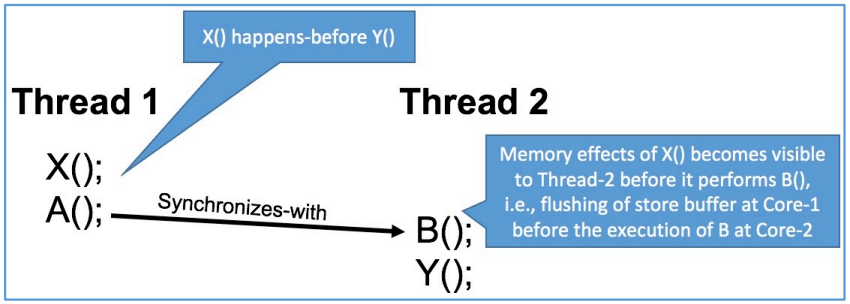
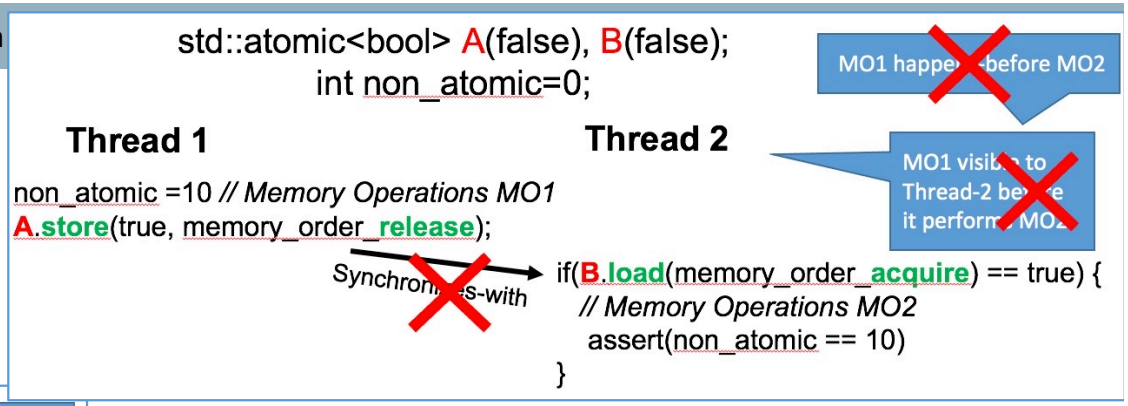
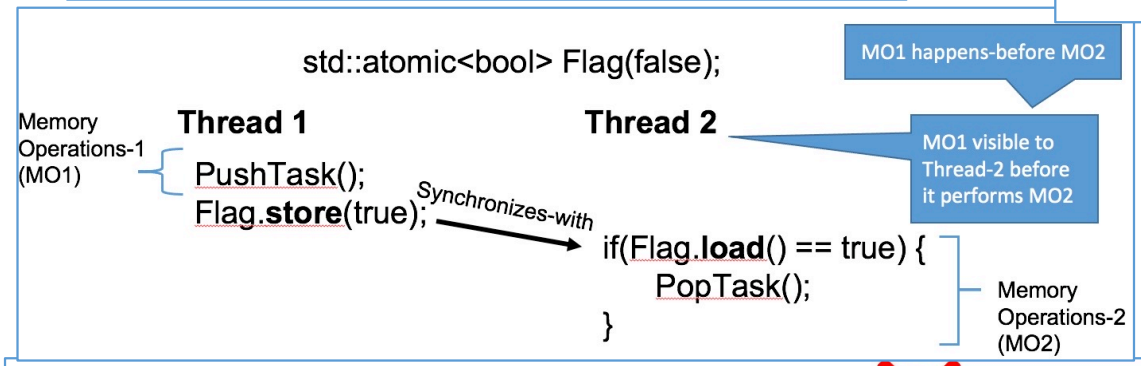
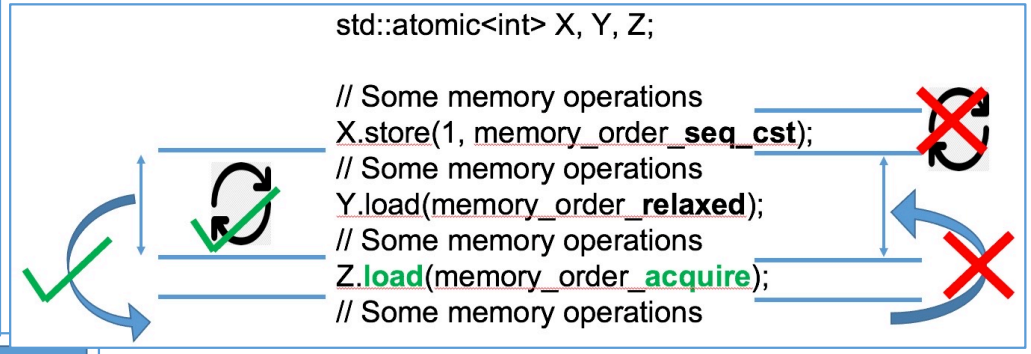
# Lecture 11: Non Uniform Memory Access Architecture

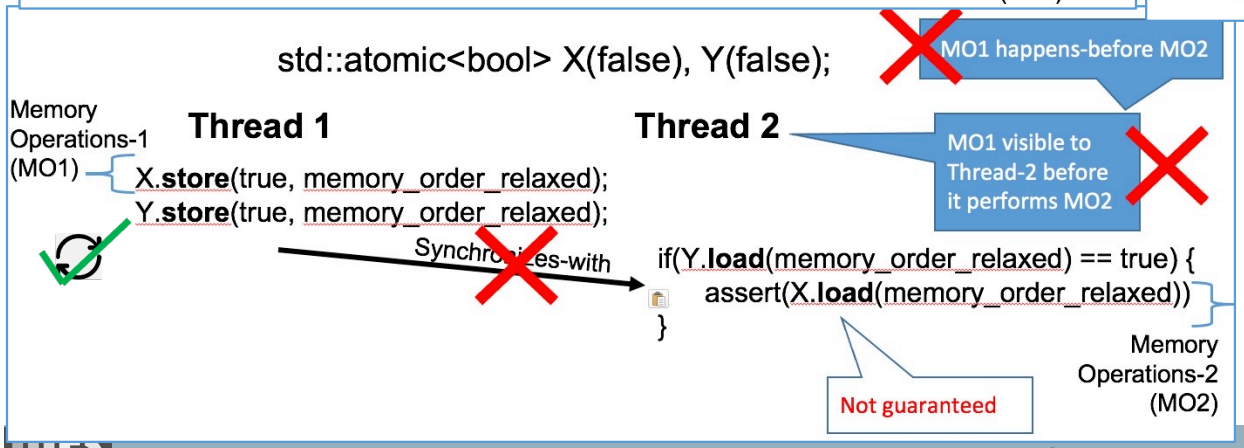
Vivek Kumar
Computer Science and Engineering
IIIT Delhi
vivekk@iiitd.ac.in




