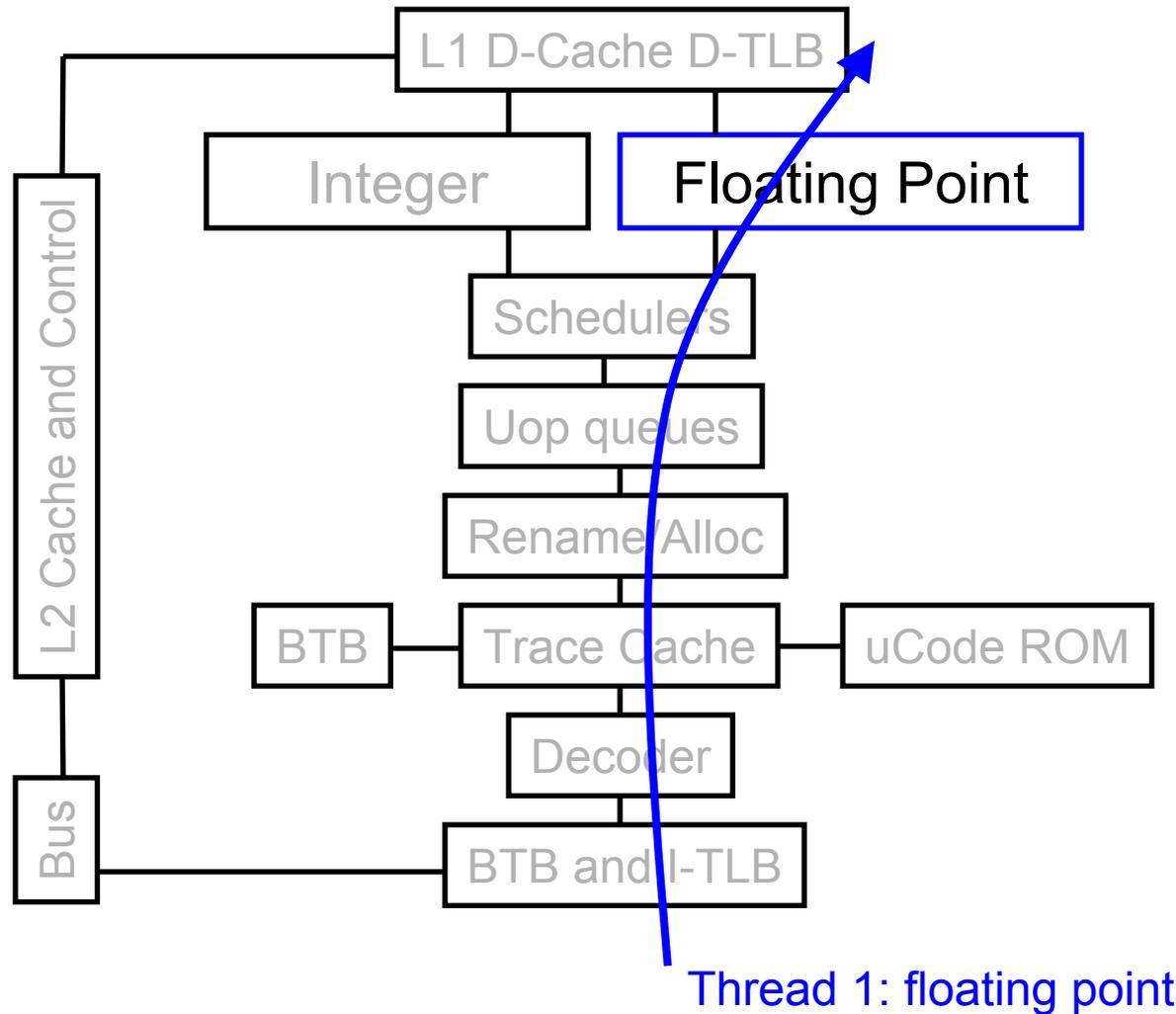


Source: Intel

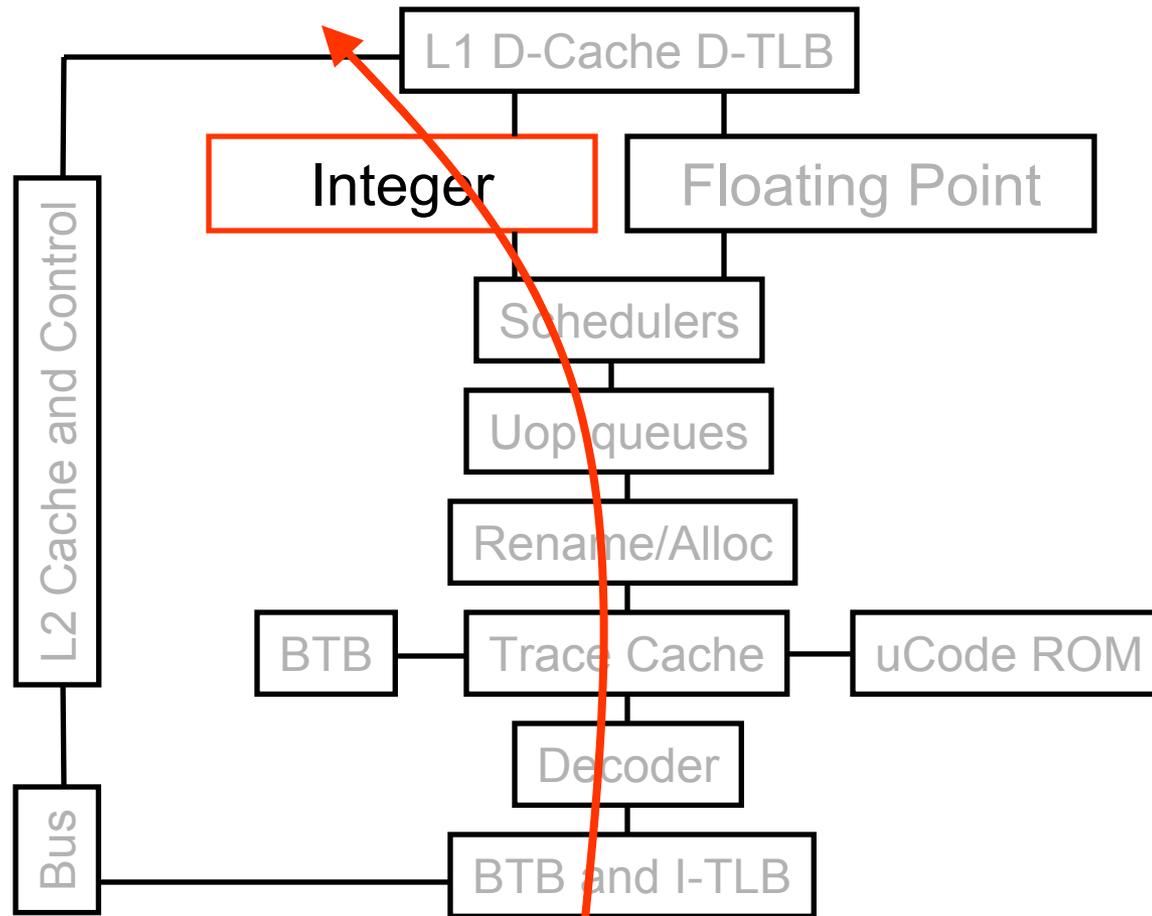
# Simultaneous multithreading (SMT)

- Permits multiple independent threads to execute **SIMULTANEOUSLY** on the **SAME** core
- Weaving together multiple “threads” on the same core
- Example: if one thread is waiting for a floating point operation to complete, another thread can use the integer units

