Parallel Program Design Patterns and Strategies

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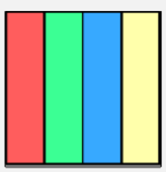
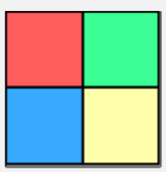
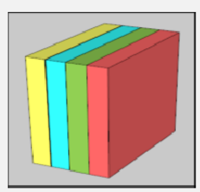
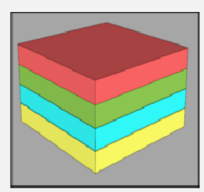
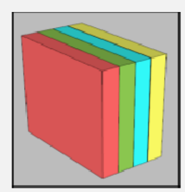
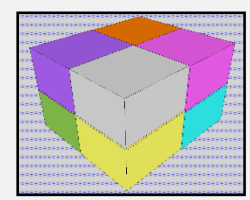
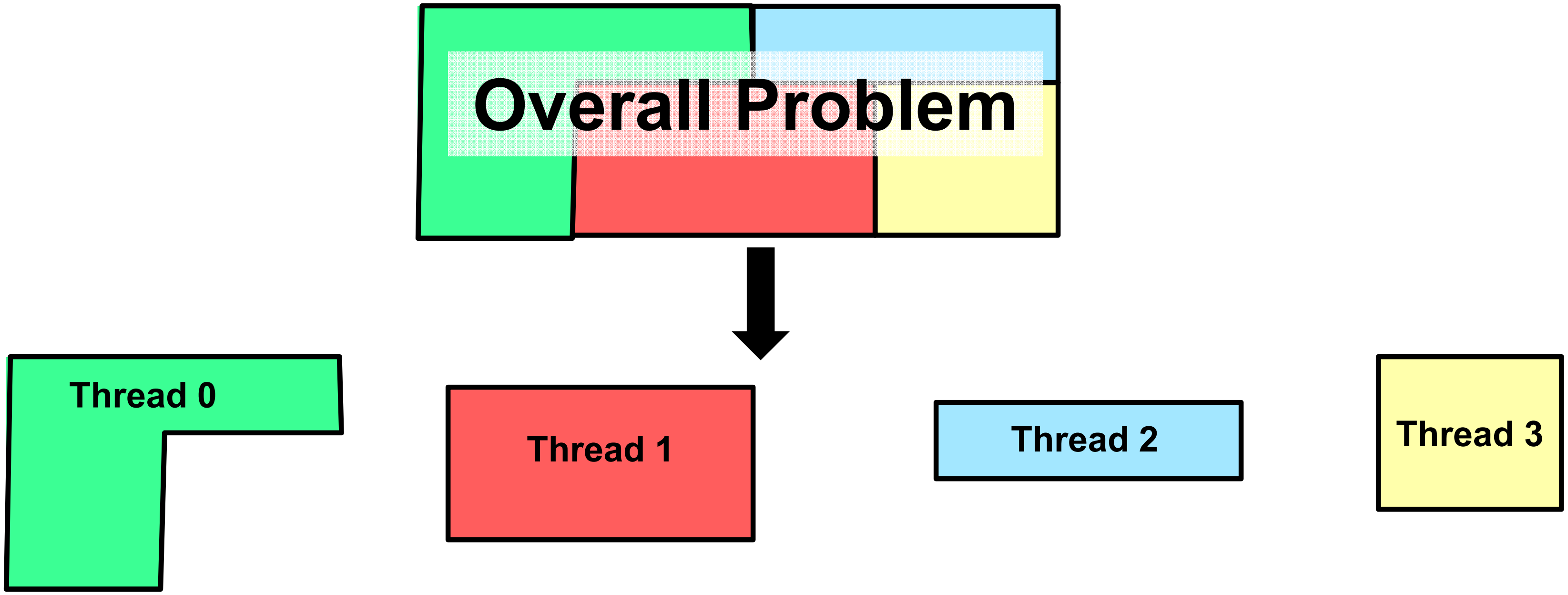







Contents

The goal of this section is to look at some of the common design and programming patterns one encounters in parallel programming and to understand some of the nuances one encounters.

The Functional Decomposition Design Pattern



The Functional (or Task) Decomposition Design Pattern

Climate

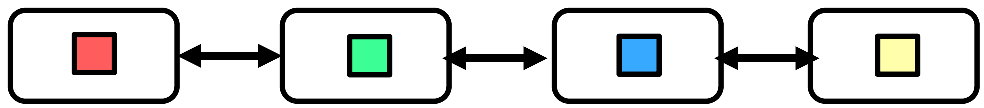
Animals

Plants

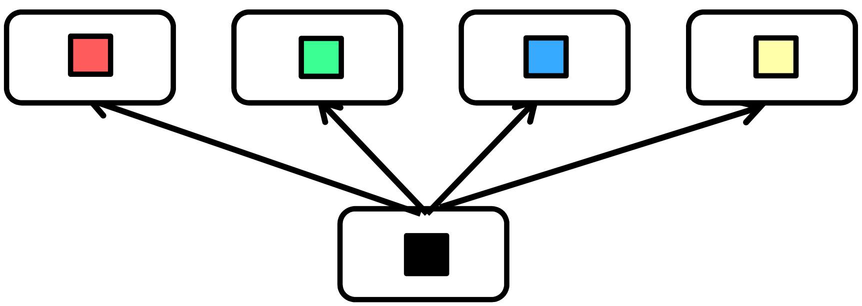
Money

Credit: Maxis (Sim Park)

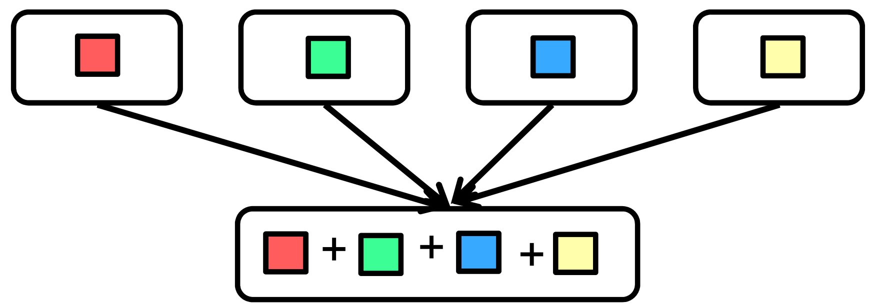
Task Distribution Design Patterns for Parallelism