# Last Lecture (Recap)

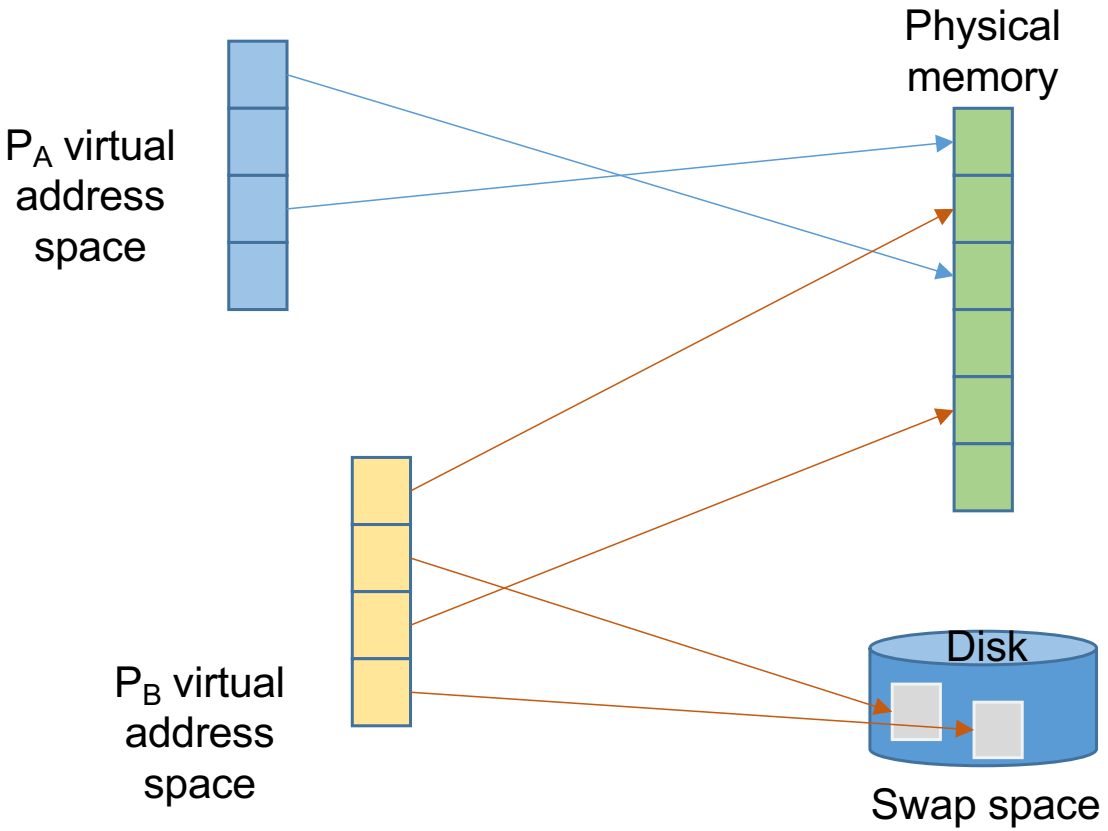
# Today's Lecture

- Non uniform memory accesses
- Page allocation policies
- NUMA aware parallel runtime

# Recall: Virtual VS. Physical Memory

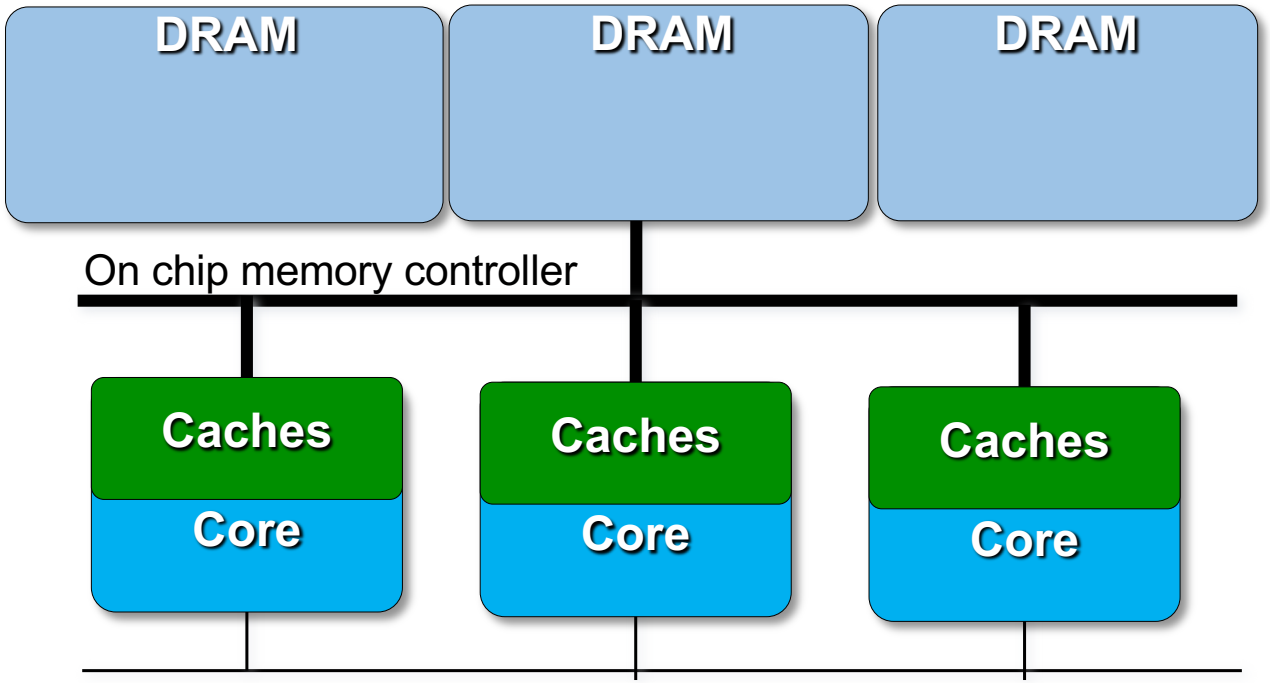
- Programs refers to virtual memory addresses
  - Memory can be thought of large array of bytes
  - System provides private address space to each of the processes
- Problems
  - How does the memory for all the processes fit?
    - Virtual address can address exabytes (64-bit), whereas physical memory ranges between some gigabytes
  - Processes shouldn't access/change other processes address space
- Solution
  - OS manages the mapping of the virtual memory to physical memory