# Without SMT, only a single thread can run at any given time

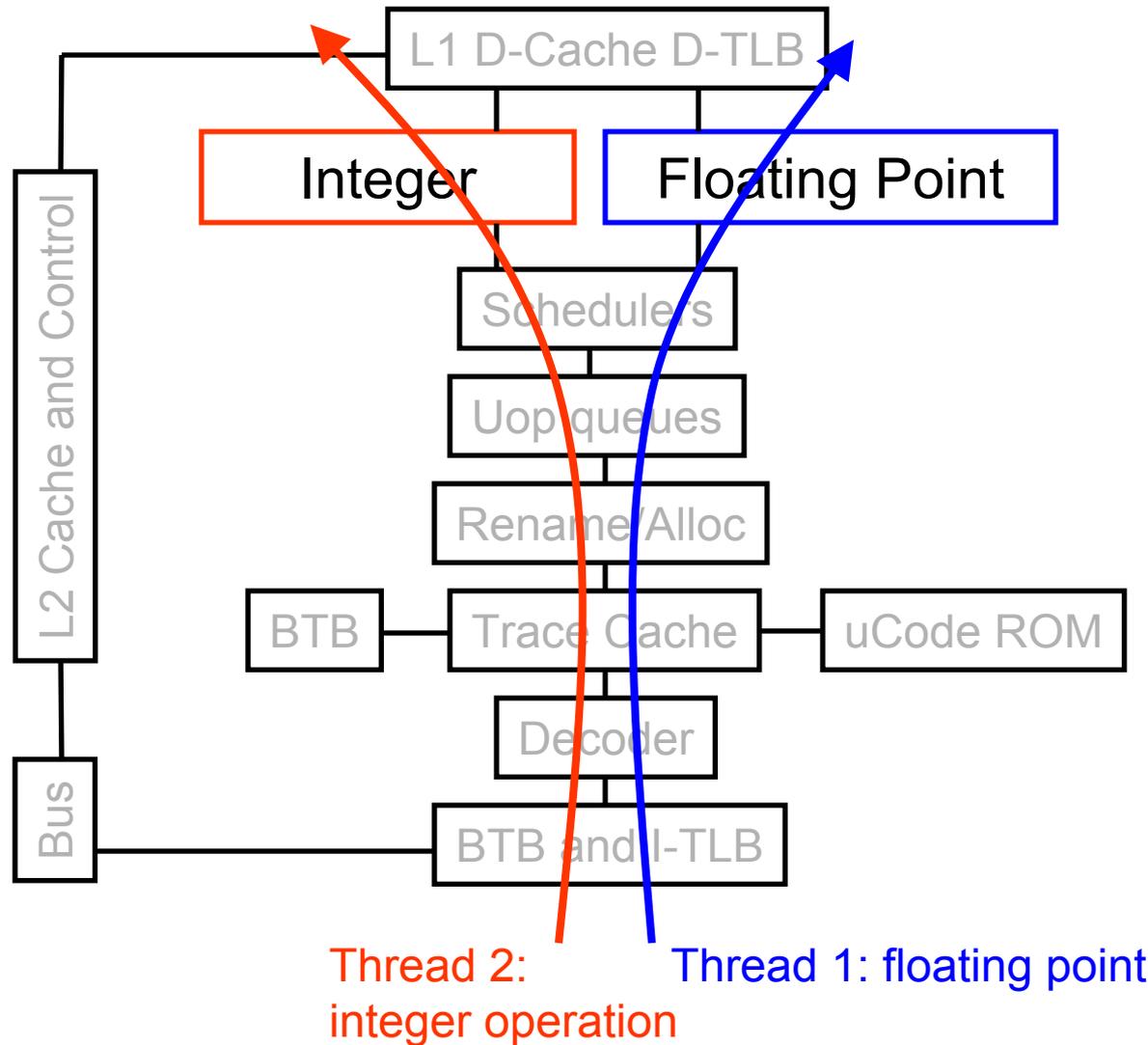


# Without SMT, only a single thread can run at any given time

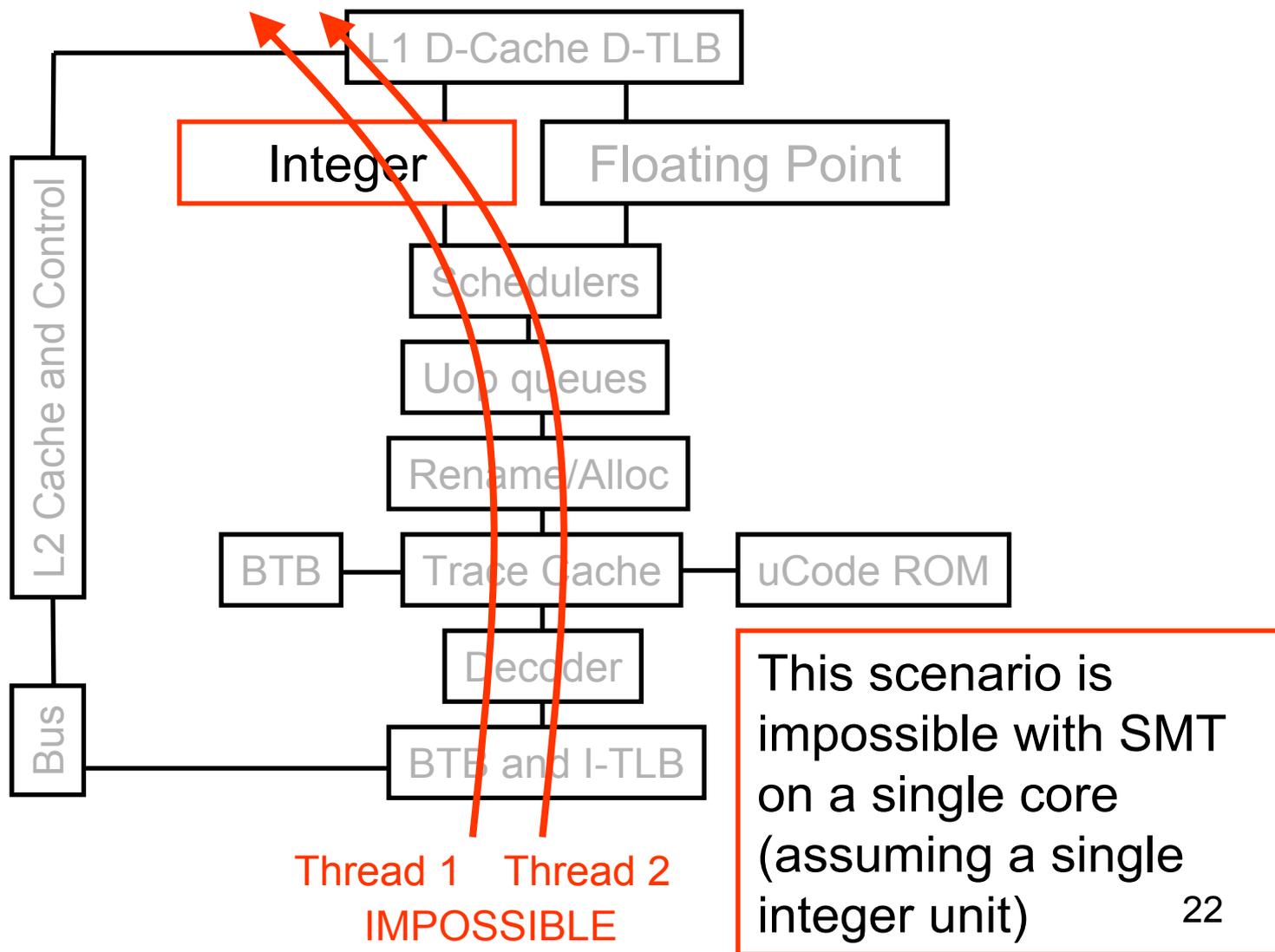


Thread 2:  
integer operation

# SMT processor: both threads can run concurrently



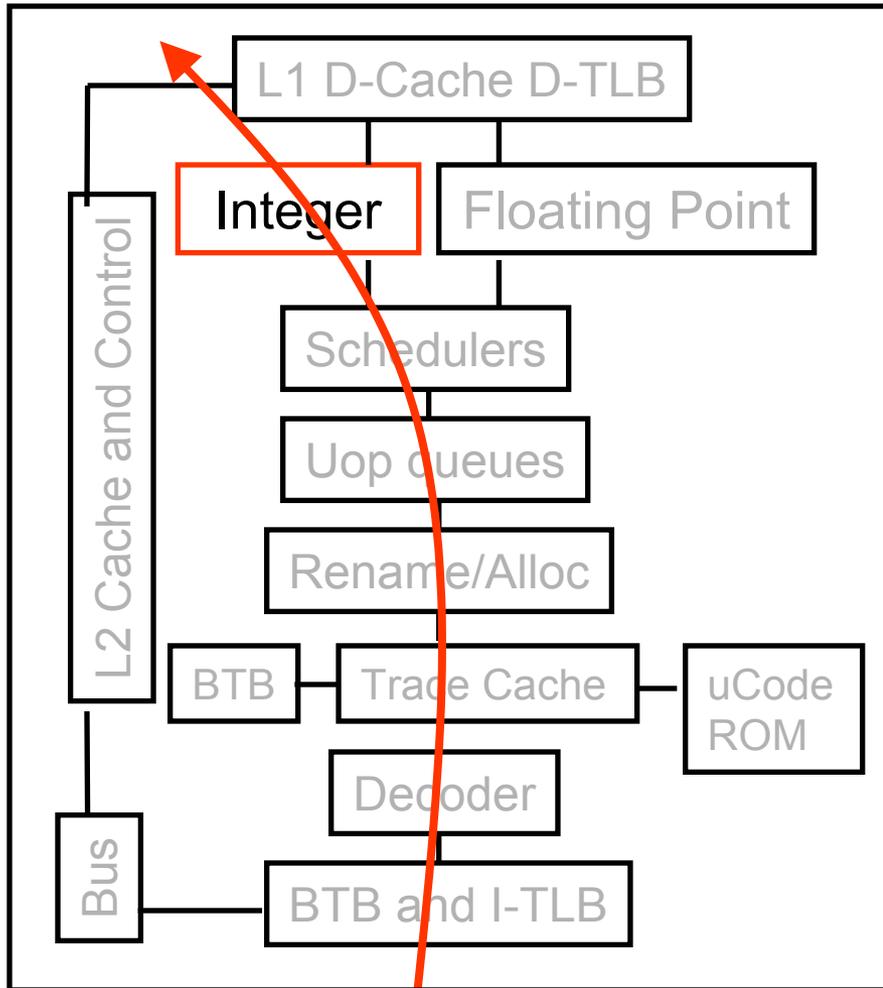
# But: Can't simultaneously use the same functional unit



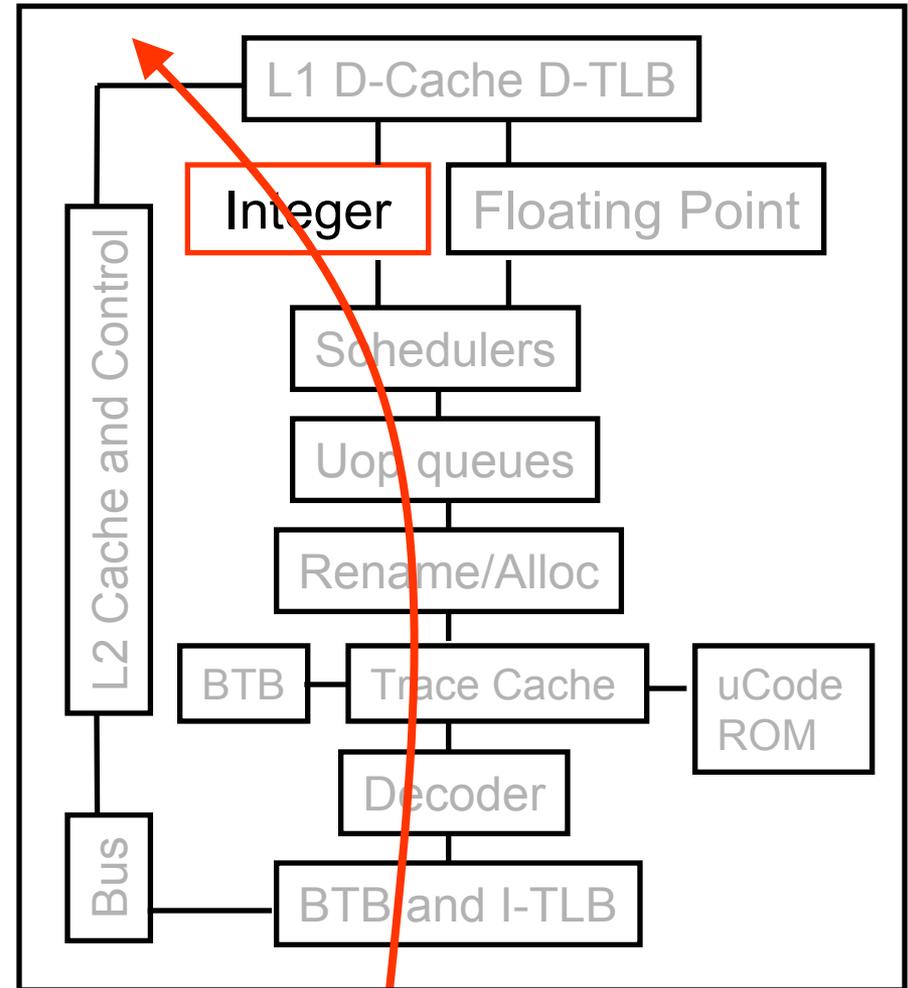
# SMT not a “true” parallel processor

- Enables better threading (e.g. up to 30%)
- OS and applications perceive each simultaneous thread as a separate “virtual processor”
- The chip has only a single copy of each resource
- Compare to multi-core:  
each core has its own copy of resources