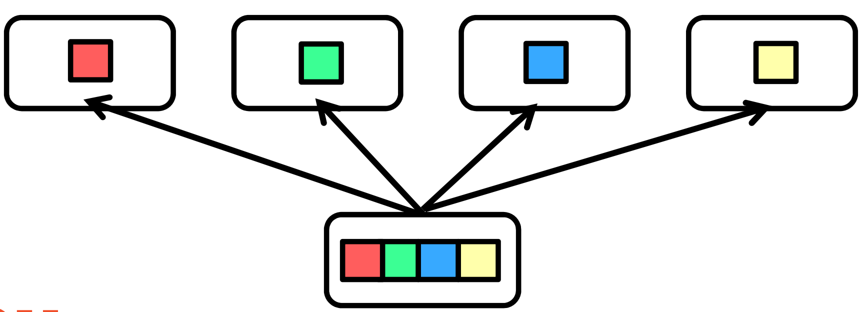
Thread-to-Thread



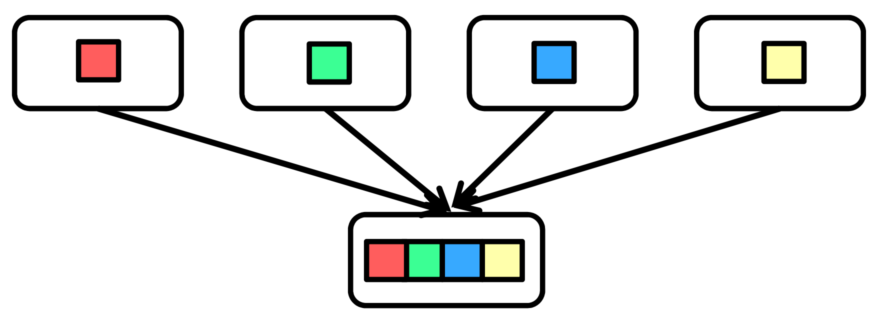
Broadcast



Reduction



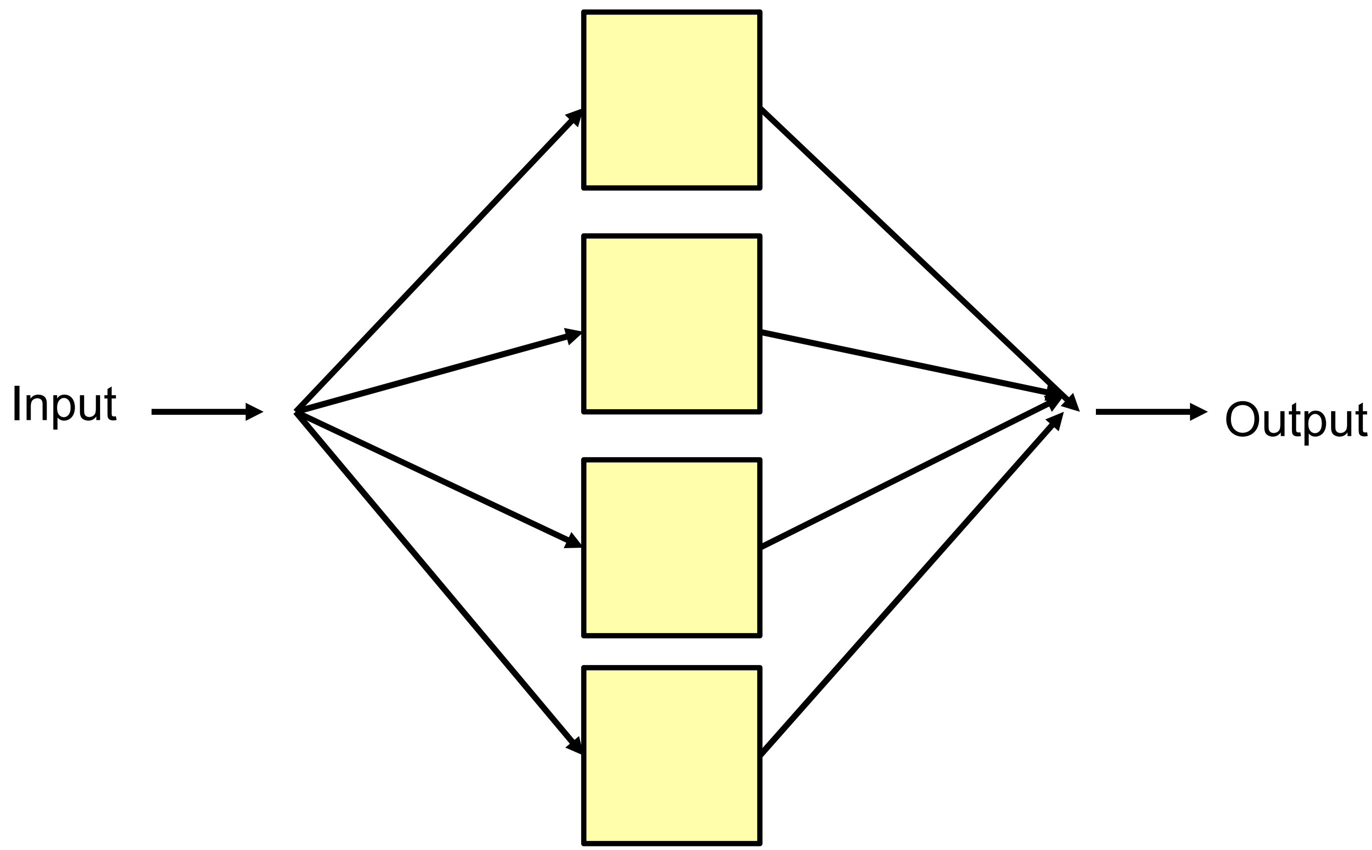
Scatter



Gather

Task Distribution Design Patterns for Parallelism

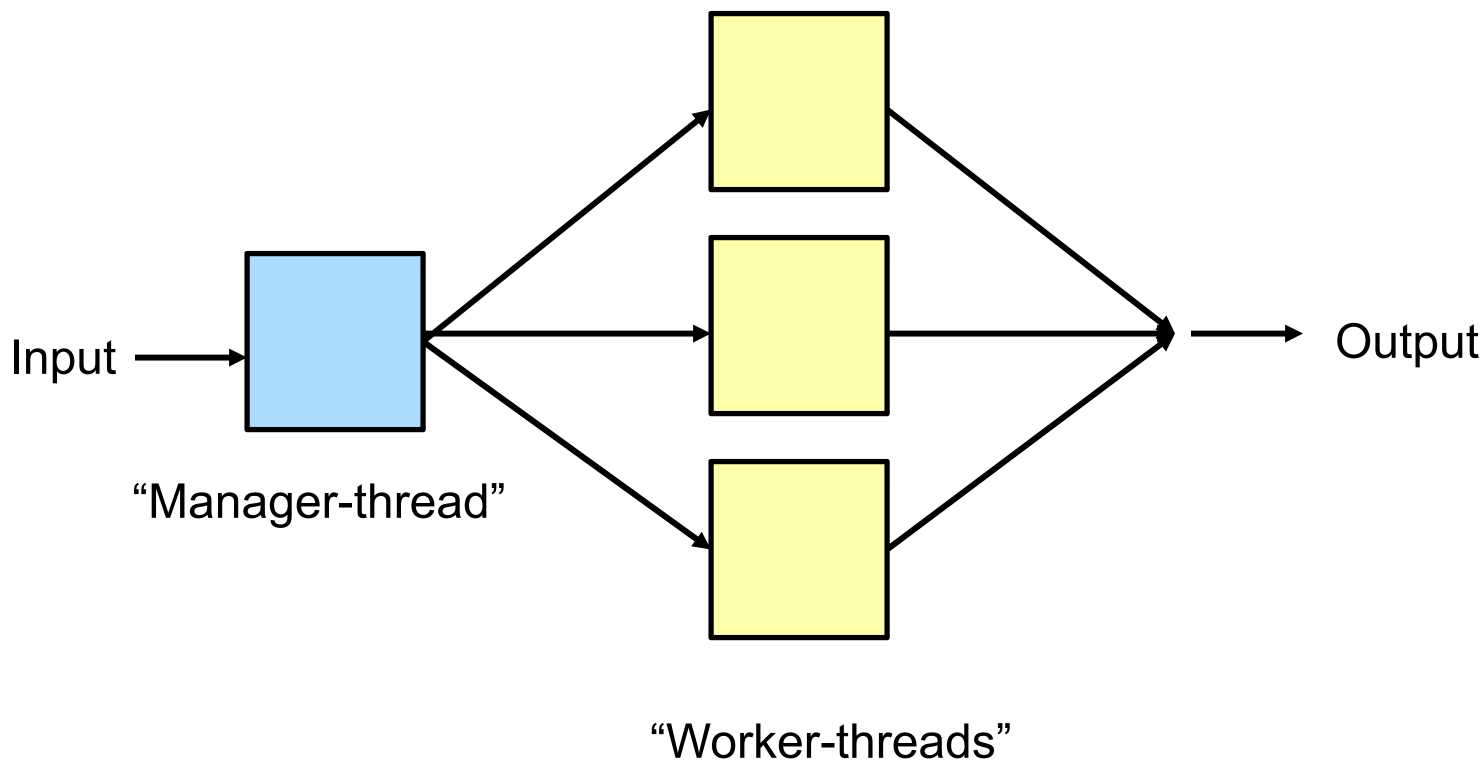
Decentralized (Peer)