# Recall: Virtual VS. Physical Memory



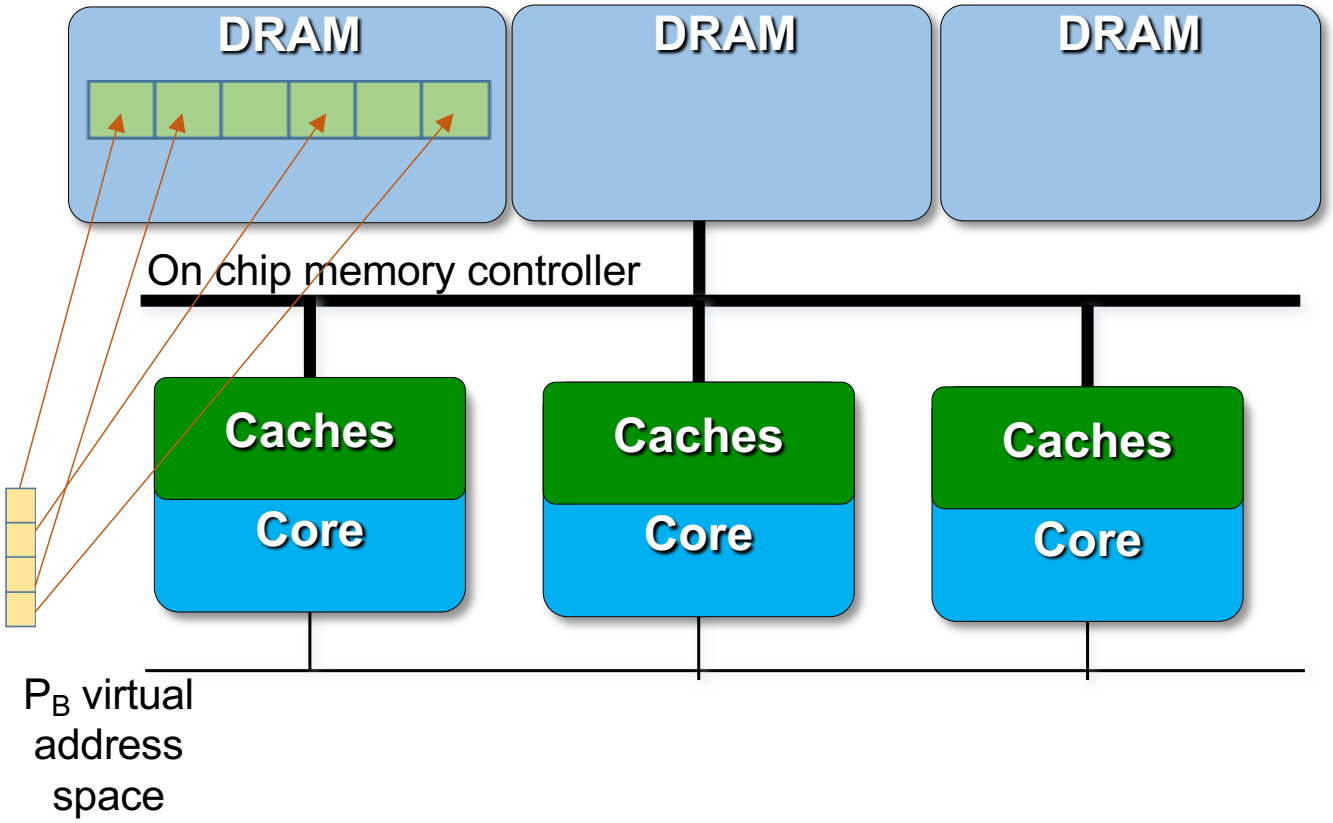

- Granularity of address spaces (virtual or physical)
  - Typically 4KB
    - Linux OS makes it possible to support larger page size
- Virtual memory helps in efficient use of DRAM
  - Uses DRAM as a cache
  - Non-cached data on disk
- Simplifies memory management

# Uniform Memory Access (UMA)



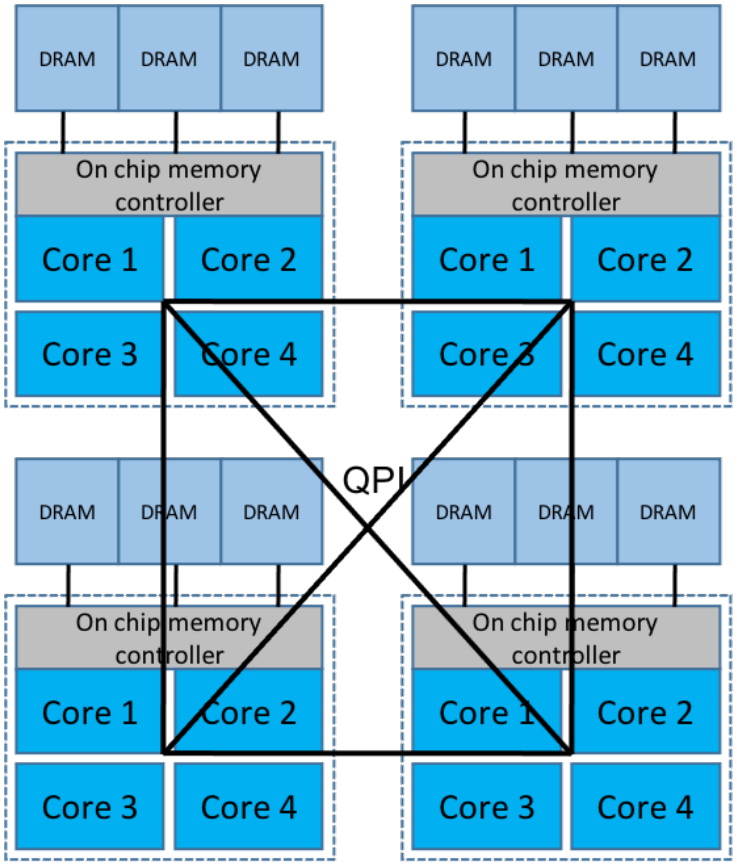

- All memory is equidistant from all the cores
  - Equal access times to memory units
- Also known as CC-UMA
  - Cache Coherent UMA
- Disadvantage?
  - Hard to scale with increasing number of cores

# Virtual to Physical Mapping in UMA



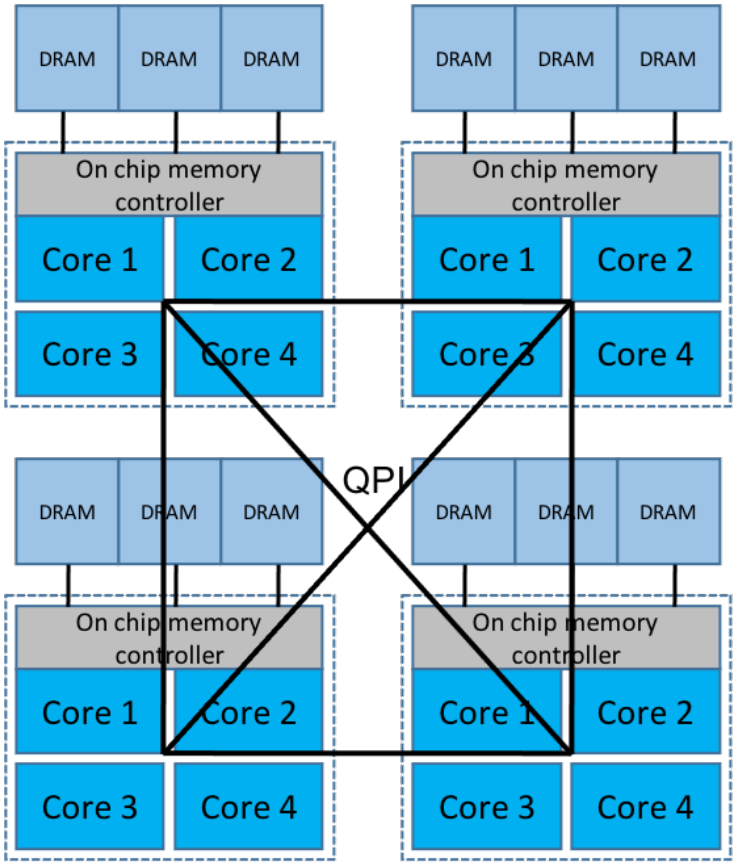

- As memory is equidistant, same latency to access each physical pages of $P_B$'s virtual address space
  - Equal number of hops