# Multi-core: threads can run on separate cores

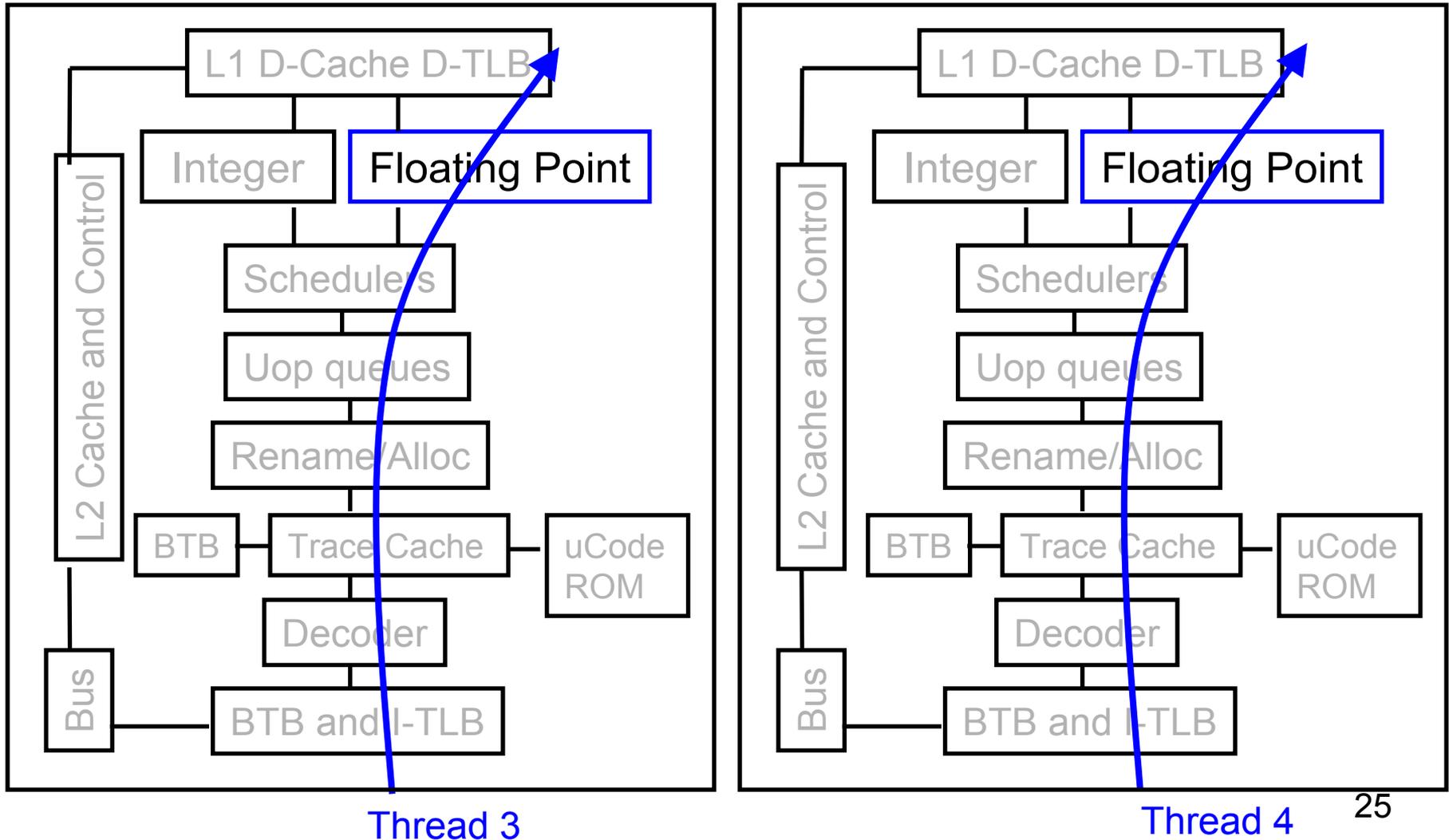


Thread 1



Thread 2

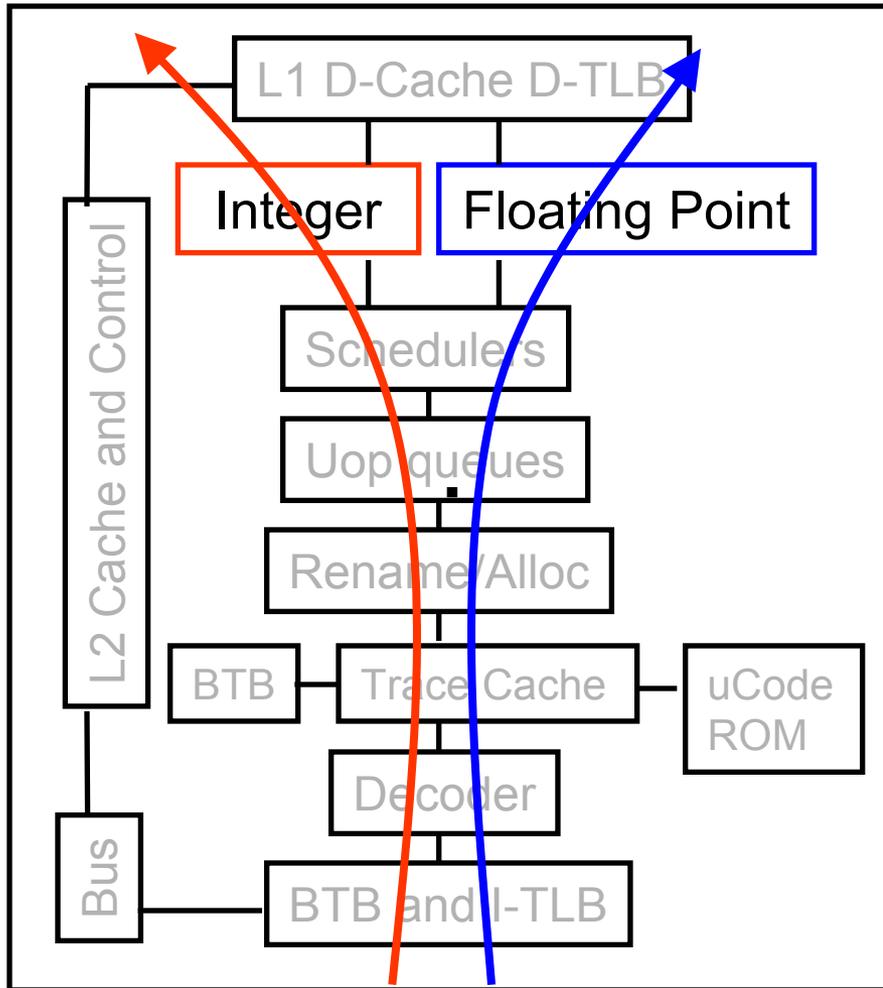
# Multi-core: threads can run on separate cores



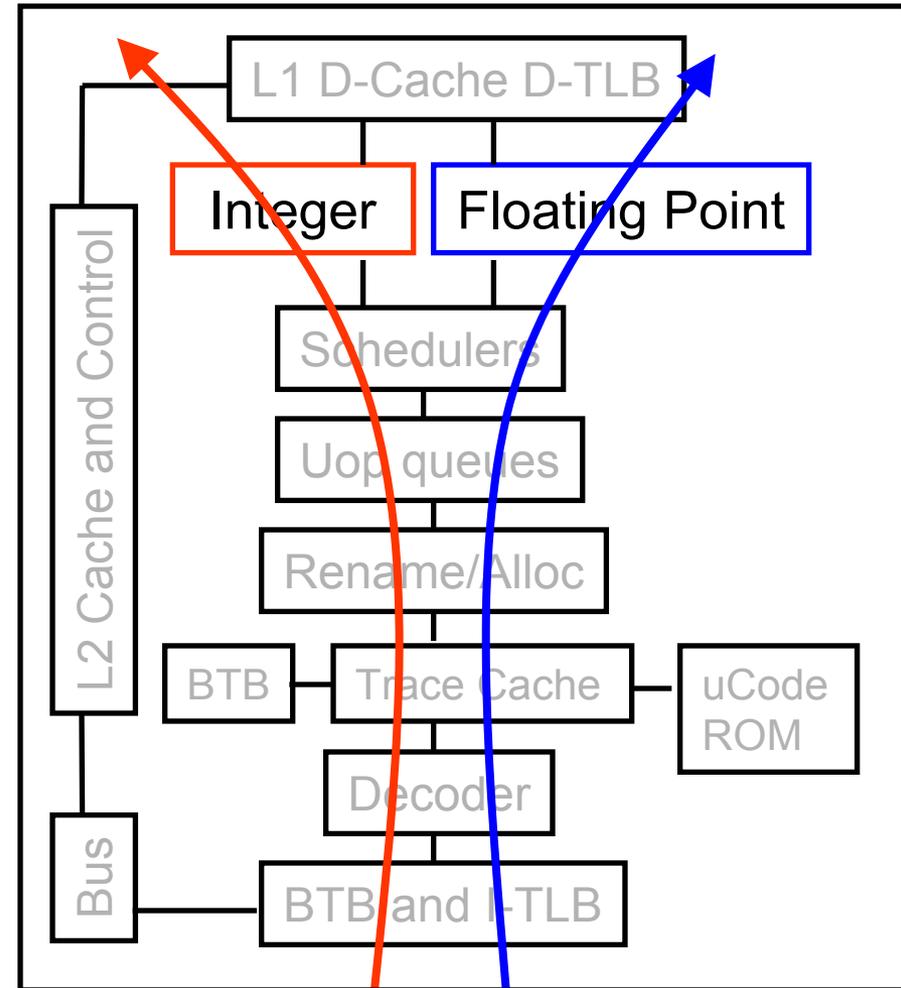
# Combining Multi-core and SMT

- Cores can be SMT-enabled (or not)
- The different combinations:
  - Single-core, non-SMT: standard uniprocessor
  - Single-core, with SMT
  - Multi-core, non-SMT
  - Multi-core, with SMT: our fish machines
- The number of SMT threads:  
2, 4, or sometimes 8 simultaneous threads
- Intel calls them “hyper-threads”

# SMT Dual-core: all four threads can run concurrently



Thread 1 Thread 3



Thread 2 Thread 4

# Comparison: multi-core vs SMT

- Advantages/disadvantages?

# Comparison: multi-core vs SMT

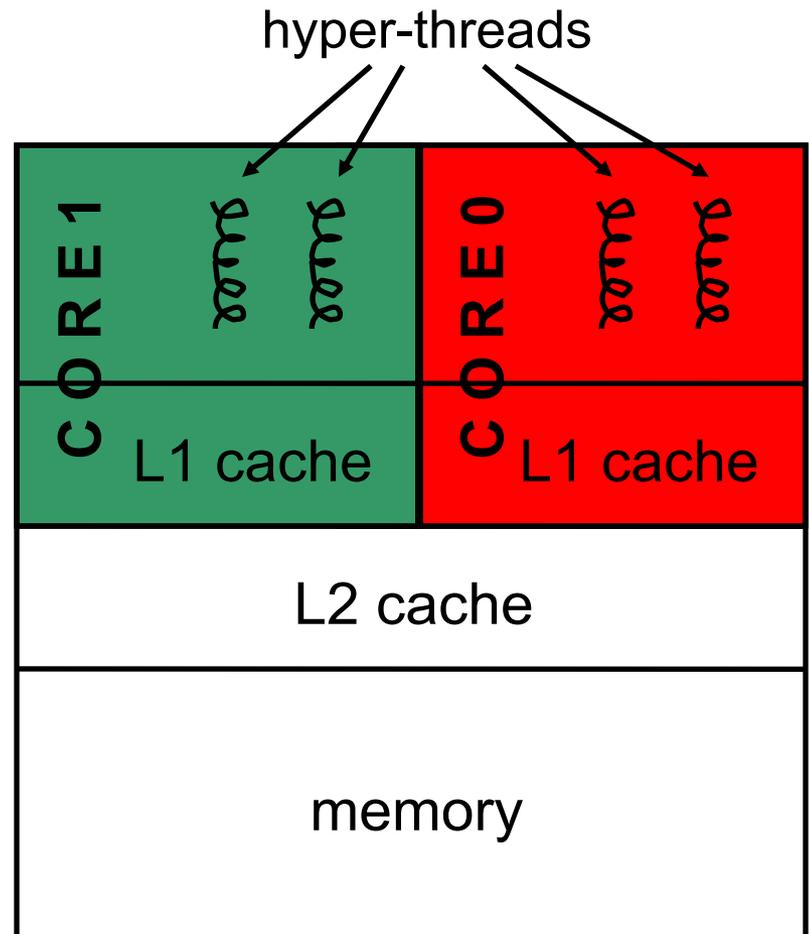
- Multi-core:
  - Since there are several cores, each is smaller and not as powerful (but also easier to design and manufacture)
  - However, great with thread-level parallelism
- SMT
  - Can have one large and fast superscalar core
  - Great performance on a single thread
  - Mostly still only exploits instruction-level parallelism

# The memory hierarchy

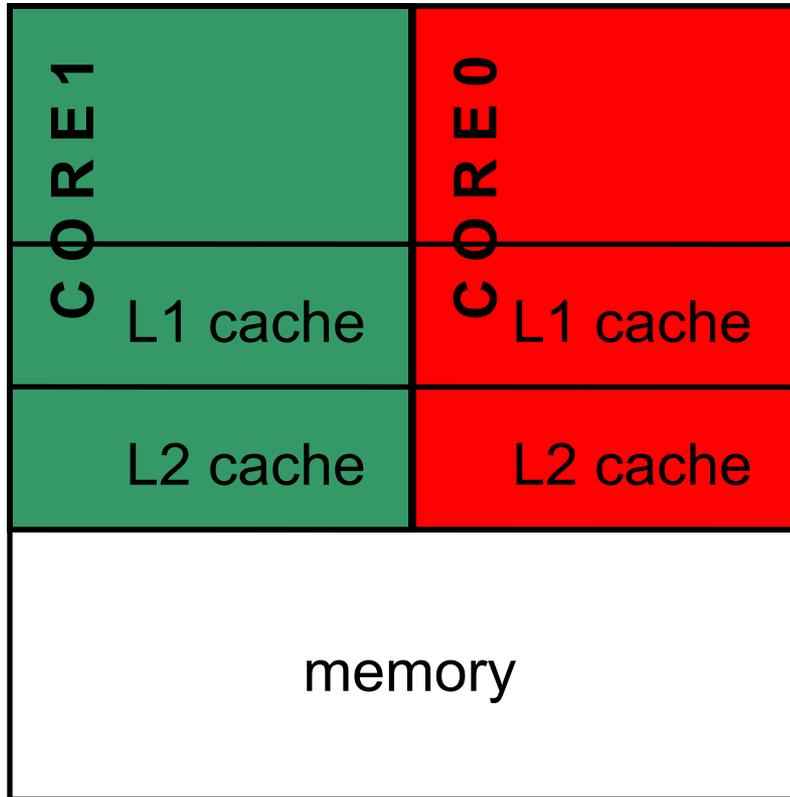
- If simultaneous multithreading only:
  - all caches shared
- Multi-core chips:
  - L1 caches private
  - L2 caches private in some architectures and shared in others
- Memory is always shared