"Peer-threads"

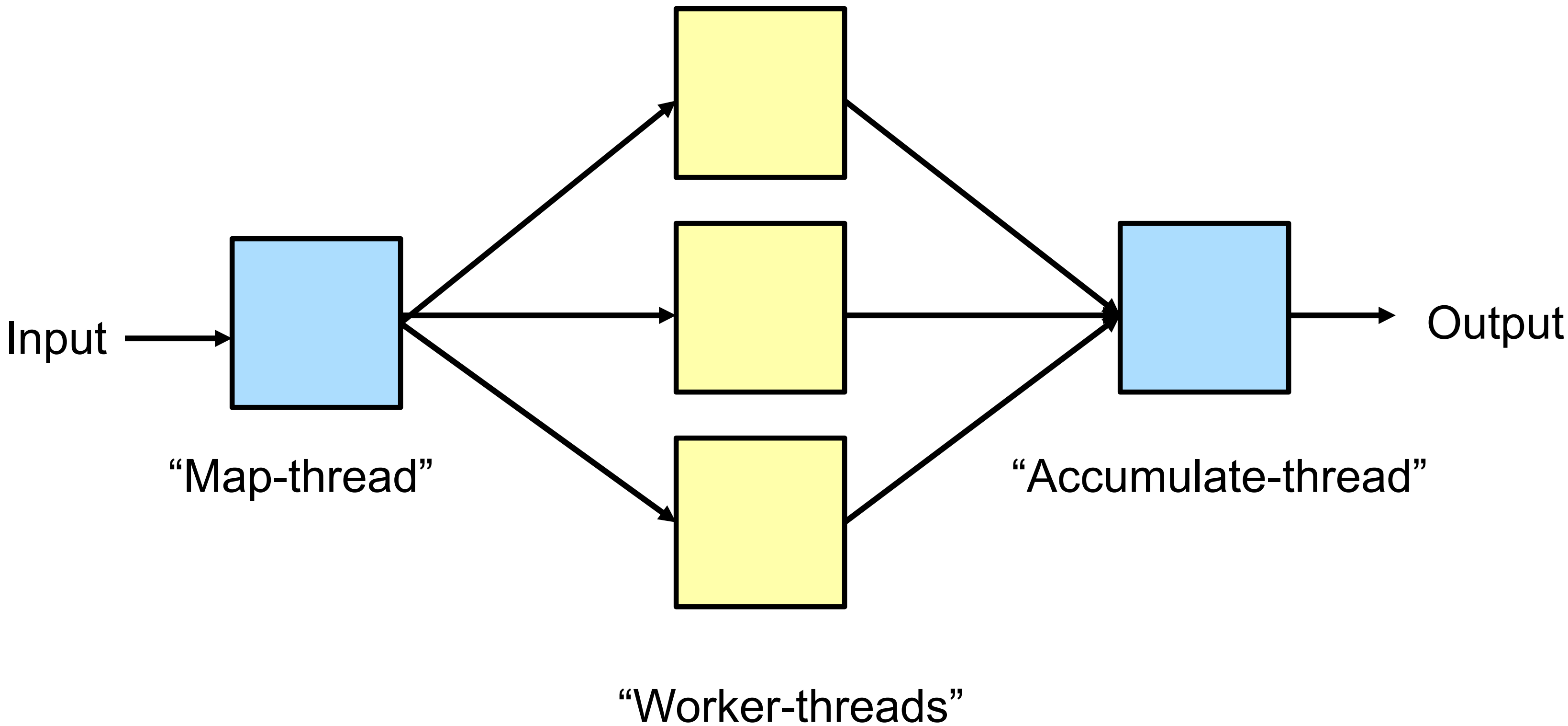
Task Distribution Design Patterns for Parallelism

Manager / workers



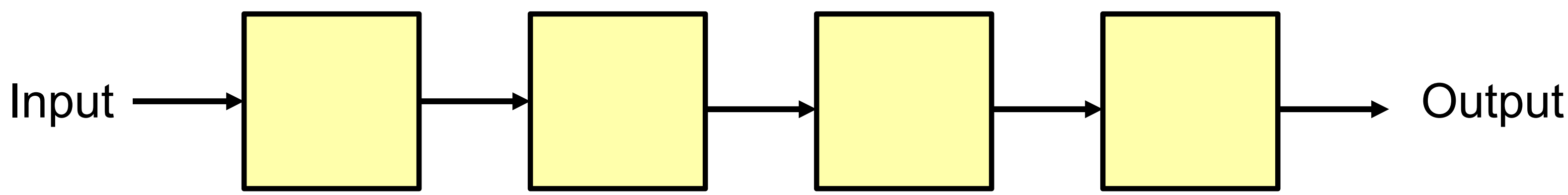
Task Distribution Design Patterns for Parallelism

Map-Reduce



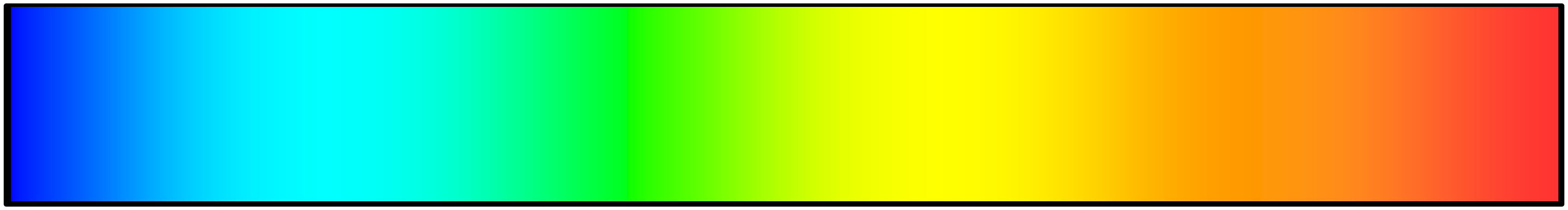
Task Distribution Design Patterns for Parallelism

Pipeline



Requires some sort of queue between the stages

Multicore Block Data Decomposition: 1D Heat Transfer Example



You have a steel bar. Each section of the bar starts out at a different temperature. There are no incoming heat sources or outgoing heat sinks (i.e., ignore boundary conditions). Ready, go! How do the temperatures change over time?