# Non Uniform Memory Access (NUMA)




- Generally made by physically linking two or more multicore processors (i.e., socket) on the same motherboard
  - Single processor can also have a NUMA architecture (e.g., AMD EPYC processors)
- One socket can directly access memory of another socket
  - Both DRAM and caches (e.g., LLC)
- Cache coherent NUMA architecture called as CC-NUMA
  - Cache Coherent NUMA
- Cache coherent interconnect (e.g., QPI on Intel processors) used for low latency and high bandwidth memory accesses across the NUMA domains

# Virtual to Physical Mapping in NUMA




- Each NUMA domain has its own physical pool of memory
- Local memory offers higher bandwidth and lower latency than remote memory
- Even if it's a cc-NUMA system where memory is addressed with a global address space, accessing different parts of memory can result in different latency and bandwidth
  - Imagine LLC on socket-1 is sharing a cache line residing on the LLC of socket-2
- High performance can only be achieved by placing the computation and its data inside the same NUMA domain
  - What about the energy usage?

# Getting CPU & NUMA Information on Linux

```
vivek@hippo:~$ numactl --hardware
available: 4 nodes (0-3)
node 0 cpus: 0 1 2 3 4 5 6 7 32 33 34 35 36 37 38 39
node 0 size: 15943 MB
node 0 free: 14753 MB
node 1 cpus: 8 9 10 11 12 13 14 15 40 41 42 43 44 45 46 47
node 1 size: 16121 MB
node 1 free: 10956 MB
node 2 cpus: 16 17 18 19 20 21 22 23 48 49 50 51 52 53 54 55
node 2 size: 16121 MB
node 2 free: 13932 MB
node 3 cpus: 24 25 26 27 28 29 30 31 56 57 58 59 60 61 62 63
node 3 size: 16120 MB
node 3 free: 15058 MB
node distances:
node   0   1   2   3
  0:  10  16  16  16
  1:  16  10  16  16
  2:  16  16  10  16
  3:  16  16  16  10
```

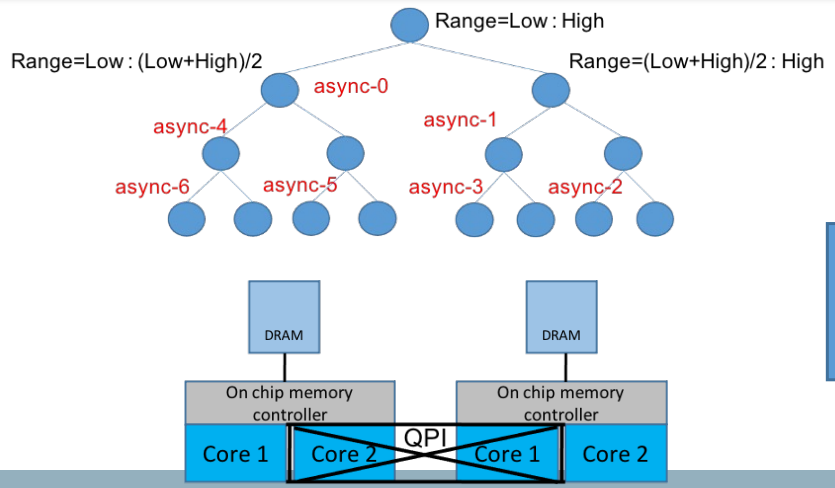
NUMA node memory

Logical core IDs

Node distance measures the relative cost to access the memory of another NUMA-node. A NUMA-node has always a distance 10 to itself (lowest possible value)

# Recursive Array Sum on NUMA Processor

```
int array_sum(int low, int high) {
  if(high – low > THRESHOLD) {
    int mid = (low + high)/2;
    future<int> left = async([=]() { return array_sum(low, mid); });
    right = array_sum(mid, high);
    return left.get() + right;
  } else {
    int sum = 0;
    for(int i=low; i<high; i++) {
       sum += array[i];
    }
    return sum;
  }
}
```




Why we are not using Fib as an example here?

- Async would be executing on cores of both the sockets
- Overheads?
  - Remote DRAM accesses
  - Cache lines shared across caches on both socket. Can we fix it?
    - Easily resolvable by setting THRESHOLD as multiple of cache line size (64Bytes on x86)
- Physical page allocations
  - Only on socket-1
    - Local DRAM accesses at socket-1, but remote DRAM accesses at socket-2
  - Only on socket-2
    - Local DRAM accesses at socket-2, but remote DRAM accesses at socket-2
  - Shared between socket-1 and socket-2
    - Random work-stealing will lead to remote DRAM accesses

# Recursive Array Sum on NUMA Processor

```
int array_sum(int low, int high) {
  if(high – low > THRESHOLD) {
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    right = array_sum(mid, high);
    return left.get() + right;
  } else {
    int sum = 0;
    for(int i=low; i<high; i++) {
       sum += array[i];
    }
    return sum;
  }
}
```
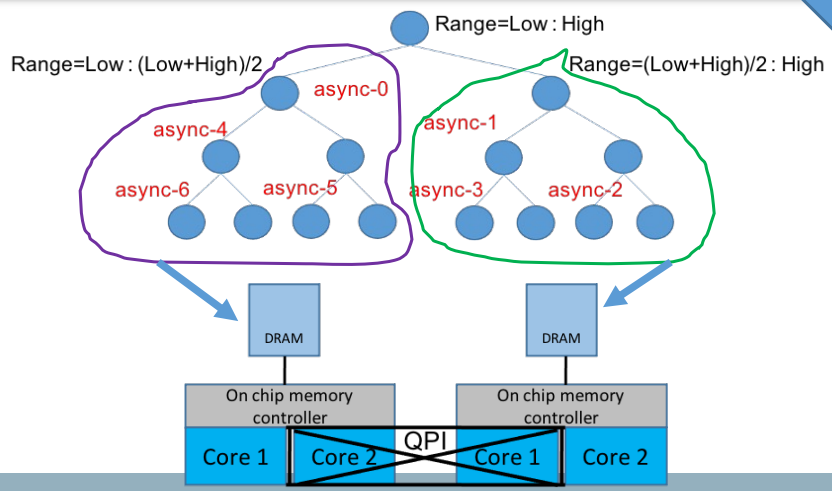

Two issues to resolve:
a) Ensuring pages allocations at right place
b) Partitioning computation at each socket