# “Fish” machines

- Dual-core Intel Xeon processors
- Each core is hyper-threaded
- Private L1 caches
- Shared L2 caches

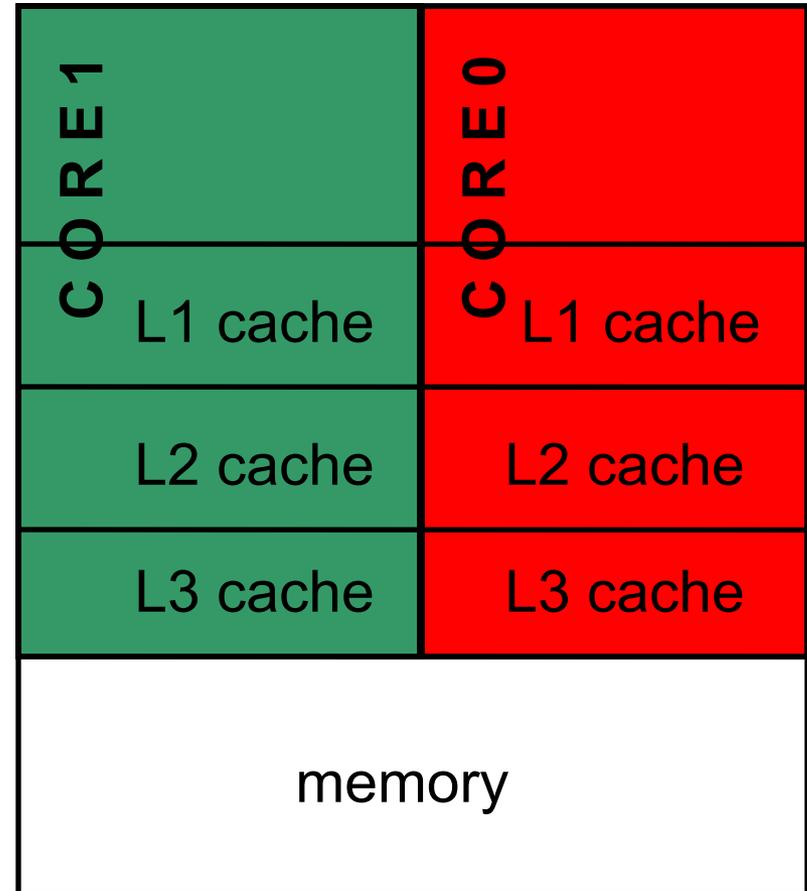


# Designs with private L2 caches



Both L1 and L2 are private

Examples: AMD Opteron,  
AMD Athlon, Intel Pentium D



A design with L3 caches

Example: Intel Itanium 2 32

# Private vs shared caches?

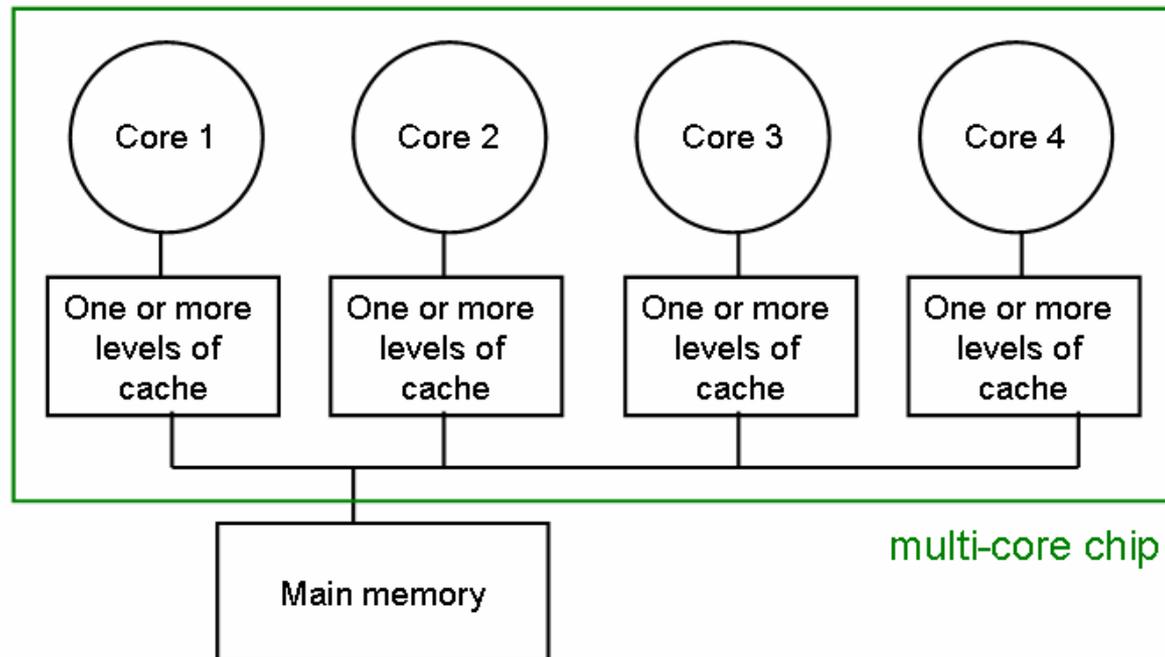
- Advantages/disadvantages?

# Private vs shared caches

- Advantages of private:
  - They are closer to core, so faster access
  - Reduces contention
- Advantages of shared:
  - Threads on different cores can share the same cache data
  - More cache space available if a single (or a few) high-performance thread runs on the system

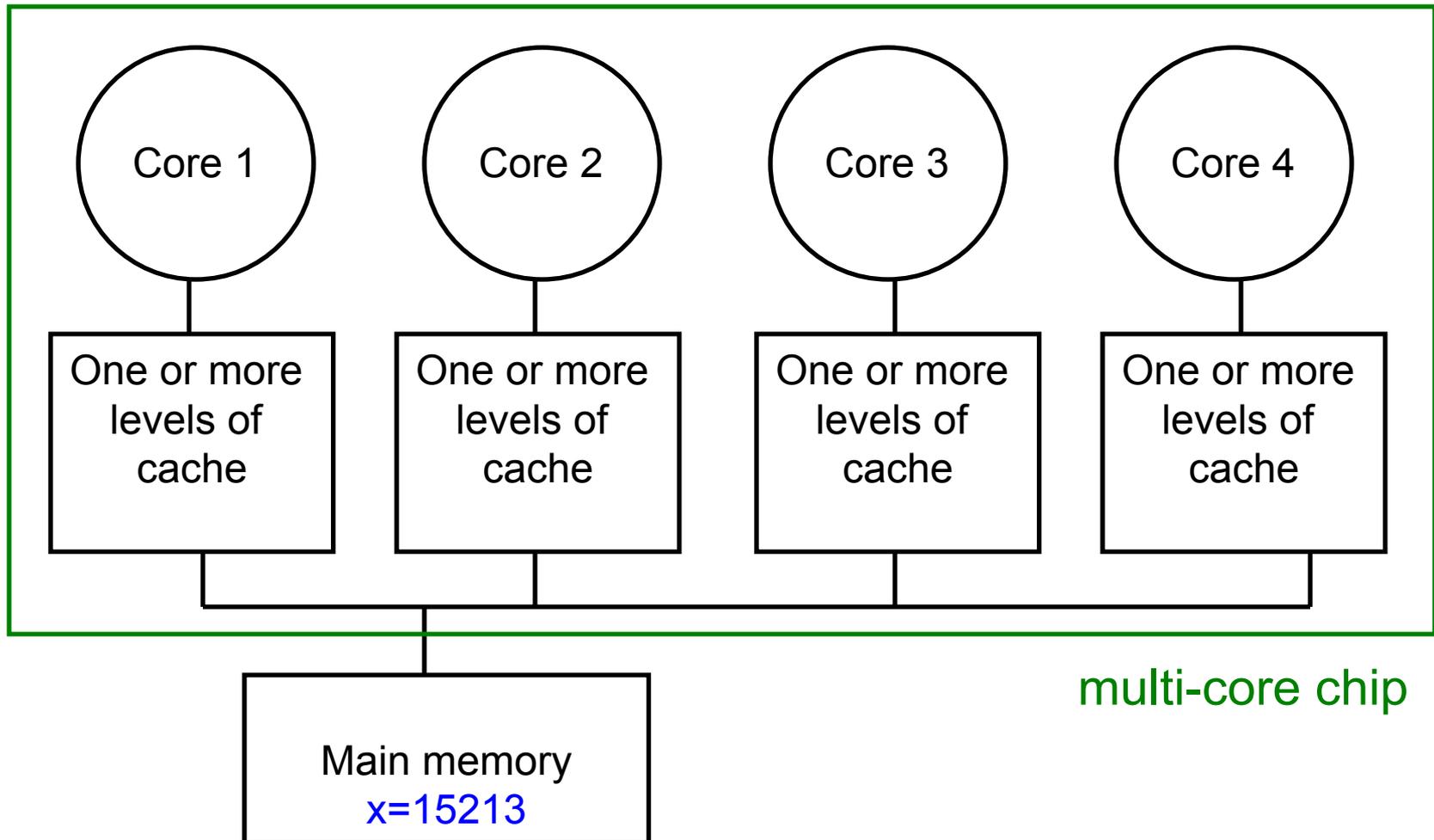
# The cache coherence problem

- Since we have private caches:  
How to keep the data consistent across caches?
- Each core should perceive the memory as a monolithic array, shared by all the cores