The fundamental differential equation here is:

$$\rho C \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}\right)$$

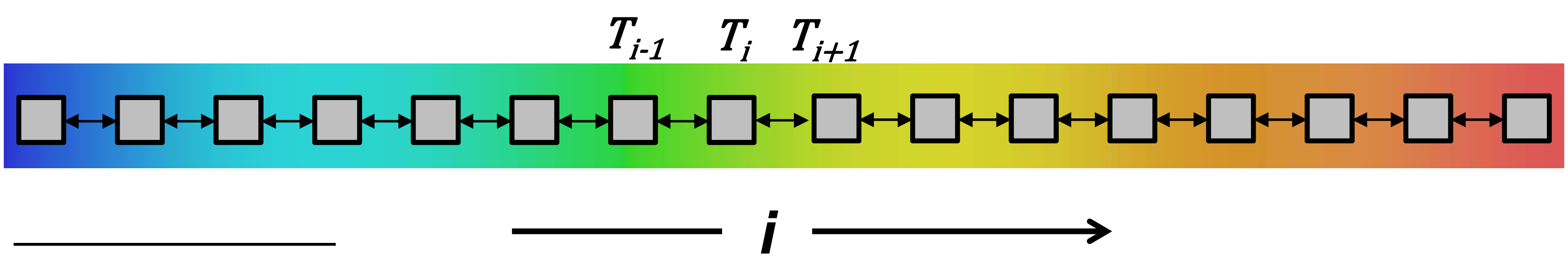
where:
ρ is the density in kg/m^3
C is the specific heat capacity measured in Joules / (kg·°K)
k is the coefficient of thermal conductivity measured in Watts / (meter·°K)
(These units work because a Watt is a Joule/second.)

In plain words, this all means that temperatures, left to themselves, try to even out. The greater the temperature differential, the faster the evening-out process goes.

Numerical Methods:
Changing a Derivative into Discrete Arithmetic

$$\frac{\partial T}{\partial t} = \frac{T_{t+\Delta t} - T_t}{\Delta t}$$

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i-1} - 2T_i + T_{i+1}}{(\Delta x)^2}$$

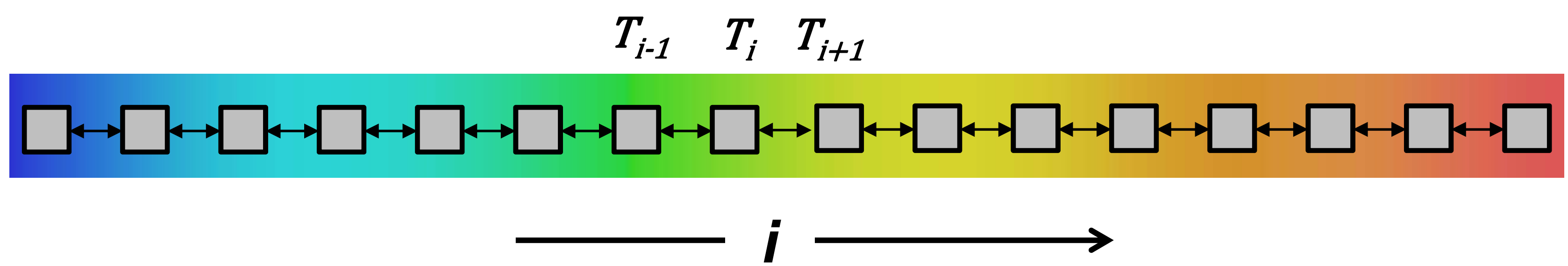


Multicore Block Data Decomposition: 1D Heat Transfer Example

$$\rho C \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}\right)$$

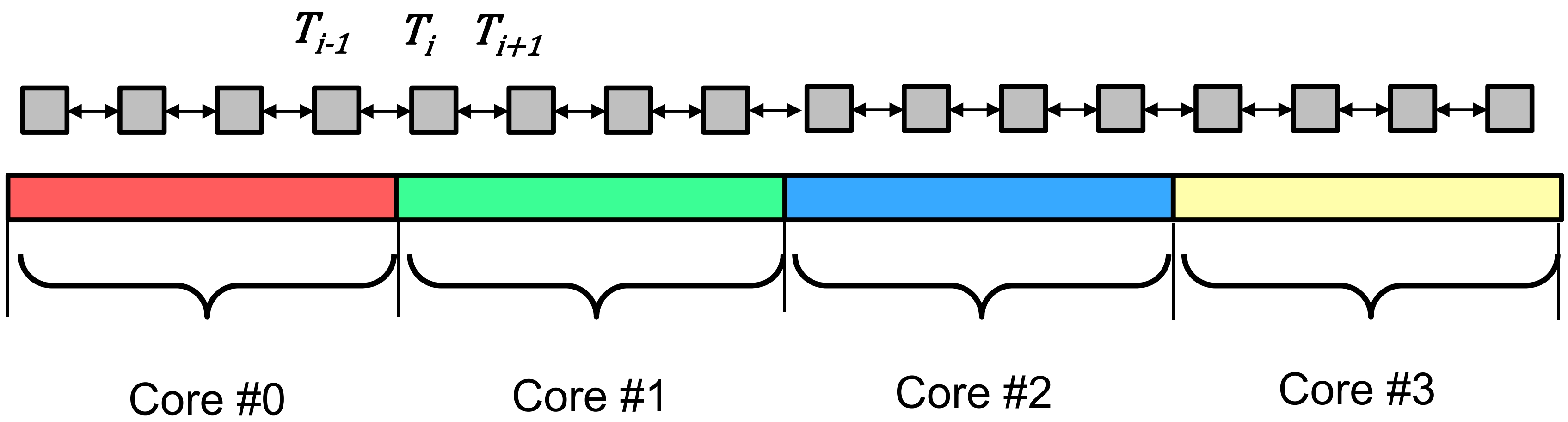
$$\downarrow$$

$$\frac{\Delta T}{\Delta t} = \frac{k}{\rho C}\left(\frac{\Delta^2 T}{\Delta x^2}\right) \longrightarrow \Delta T_i = \left(\frac{k}{\rho C}\right)\left(\frac{T_{i-1} - 2T_i + T_{i+1}}{(\Delta x)^2}\right)\Delta t$$



As a side note: the quantity ***k/(ρC)*** has the unlikely units of m^2/sec!

1D Data Decomposition: Partitioning Strategies



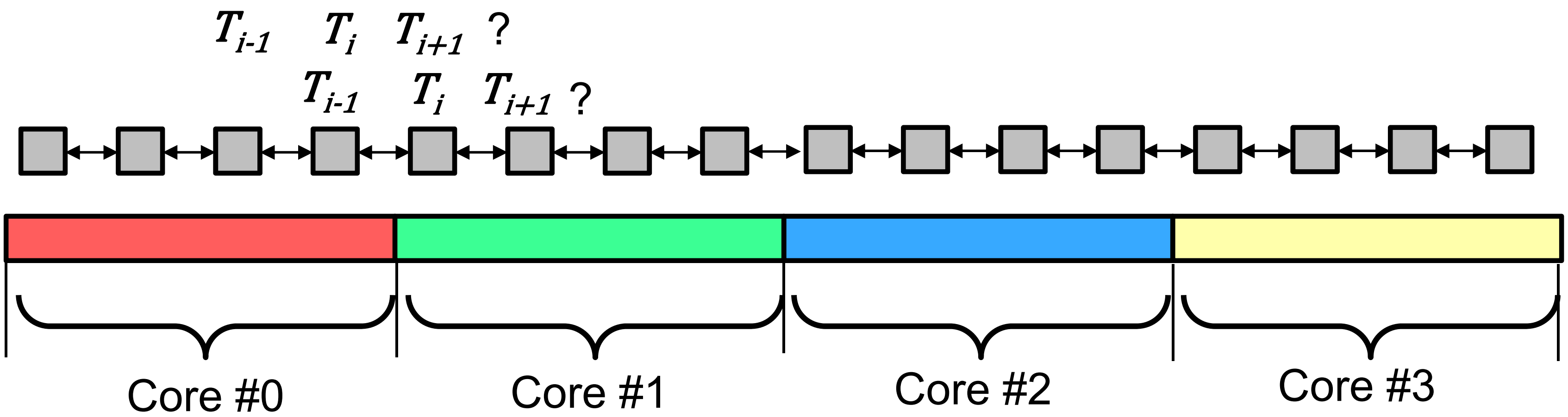
Should you allocate the data as one large global-memory block (i.e., shared)?