- Async would be executing on cores of both the sockets
- Overheads?
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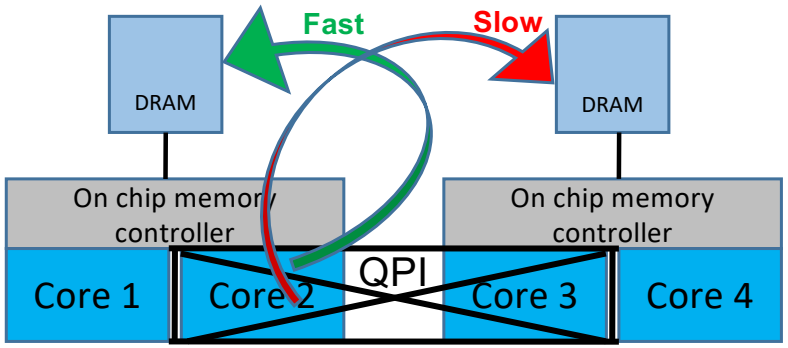
  - Only on socket-2
    - Local DRAM accesses at socket-2, but remote DRAM accesses at socket-2
  - Shared between socket-1 and socket-2
    - Random work-stealing will lead to remote DRAM accesses
- High performance **only** if
  - Physical pages for left half of the array on **socket-1**'s DRAM and left subtree executes on **socket-1**
  - Physical pages for right half of the array on **socket-2**'s DRAM and right subtree executes on **socket-2**

# Today's Lecture

- Non uniform memory accesses
- Page allocation policies
- NUMA aware parallel runtime

# Page Allocation Policy on Linux

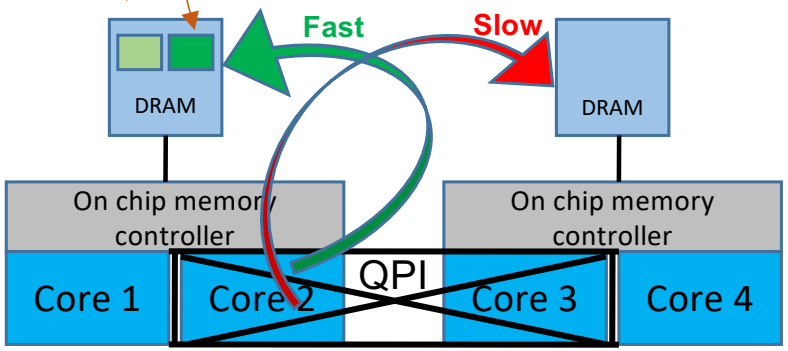
```
int * array = new int[2048]; // Two pages
```




- First Touch Policy
  - Calling malloc/new doesn't allocate the physical pages on a NUMA node

# Page Allocation Policy on Linux

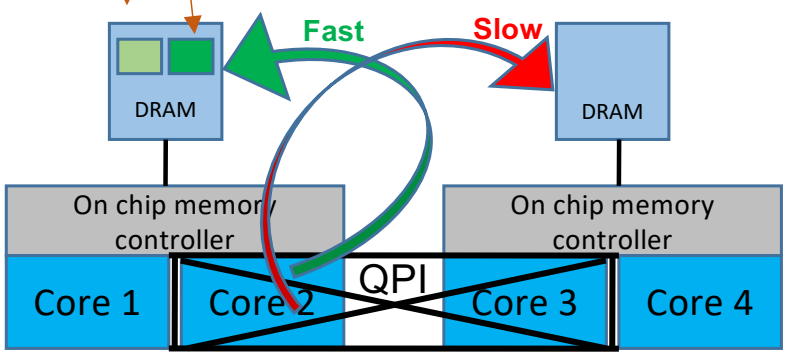
```
int * array = new int[2048]; // Two pages
for(int i=0; i<size; i++) {
  array[i] = 0;
}
```




- First Touch Policy
  - Calling malloc/new doesn't allocate the physical pages on a NUMA node
    - It is allocated only when those addresses are first "touched"
    - The physical page is allocated during page-fault handling
      - A hardware fault will be generated when a process touches an address (page fault) that has not been used yet
  - Allocates the physical page in the memory closest to the thread/process accessing this page for the first time
    - Default policy on Linux

# Page Allocation Policy on Linux

```
int * array = new int[2048]; // Two pages
int mid = 2048/2;
std::thread T1([=]() {
  for(int i=0; i<1024; i++) {
    array[i] = 0;
  }
});
std::thread T1([=]() {
  for(int i=1024; i<2048; i++) {
    array[i] = 0;
  }
});
```

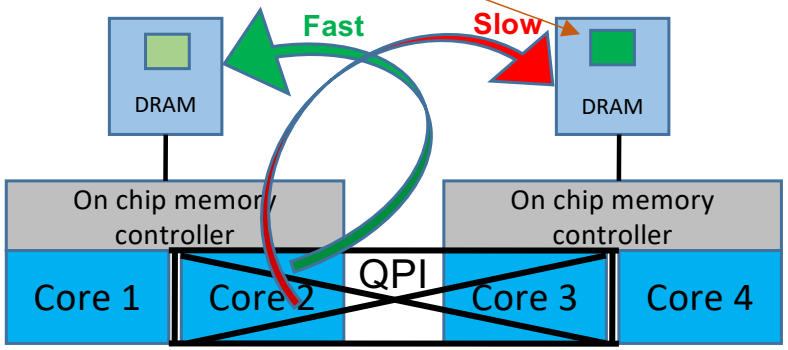



- First Touch Policy
  - Where both the pages will be allotted in the shown program?
    - Not guaranteed, may even be on a single socket if both the threads are going to run on a single socket

How to ensure each thread runs on different socket?

# Page Allocation Policy on Linux

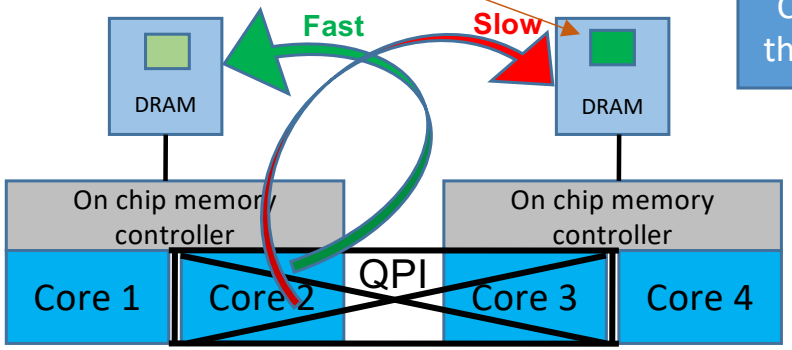
```
int * array = new int[2048]; // Two pages
int mid = 2048/2;
std::thread T1([=]() { //set affinity(C1)
  for(int i=0; i<1024; i++) {
    array[i] = 0;
  }
});
std::thread T1([=]() {//set affinity(C3)
  for(int i=1024; i<2048; i++) {
    array[i] = 0;
  }
});
```




- First Touch Policy
  - Where both the pages will be allotted in the shown program?
    - Not guaranteed, may even be on a single socket if both the threads are going to run on a single socket
      - To ensure they are allotted on different sockets, they must be mapped to two different sockets
        - Set the CPU affinity of a thread using **sched_setaffinity** before letting them "touch" the memory
      - Even if there are only two threads, and two dual core sockets, why should we still set their affinities on two different sockets?
        - Lesser contention over on-chip memory controller

# Page Allocation Policy on Linux

```
int * array = new int[2048]; // Two pages
int mid = 2048/2;
std::thread T1([=]() { //set affinity(C1)
  for(int i=0; i<1024; i++) {
    array[i] = 0;
  }
});
std::thread T1([=]() {//set affinity(C3)
  for(int i=1024; i<2048; i++) {
    array[i] = 0;
  }
});
```




Can we improve the performance?