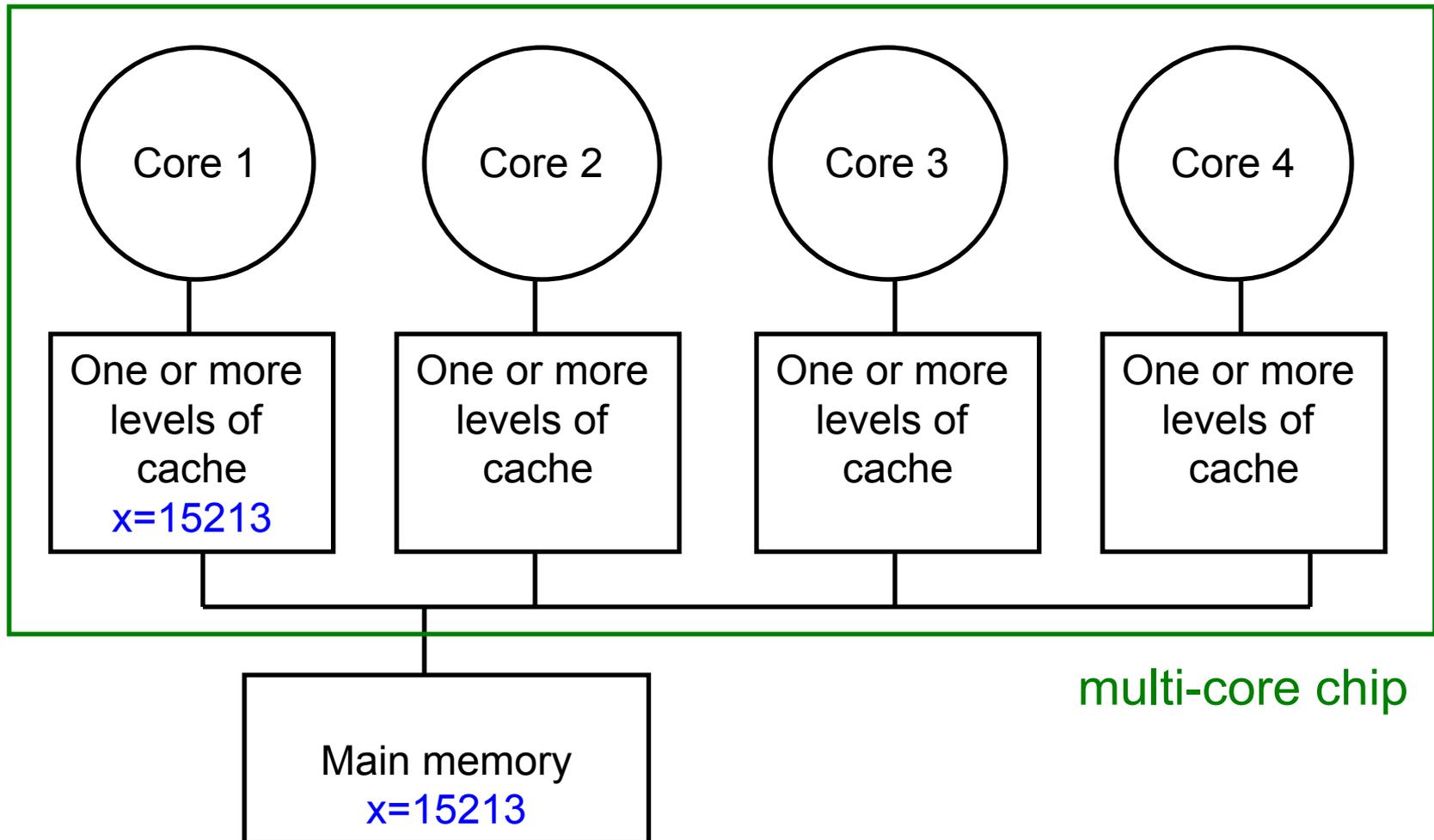
# The cache coherence problem

Suppose variable  $x$  initially contains 15213



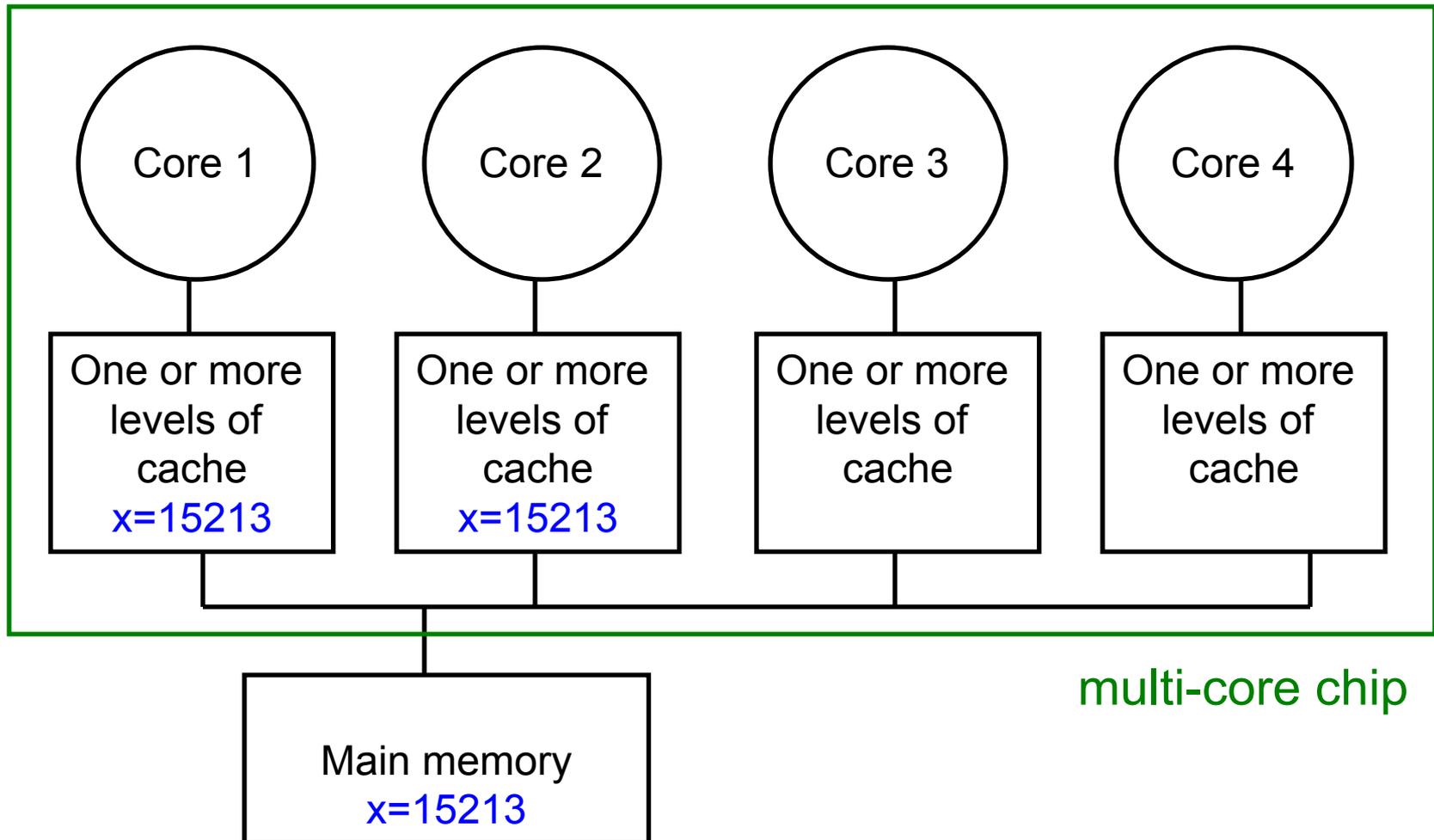
# The cache coherence problem

Core 1 reads  $x$



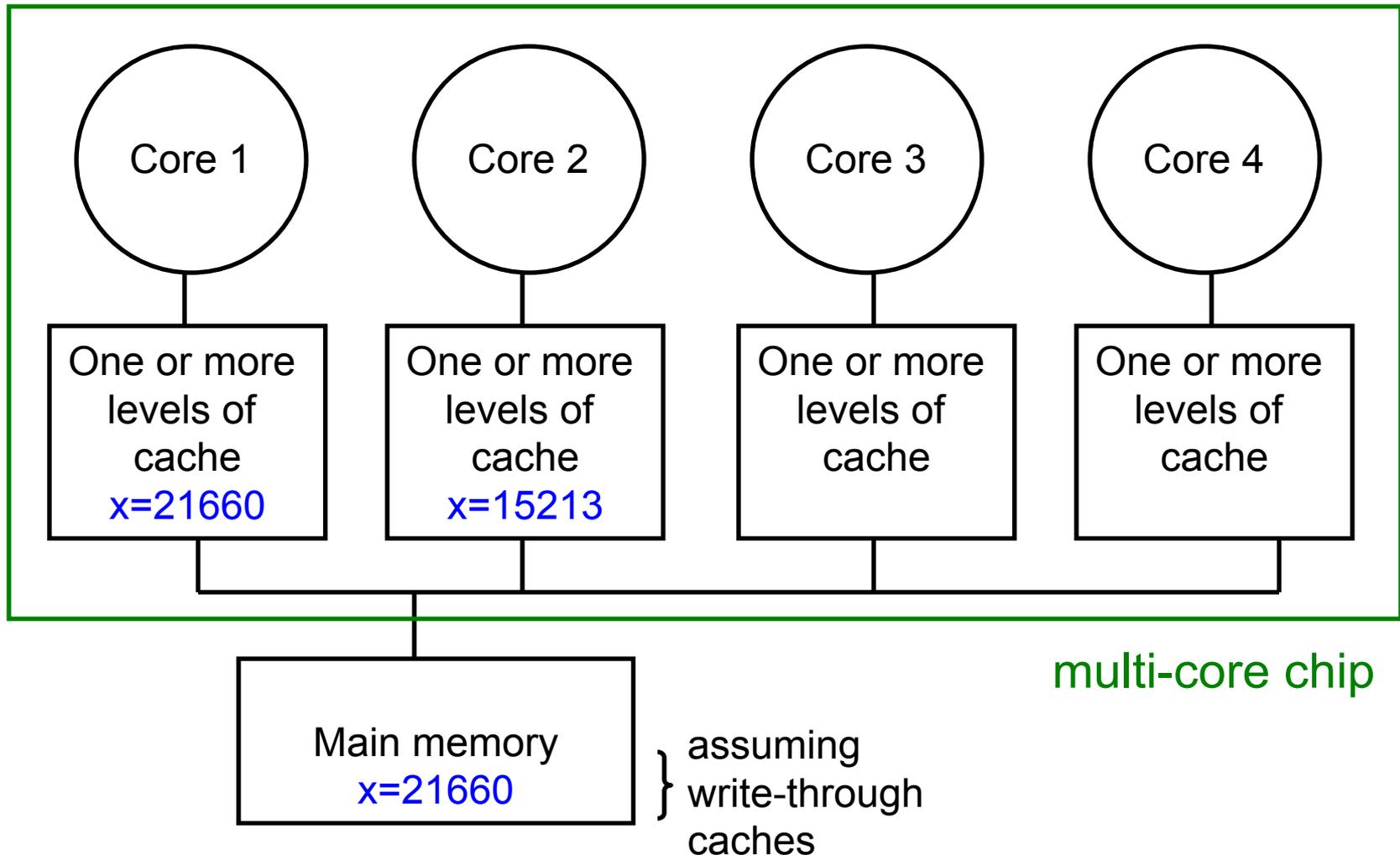
# The cache coherence problem

Core 2 reads  $x$



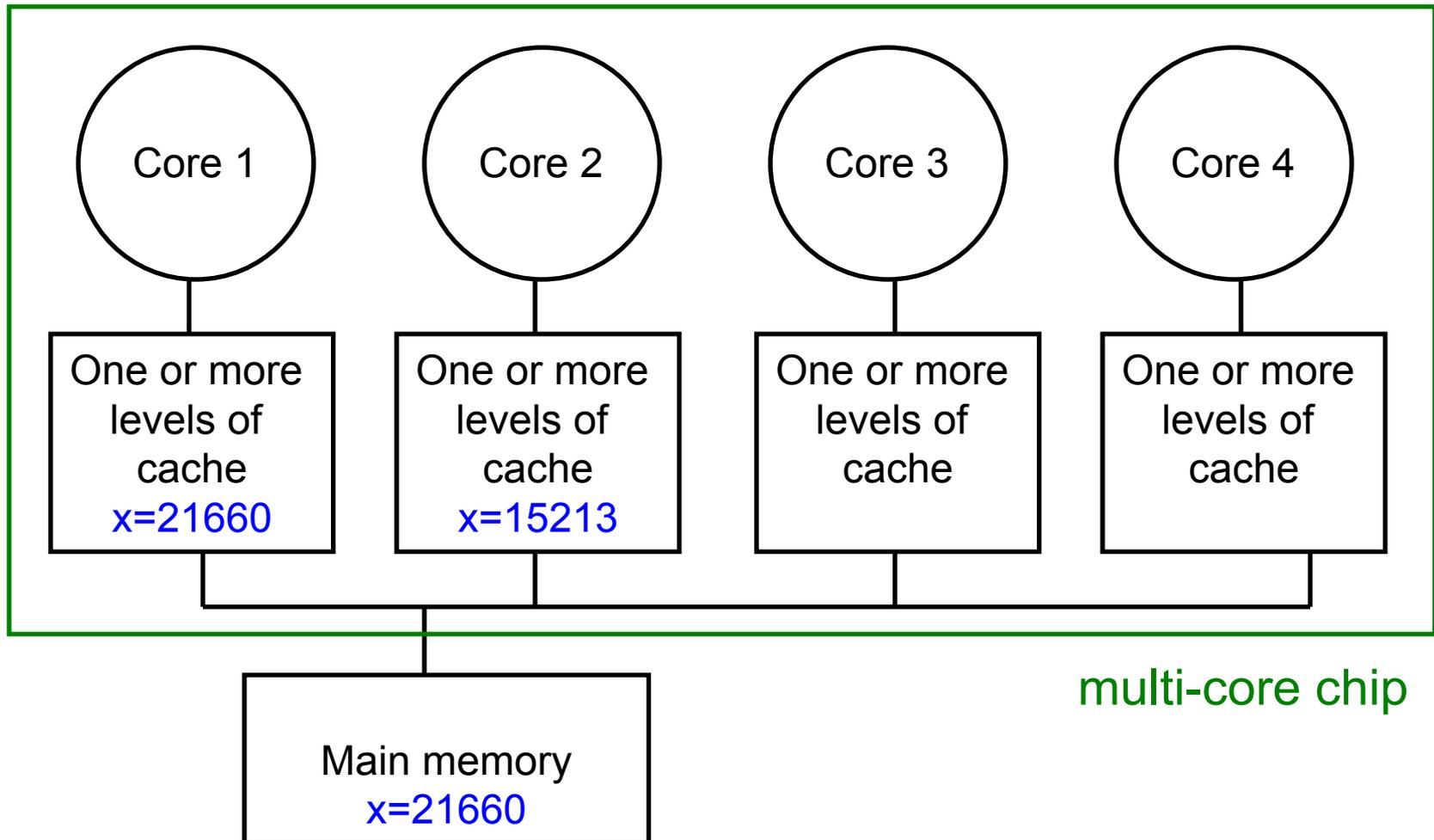
# The cache coherence problem

Core 1 writes to  $x$ , setting it to 21660



# The cache coherence problem

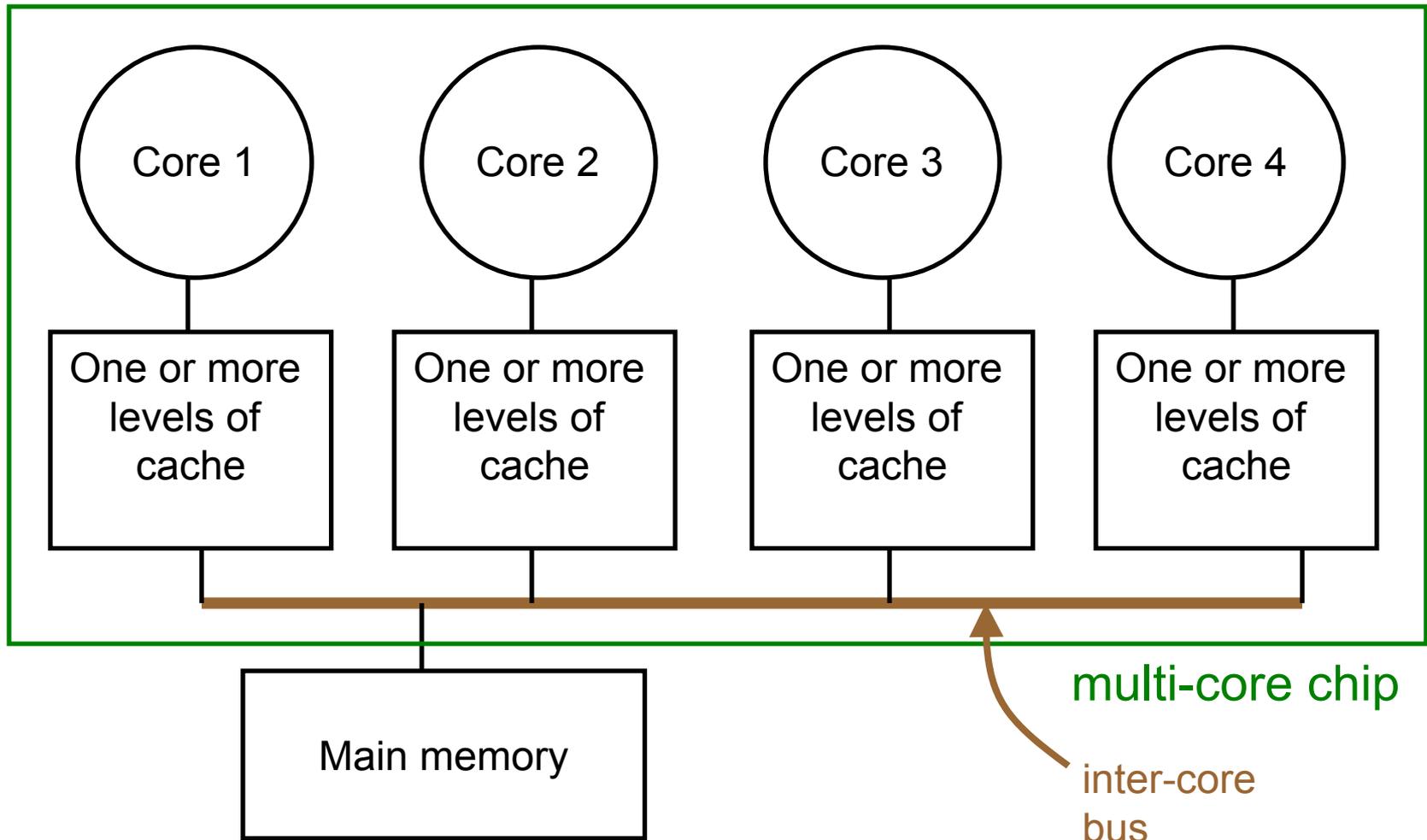
Core 2 attempts to read  $x$ ... gets a stale copy