Or, should you allocate it as separate arrays, each dedicated to its own core?

Does it matter?

.

Allocate as One Large Continuous Global or Malloc'ed Array



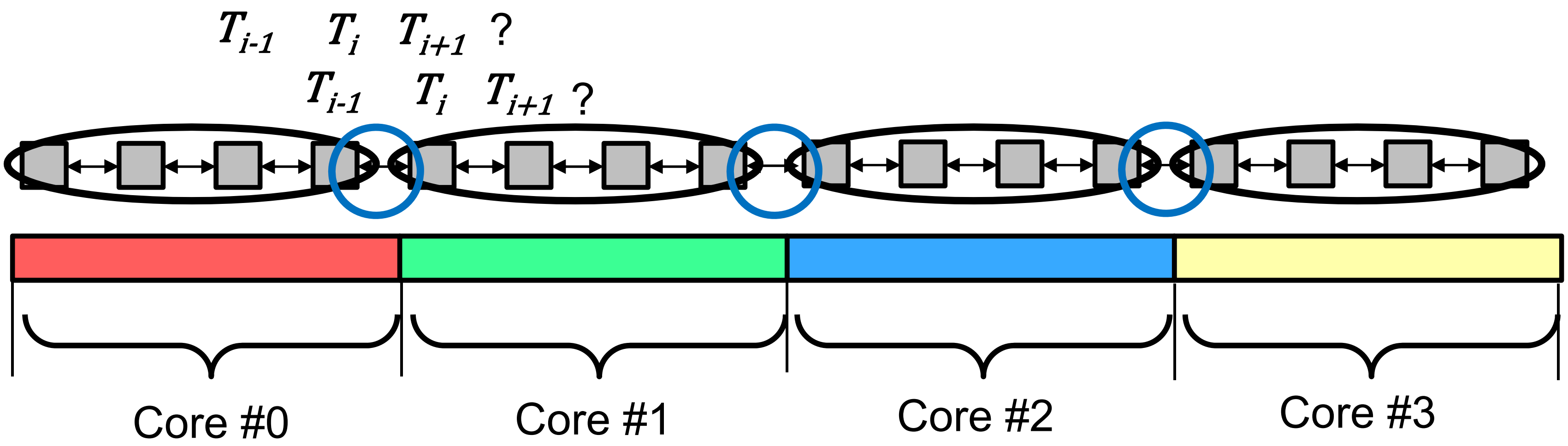
float Temps[ARRAYSIZE];
float *Temps = (float *)malloc(ARRAYSIZE*sizeof(float));
float *Temps = new float[ARRAYSIZE];
<< allocate a new[ ] array the same way >>

Pick one way of allocating global or heap data

omp_set_num_threads(4);
for(int t = 0; t < NUM_TIME_STEPS; t++)
{
#pragma omp parallel for default(none), shared(Temperatures)
for(int i = 1; i < ARRAYSIZE-1; i++)
{
<< compute ΔT_i using T_{i-1}, T_i, and T_{i+1} >>
new[i] = Temps[i] + ΔT_i;
}
<< copy the new[ ] array to the Temps[ ] array >>
}

What happens when computing at the boundaries? Two cores are accessing the same cache line.
False Sharing!

Allocate as Separate Sub-arrays



We could make each sub-array as a thread-local (i.e., private) variable. This would put each sub-array on each thread's individual stack. But, let's not do that just in case these arrays might be large enough to overflow the stack. Although, if we did, it wouldn't change this story.

Be sure to start each sub-array on its own cache line boundary. (See cache notes.)

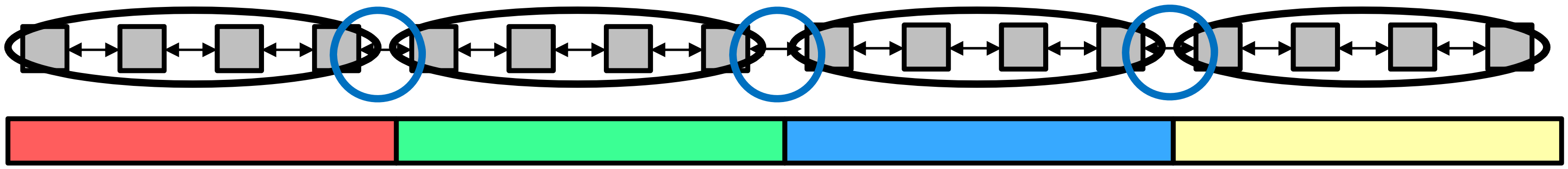
But, now when we

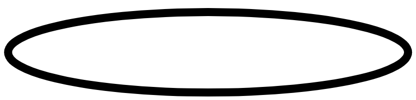
<< compute ΔT_i using T_{i-1}, T_i, and T_{i+1} >>

at the boundaries, T_{i-1} or T_{i+1} might be in another sub-array.

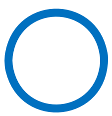
So, we need some logic to reach into the other sub-array to get the adjacent temperature. It is no longer as easy as saying Temps[i-1] or Temps[i+1]. .

1D Compute-to-Communicate Ratio





Intracore computing



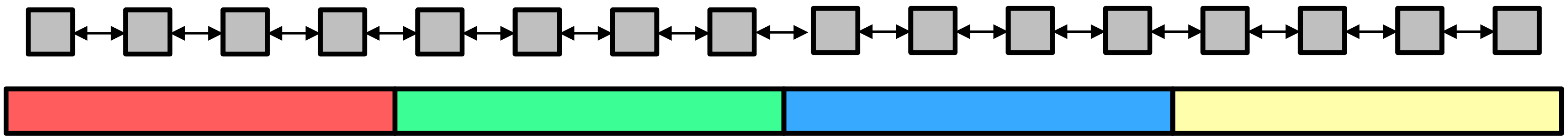
Intercore communication

Compute : Communicate ratio = N : 2

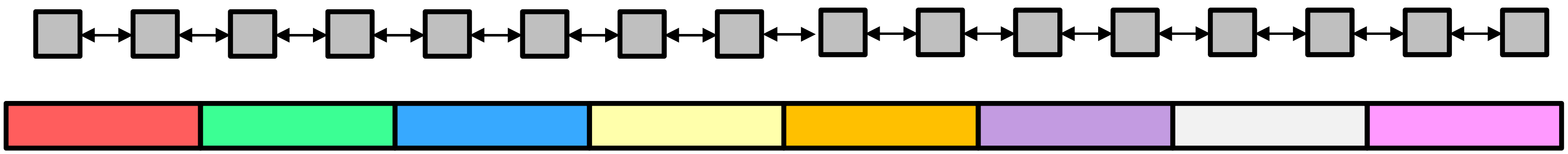
where N is the number of compute cells per core

In the above drawing, Compute : Communicate is 4 : 2

How do more Cores Interact with the Compute-to-Communicate Ratio?