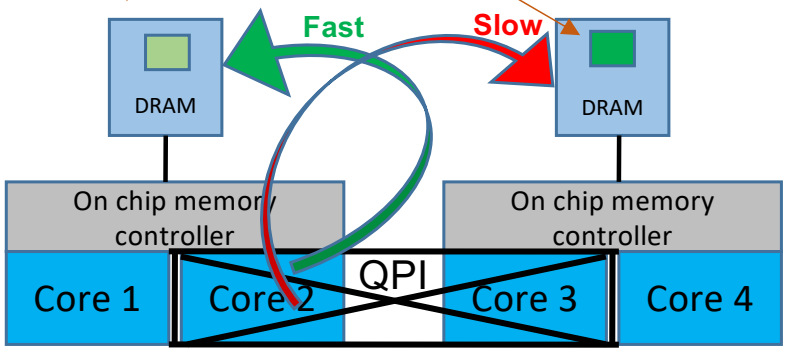
- First Touch Policy
  - Where both the pages will be allotted in the shown program?
    - Not guaranteed, may even be on a single socket if both the threads are going to run on a single socket

      To ensure they are allotted on different sockets, they must be mapped to two different sockets
      - Set the CPU affinity of a thread using **sched_setaffinity** before letting them "touch" the memory
    - Even if there are only two threads, and two dual core sockets, why should we still set their affinities on two different sockets?
      - Lesser contention over on-chip memory controller

# Page Allocation Policy on Linux

```
posix_memalign(&array, ...); // Two pages

std::thread T1([=]() { //set affinity(C1)
    array[0] = 0;     //array is int type
});
std::thread T1([=]() {//set affinity(C3)
    array[1024] = 0;
});
```




- First Touch Policy
  - Another way to achieve the same result, but with only a few CPU cycles
    - Using posix_memaling

# Alternative Allocation Policies

```
usage: numactl [--all | -a] [--interleave= | -i <nodes>] [--preferred= | -p <node>]
               [--physcpubind= | -C <cpus>] [--cpunodebind= | -N <nodes>]
               [--membind= | -m <nodes>] [--localalloc | -l] command args ...
       numactl [--show | -s]
       numactl [--hardware | -H]
       numactl [--length | -l <length>] [--offset | -o <offset>] [--shmmode | -M <shmmode>]
               [--strict | -t]
               [--shmid | -I <id>] --shm | -S <shmkeyfile>
               [--shmid | -I <id>] --file | -f <tmpfsfile>
               [--huge | -u] [--touch | -T]
               memory policy | --dump | -d | --dump-nodes | -D

memory policy is --interleave | -i, --preferred | -p, --membind | -m, --localalloc | -l
<nodes> is a comma delimited list of node numbers or A-B ranges or all.
Instead of a number a node can also be:
  netdev:DEV the node connected to network device DEV
  file:PATH  the node the block device of path is connected to
  ip:HOST    the node of the network device host routes through
  block:PATH the node of block device path
  pci:[seg:]bus:dev[:func] The node of a PCI device
<cpus> is a comma delimited list of cpu numbers or A-B ranges or all
all ranges can be inverted with !
all numbers and ranges can be made cpuset-relative with +
the old --cpubind argument is deprecated.
use --cpunodebind or --physcpubind instead
<length> can have g (GB), m (MB) or k (KB) suffixes
```

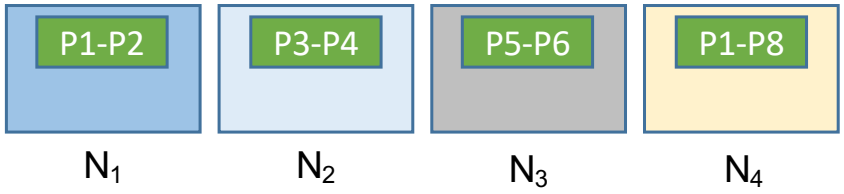
- numactl
  - Linux tool to control NUMA policy for launching processes or allocating shared memory
  - Controls the policy for the entire program, but not to individual memory areas
- Libnuma
  - Shared library that can be linked to programs and offers several policies for NUMA allocations that could be used differently for different memory areas

# Few Routines from libnuma

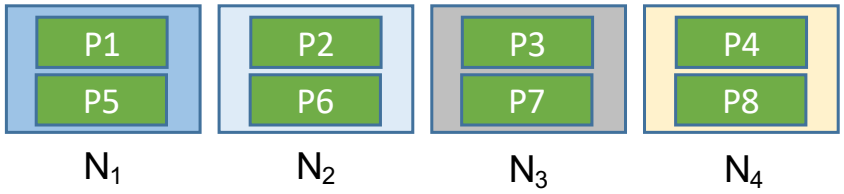
- numa_max_node()
  - How many nodes are there?
- numa_alloc_onnode()
  - Alloc memory on a particular node
- numa_alloc_local()
  - Alloc memory on the current “local” node
- numa_alloc_interleaved()
  - Places memory pages across all the available NUMA nodes in round robin
- numa_free()
  - Free the memory
- numa_run_on_node()
  - Run thread and it’s children on this node
- numa_node_of_cpu()
  - My current NUMA node

# Frequently used Page Allocation Policies

- Allocating an integer array of size 8192
  - Assuming page aligned memory allocation, total pages are 8 (4KB each)
    - Assume physical page ids P1-P8
  - Total 4 NUMA nodes
    - $N_1$-$N_3$
- Block cyclic
  - Block size is ratio of total pages and number of NUMA nodes




- Interleaved

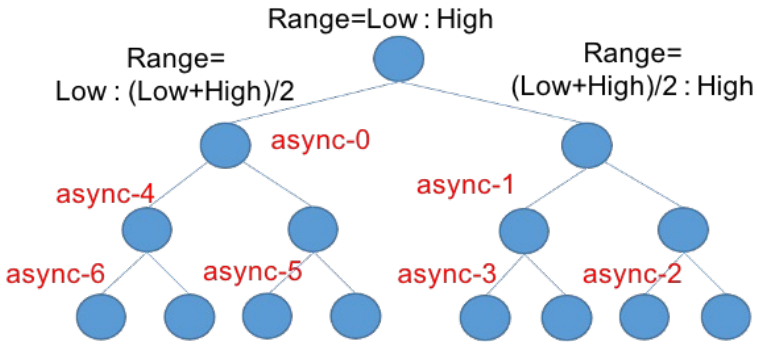



Question: which of these two policies you would choose, if you have to run recursive task parallel implementation of vector addition using the traditional random work-stealing runtime?