# Solutions for cache coherence

- This is a general problem with multiprocessors, not limited just to multi-core
- There exist many solution algorithms, coherence protocols, etc.
- A simple solution:  
*invalidation*-based protocol with *snooping*

# Inter-core bus

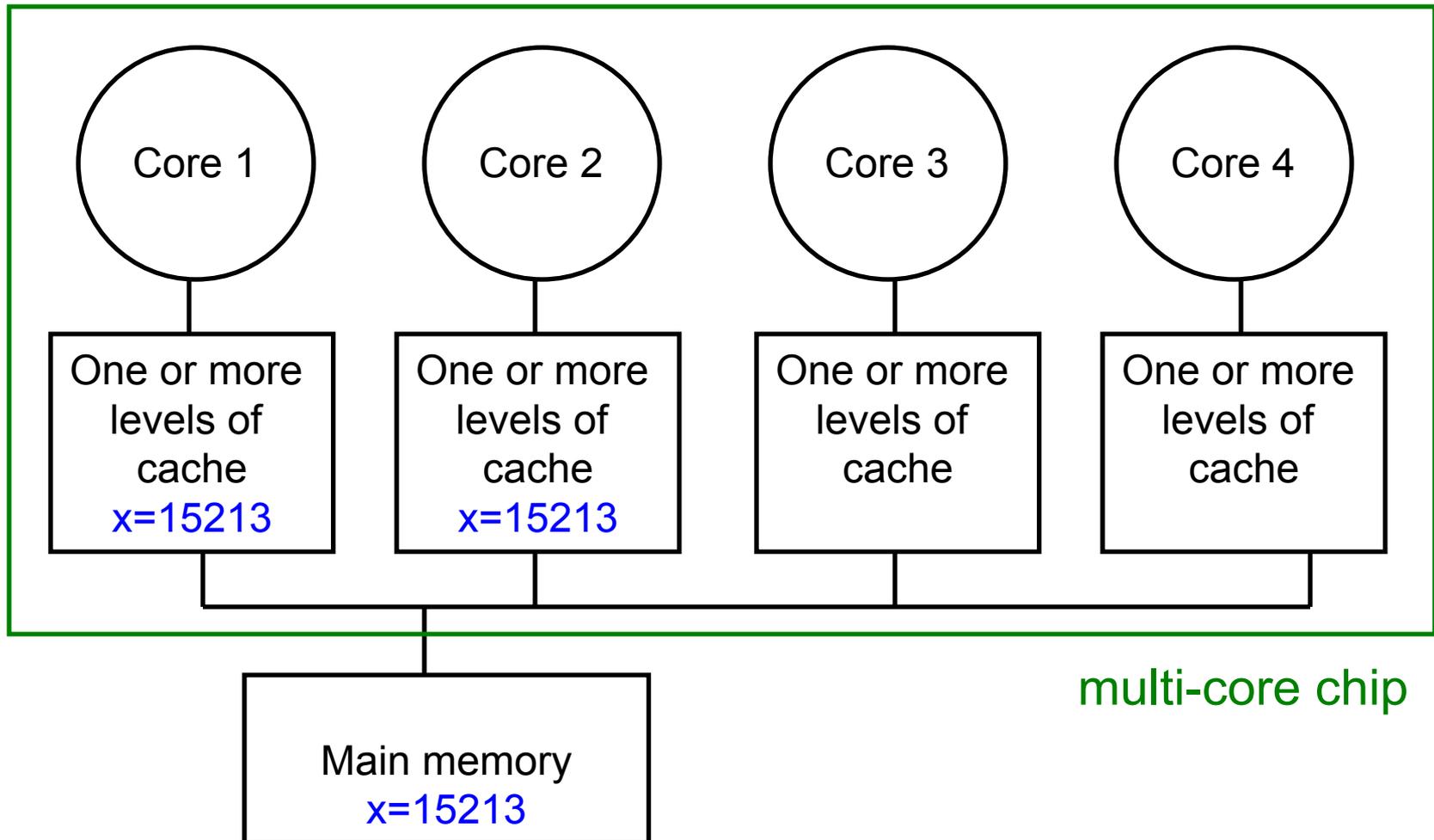


# Invalidation protocol with snooping

- Invalidation:  
If a core writes to a data item, all other copies of this data item in other caches are *invalidated*
- Snooping:  
All cores continuously “snoop” (monitor) the bus connecting the cores.