In this case, with 4 cores, Compute : Communicate = 4 : 2



In this case, with 8 cores, Compute : Communicate = 2 : 2

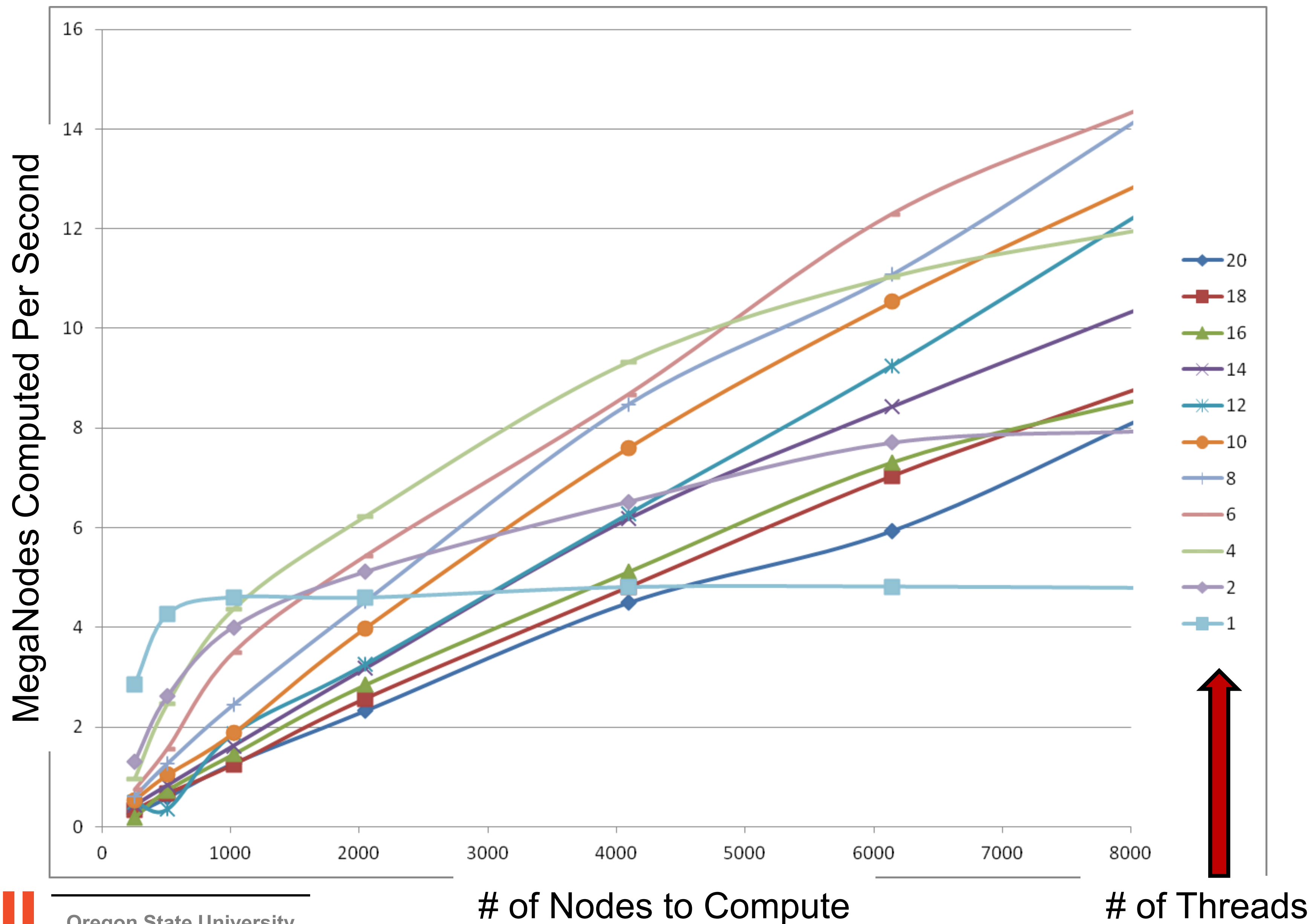
Think if it as a *Goldilocks and the Three Bears* sort of thing. :-)

Too little *Compute : Communicate* and you are spending all your time sharing data values across threads and doing too little computing

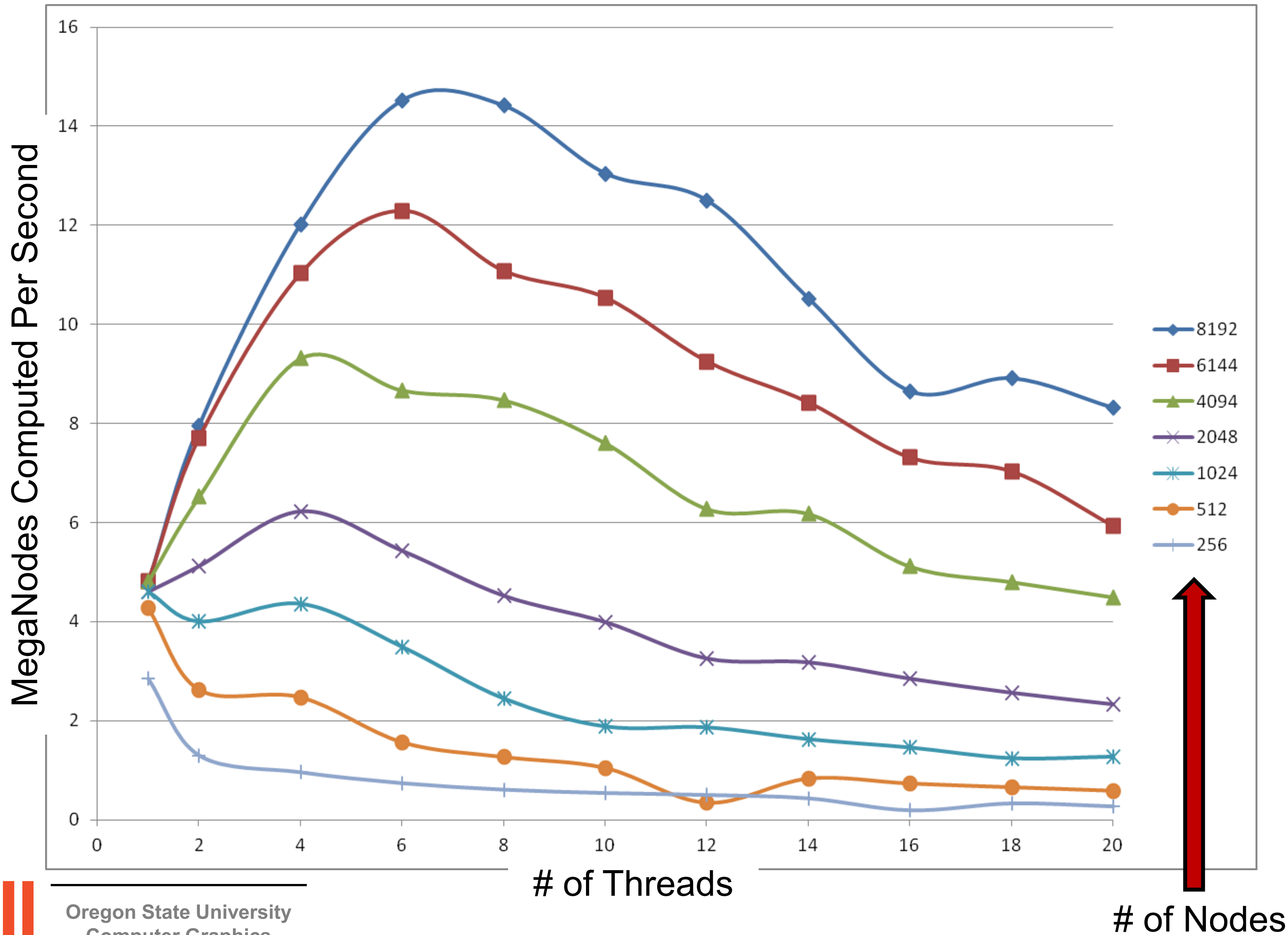
Too much *Compute : Communicate* and you are not spreading out your problem among enough threads to get good parallelism.