# Today's Lecture

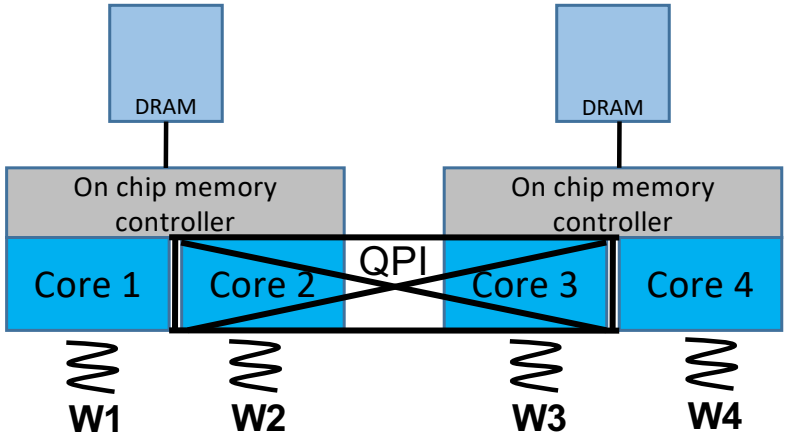
- Non uniform memory accesses
- Page allocation policies
- NUMA aware parallel runtime

# NUMA Aware Parallel Runtime: Naïve Approach

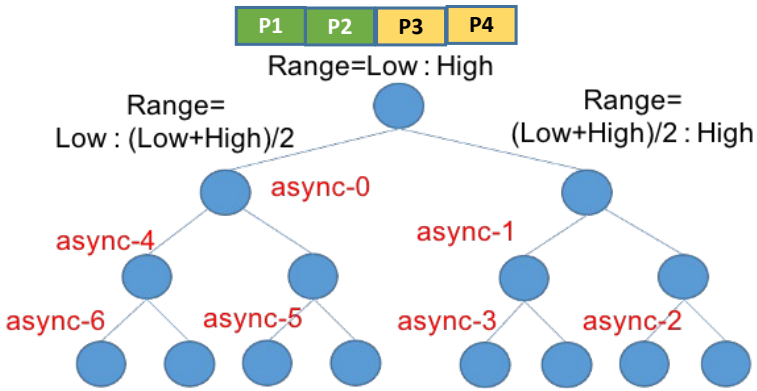


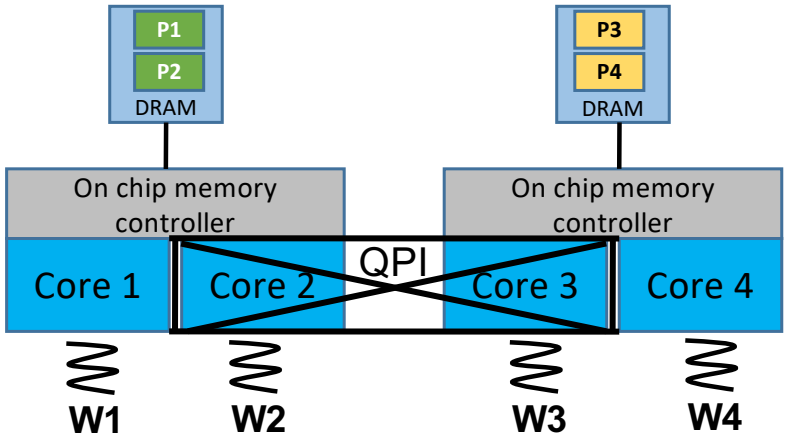

Recursive task parallel vector addition

Question: What should be our first concern, and how to resolve it?



# NUMA Aware Parallel Runtime: Naïve Approach

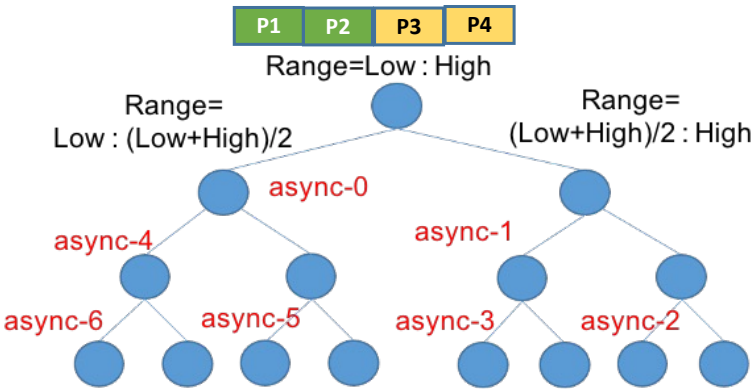



- Spread the memory evenly across all the NUMA nodes
  - Reduce bottleneck at individual node's memory controller
  - Improving locality

Question: How to improve locality in random work-stealing?

# NUMA Aware Parallel Runtime: Naïve Approach




- Spread the memory evenly across all the NUMA nodes
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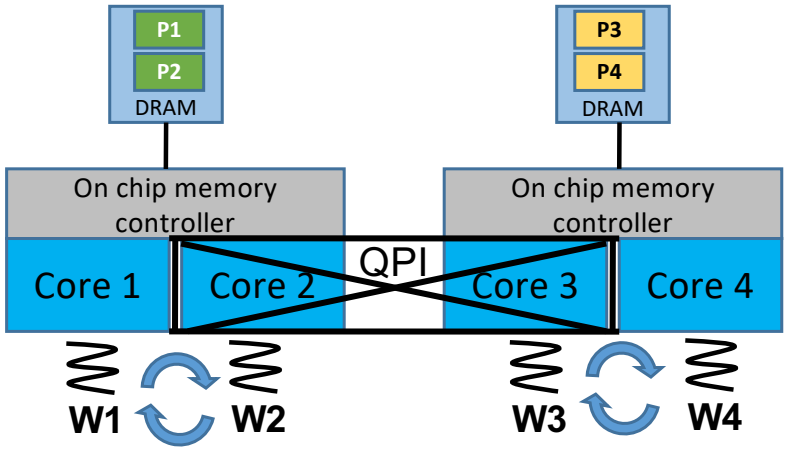
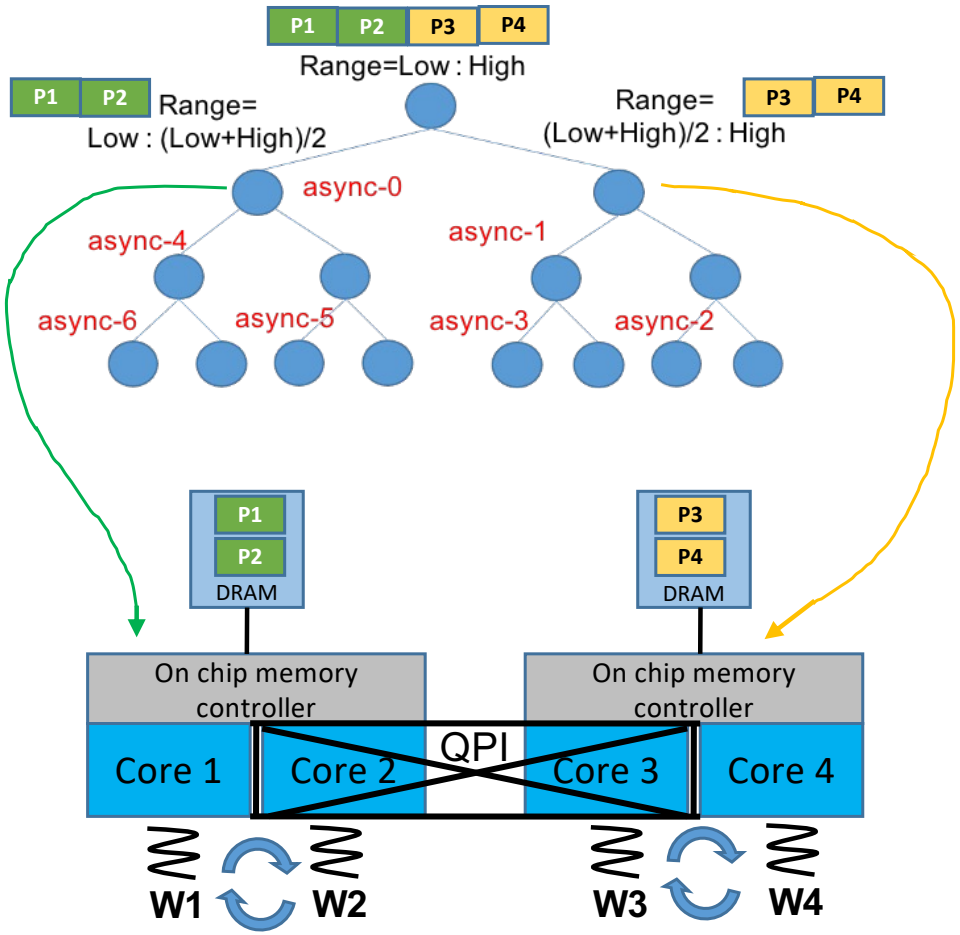
- Create teams of worker threads at each NUMA node where they can steal tasks from their local team members