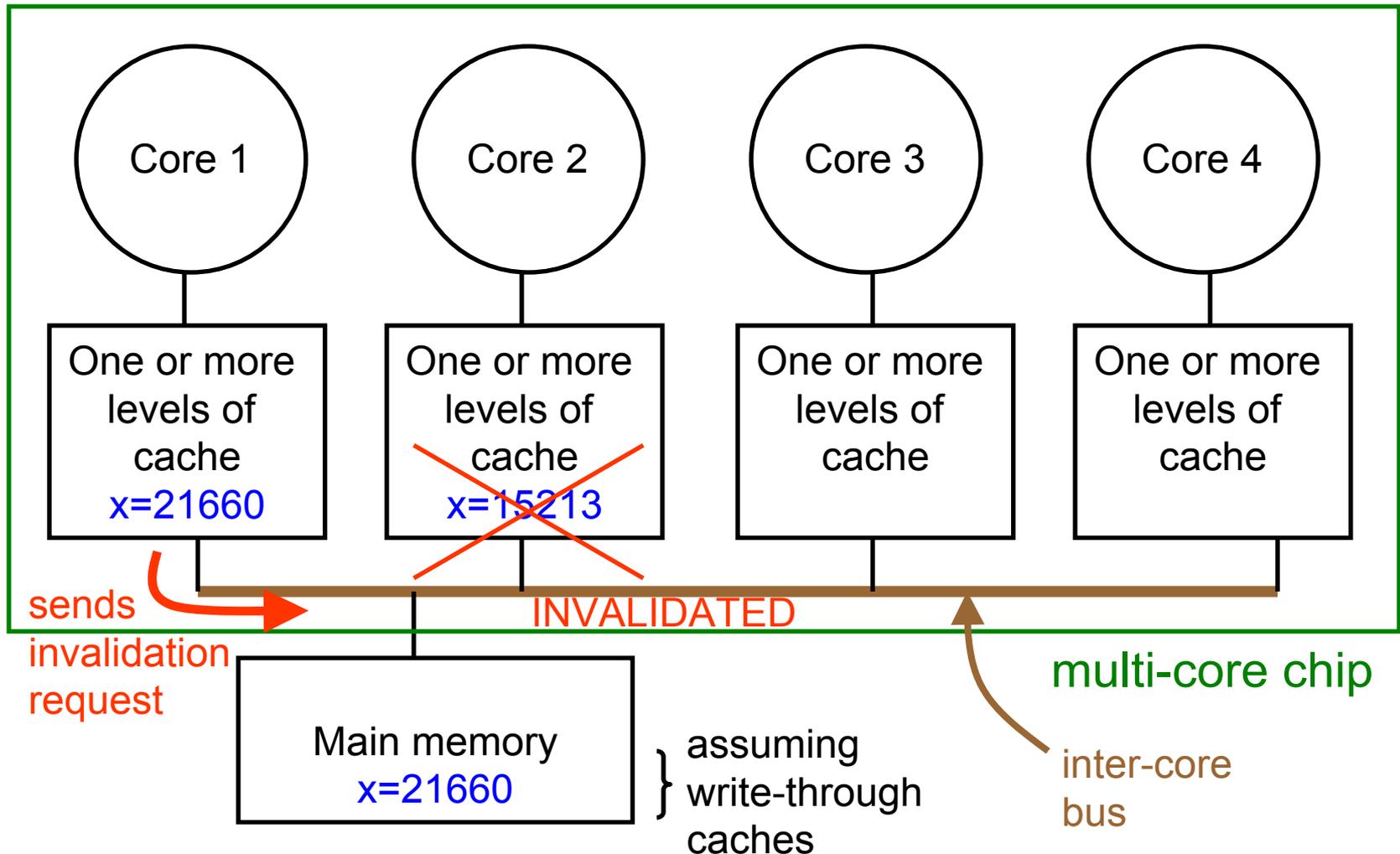
# The cache coherence problem

Revisited: Cores 1 and 2 have both read  $x$



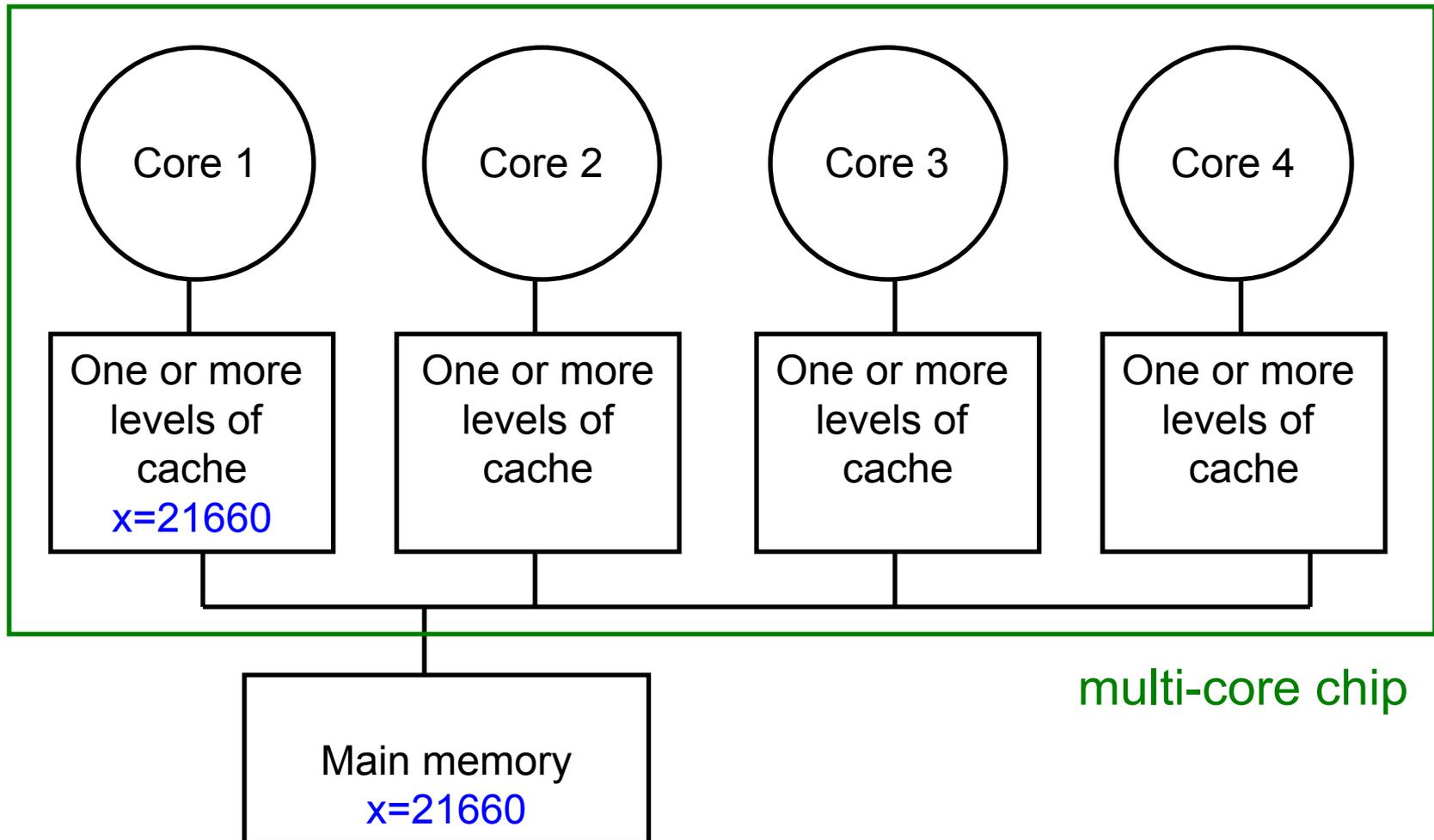
# The cache coherence problem

Core 1 writes to  $x$ , setting it to 21660



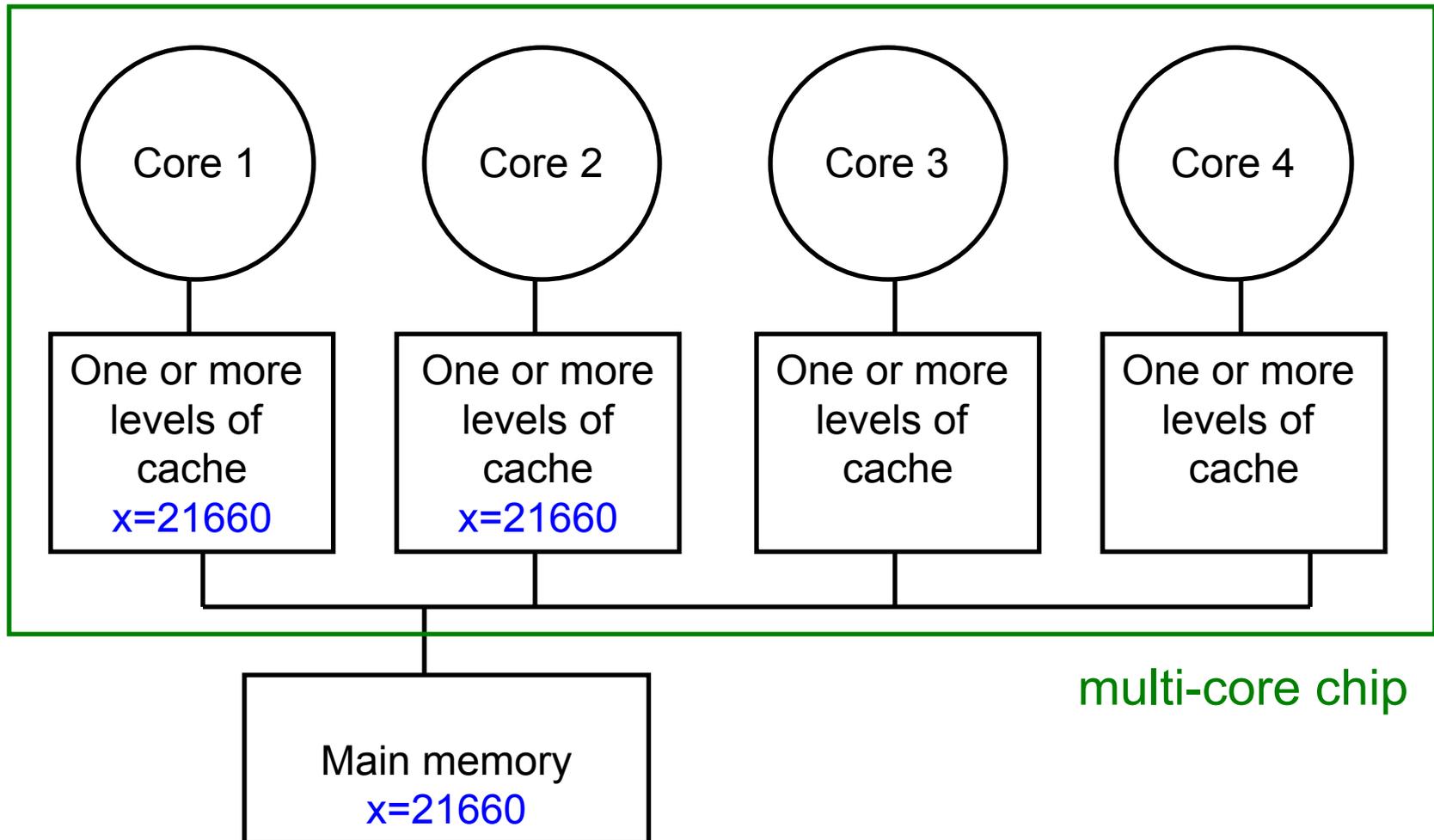
# The cache coherence problem

After invalidation:



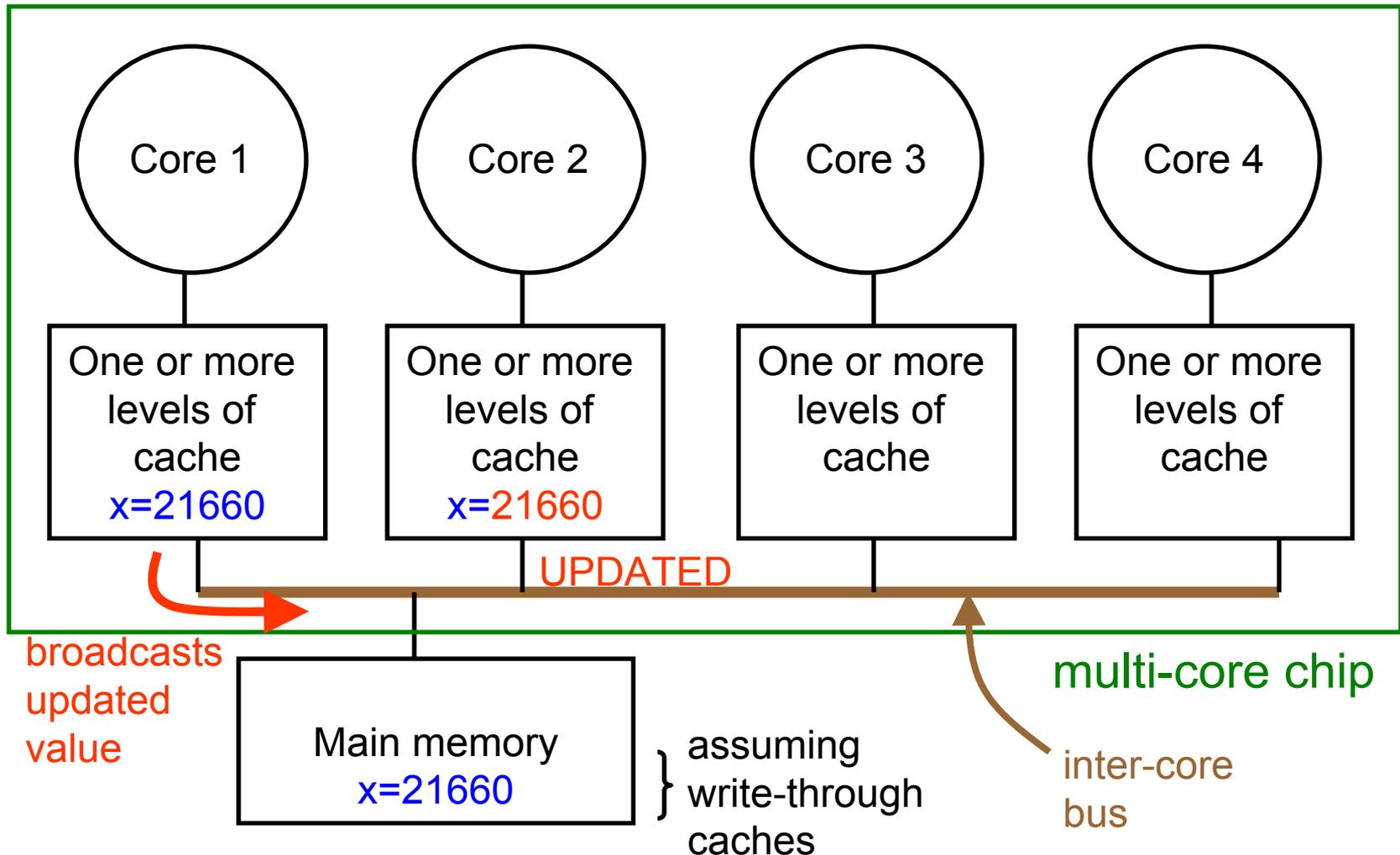
# The cache coherence problem

Core 2 reads  $x$ . Cache misses, and loads the new copy.