It's difficult to find the "sweet spot" without running experiments

Performance as a Function of Number of Nodes



Performance as a Function of Number of Threads

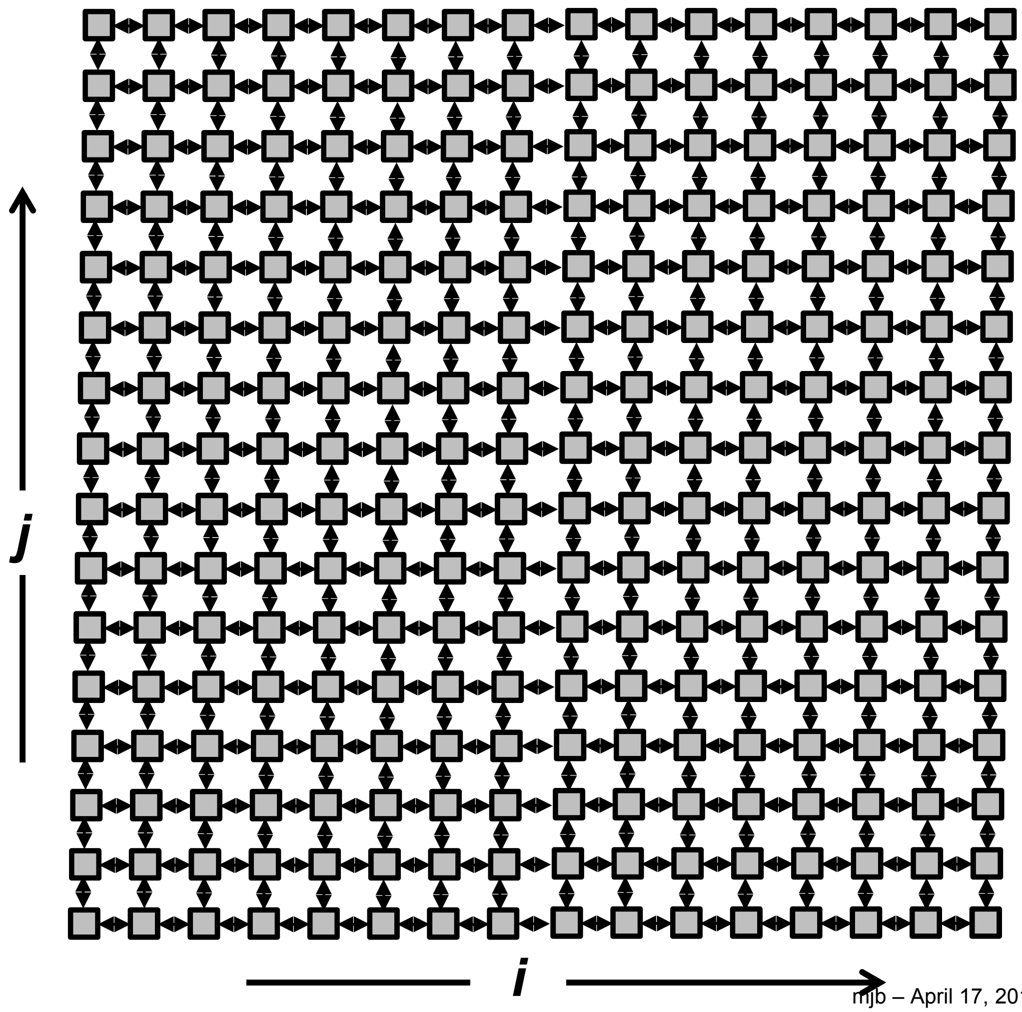


2D Heat Transfer Equation

$$\rho C \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

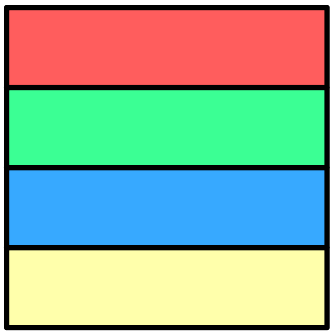
$$\Delta T_{i,j} = \left(\frac{k}{\rho C}\right)\left(\frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{\left(\Delta x\right)^2} + \frac{T_{i,j-1} - 2T_{i,j} + T_{i,j+1}}{\left(\Delta y\right)^2}\right)\Delta t$$

$$\frac{\Delta T}{\Delta t} = \frac{k}{\rho C}\left(\frac{\Delta^2 T}{\Delta x^2} + \frac{\Delta^2 T}{\Delta y^2}\right)$$

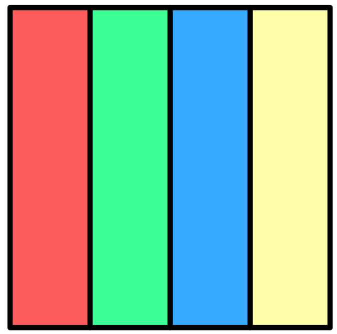


2D Domain (Data) Decomposition

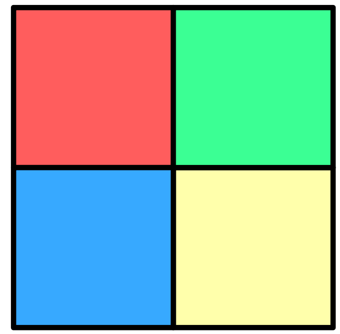
In addition to the issues of size of the compute block, you also have issues of direction.



2D *,Block



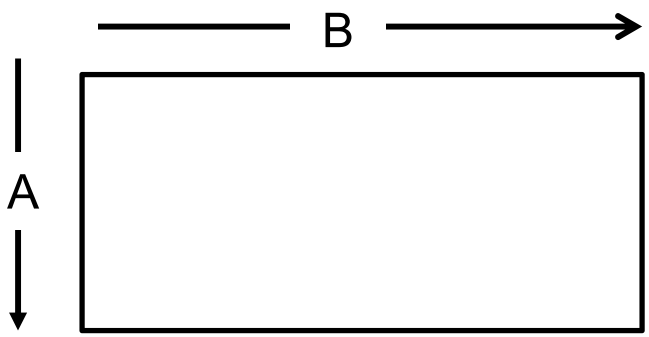
2D Block,*



2D Block, Block

Direction Issue: Decomposition Order Matters (think cache)

float Array[A][B];