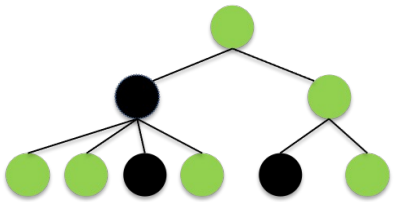

Question: How to start the execution?

# NUMA Aware Parallel Runtime: Naïve Approach

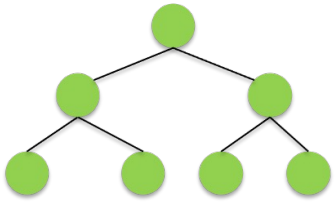



- Spread the memory evenly across all the NUMA nodes
  - Reduce bottleneck at individual node's memory controller
  - Improving locality
- Create teams of worker threads at each NUMA node where they can steal tasks from their local team members
- Give each team a seed task as per the locality of the data associated with that task

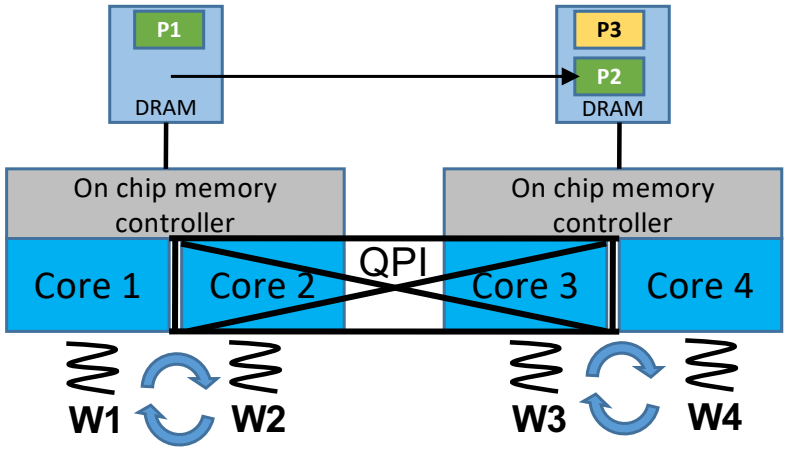
# NUMA Aware Parallel Runtime: Naïve Approach



Irregular Execution DAG



Regular Execution DAG

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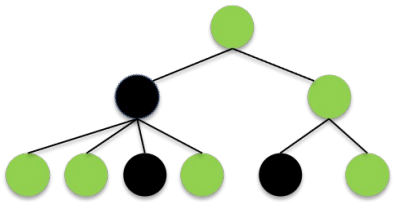
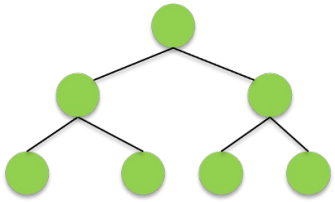
  - Improving locality
- Create teams of worker threads at each NUMA node where they can steal tasks from their local team members
- Give each team a seed task as per the locality of the data associated with that task
- Dealing with load imbalance (if any)?
  - Allow stealing from a remote team
  - Migrate the memory pages associated with that task from remote node to local node
    - numa_move_pages() in libnuma

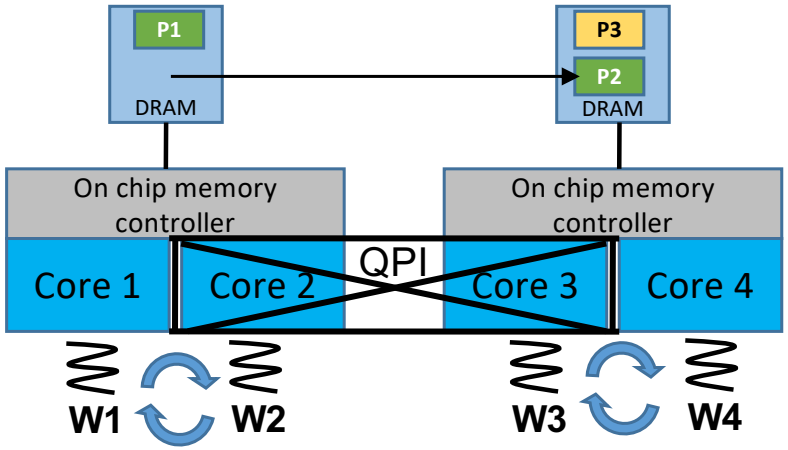
# NUMA Aware Parallel Runtime: Naïve Approach



Irregular Execution DAG



Regular Execution DAG




- Spread the memory evenly across all the NUMA nodes
  - Reduce bottleneck at individual node's memory controller
  - Improving locality
- Create teams of worker threads at each NUMA node where they can steal tasks from their local team members
- Give each team a seed task as per the locality of the data associated with that task
- Dealing with load imbalance (if any)?
  - Allow stealing from a remote team
  - Migrate the memory pages associated with that task from remote node to local node
    - numa_move_pages() in libnuma
- What if its not so easy to map seed tasks?
  - We will see in next lecture

# Reading Materials

- NUMA APIs for Linux
  - http://developer.amd.com/wordpress/media/2012/10/LibNUMA-WP-fv1.pdf
- Page migration
  - https://www.kernel.org/doc/html/v5.4/vm/page_migration.html
  - https://www.intel.com/content/www/us/en/developer/articles/technical/measuring-impact-of-numa-migrations-on-performance.html#gs.cqn3e4

# Next Lecture (L #12)

- Recursive task parallelism on NUMA architecture