# Alternative to invalidate protocol: update protocol

Core 1 writes  $x=21660$ :



Which do you think is better?  
Invalidation or update?

# Invalidation vs update

- Multiple writes to the same location
  - invalidation: only the first time
  - update: must broadcast each write  
(which includes new variable value)
- Invalidation generally performs better:  
it generates less bus traffic

# Invalidation protocols

- This was just the basic invalidation protocol
- More sophisticated protocols use extra cache state bits
- MSI, MESI  
(Modified, Exclusive, Shared, Invalid)

# Programming for multi-core

- Programmers must use threads or processes
- Spread the workload across multiple cores
- Write parallel algorithms
- OS will map threads/processes to cores

# Thread safety very important

- Pre-emptive context switching:  
context switch can happen **AT ANY TIME**
- True concurrency, not just uniprocessor time-slicing
- Concurrency bugs exposed much faster with multi-core

# However: Need to use synchronization even if only time-slicing on a uniprocessor

```
int counter=0;

void thread1() {
    int temp1=counter;
    counter = temp1 + 1;
}

void thread2() {
    int temp2=counter;
    counter = temp2 + 1;
}
```

# Need to use synchronization even if only time-slicing on a uniprocessor

```
temp1=counter;  
counter = temp1 + 1;  
temp2=counter;  
counter = temp2 + 1
```

gives counter=2

```
temp1=counter;  
temp2=counter;  
counter = temp1 + 1;  
counter = temp2 + 1
```

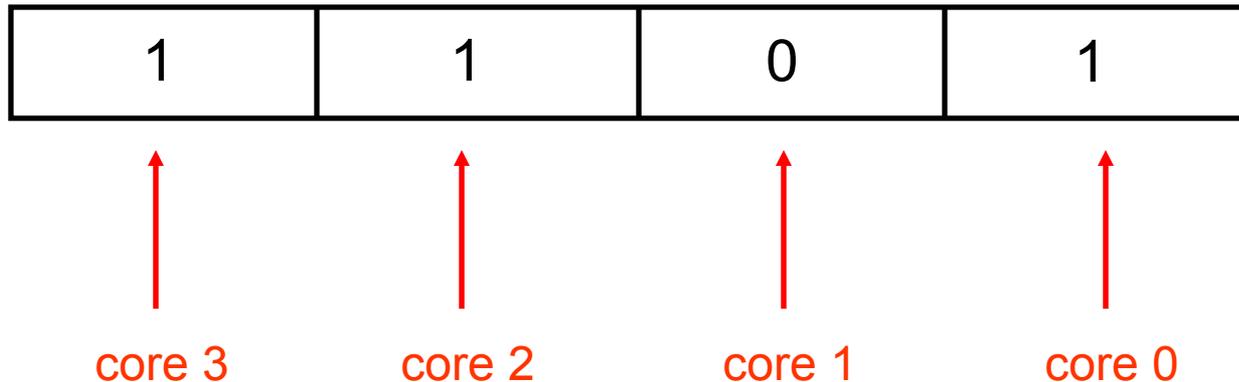
gives counter=1

# Assigning threads to the cores

- Each thread/process has an *affinity mask*
- Affinity mask specifies what cores the thread is allowed to run on
- Different threads can have different masks
- Affinities are inherited across `fork()`

# Affinity masks are bit vectors

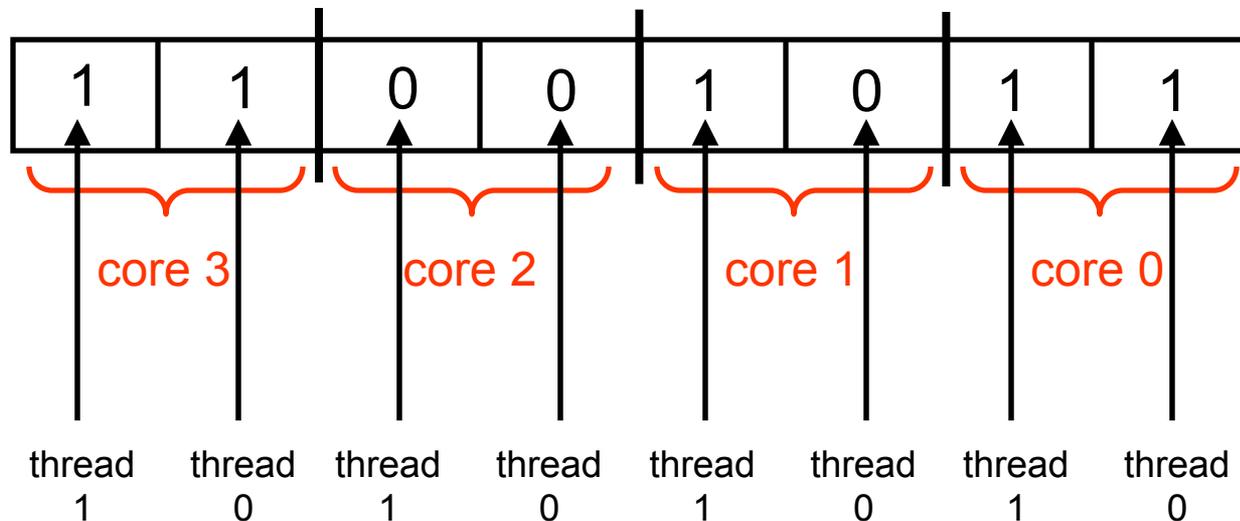
- Example: 4-way multi-core, without SMT



- Process/thread is allowed to run on cores 0,2,3, but not on core 1

# Affinity masks when multi-core and SMT combined

- Separate bits for each simultaneous thread
- Example: 4-way multi-core, 2 threads per core



- Core 2 can't run the process
- Core 1 can only use one simultaneous thread

# Default Affinities

- Default affinity mask is all 1s:  
all threads can run on all processors
- Then, the OS scheduler decides what threads run on what core
- OS scheduler detects skewed workloads, migrating threads to less busy processors

# Process migration is costly

- Need to restart the execution pipeline
- Cached data is invalidated
- OS scheduler tries to avoid migration as much as possible:  
it tends to keep a thread on the same core
- This is called *soft affinity*

# Hard affinities

- The programmer can prescribe her own affinities (hard affinities)
- Rule of thumb: use the default scheduler unless a good reason not to

# When to set your own affinities

- Two (or more) threads share data-structures in memory
  - map to same core so that can share cache
- Real-time threads:  
Example: a thread running a robot controller:
  - must not be context switched, or else robot can go unstable
  - dedicate an entire core just to this thread



Source: Sensable.com

# Kernel scheduler API

```
#include <sched.h>
int sched_getaffinity(pid_t pid,
    unsigned int len, unsigned long * mask);
```

Retrieves the current affinity mask of process 'pid' and stores it into space pointed to by 'mask'.

'len' is the system word size: sizeof(unsigned int long)

# Kernel scheduler API

```
#include <sched.h>

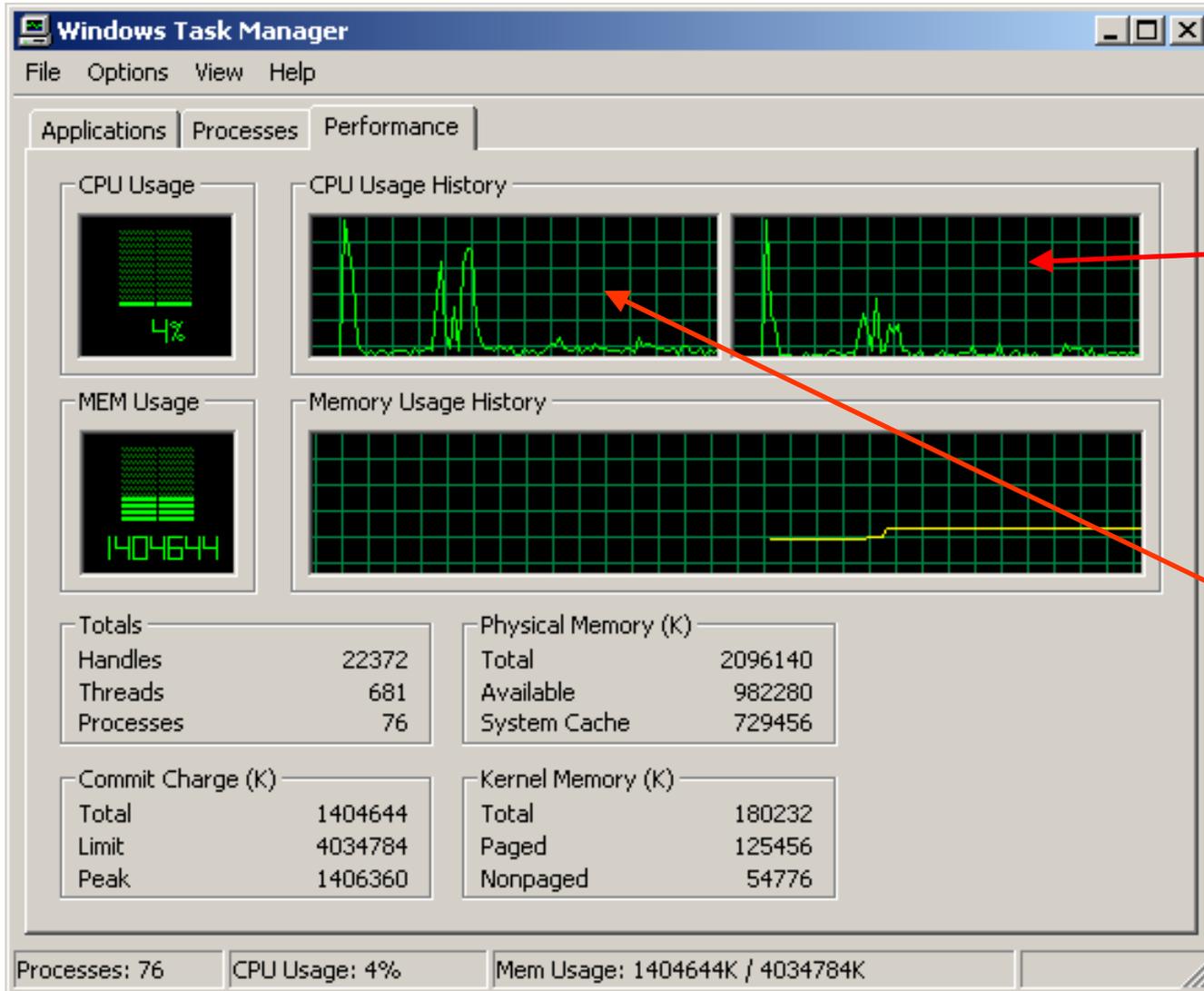
int sched_setaffinity(pid_t pid,
    unsigned int len, unsigned long * mask);
```

Sets the current affinity mask of process 'pid' to \*mask  
'len' is the system word size: sizeof(unsigned int long)

To query affinity of a running process:

```
[barbic@bonito ~]$ taskset -p 3935
pid 3935's current affinity mask: f
```

# Windows Task Manager



core 2

core 1

# Legal licensing issues

- Will software vendors charge a separate license per each core or only a single license per chip?
- Microsoft, Red Hat Linux, Suse Linux will license their OS per chip, not per core

# Conclusion

- Multi-core chips an important new trend in computer architecture
- Several new multi-core chips in design phases
- Parallel programming techniques likely to gain importance