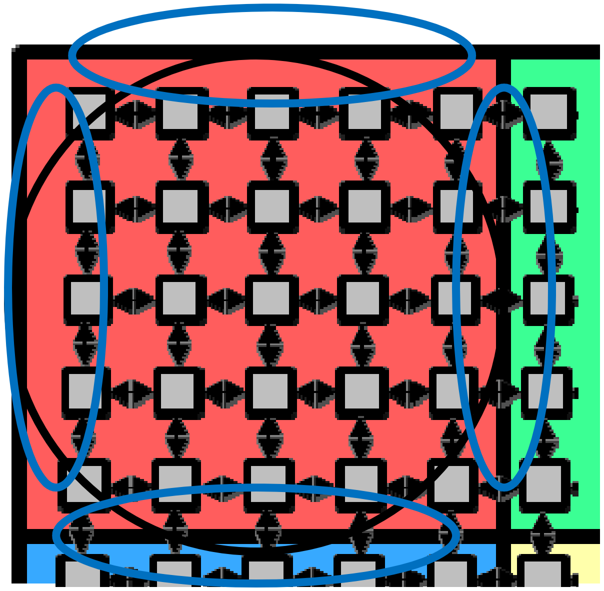


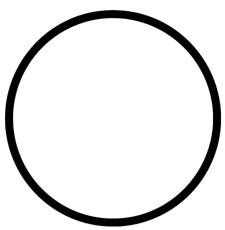
In 2D problems, this is often (but not always) thought of as:

float Array[NY][NX];

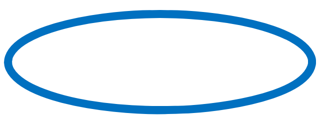
0	0
0	1
0	2
0	3
0	$...$
0	$B-1$
1	0
1	1
1	2
1	3
1	$...$
1	$B-1$
.	. .
$A-1$	0
$A-1$	1
$A-1$	2
$A-1$	3
$A-1$	$...$
$A-1$	$B-1$

2D Compute-to-Communicate Ratio





Intracore computing



Intercore communication

Compute : Communicate ratio = N^2 : 4N = N : 4

where N is the dimension of compute nodes per core

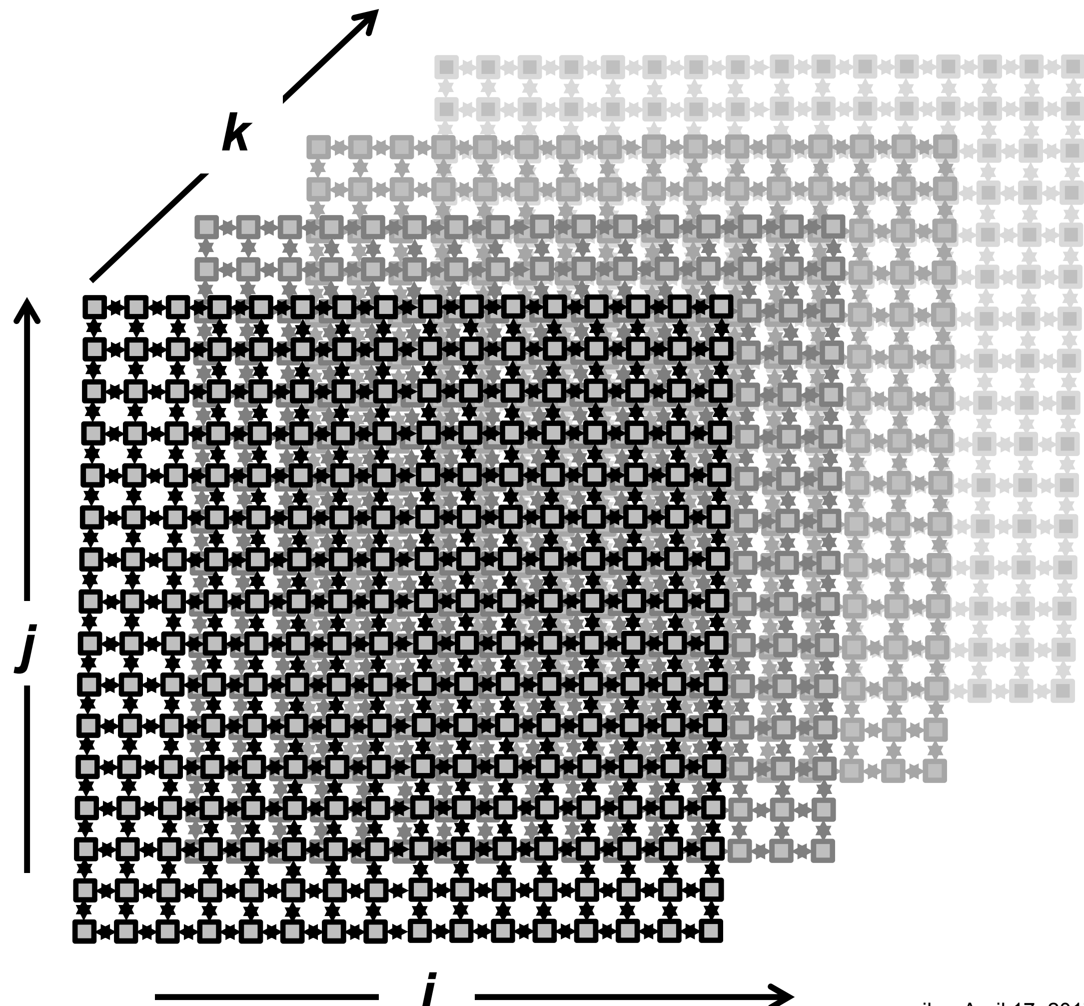
The 2D Compute : Communicate ratio is sometimes referred to as *Area-to-Perimeter*

3D Heat Transfer Equation

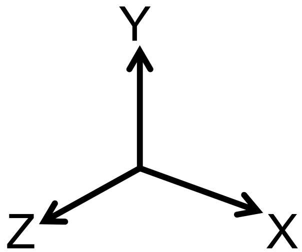
$$\rho C \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

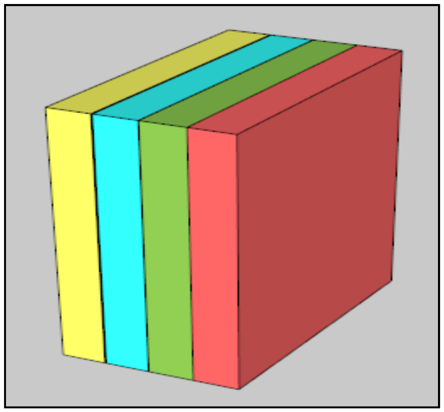
$$\frac{\Delta T}{\Delta t} = \frac{k}{\rho C}\left(\frac{\Delta^2 T}{\Delta x^2} + \frac{\Delta^2 T}{\Delta y^2} + \frac{\Delta^2 T}{\Delta z^2}\right)$$

$$\Delta T_{i,j,k} = \left(\frac{k}{\rho C}\right)\left(\frac{T_{i-1,j,k} - 2T_{i,j,k} + T_{i+1,j,k}}{\left(\Delta x\right)^2} + \frac{T_{i,j-1,k} - 2T_{i,j,k} + T_{i,j+1,k}}{\left(\Delta y\right)^2} + \frac{T_{i,j,k-1} - 2T_{i,j,k} + T_{i,j,k+1}}{\left(\Delta z\right)^2}\right)\Delta t$$

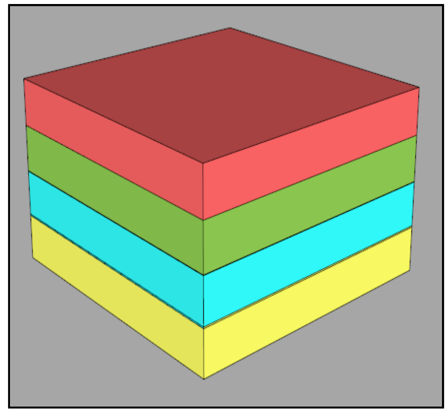


3D Domain (Data) Decomposition

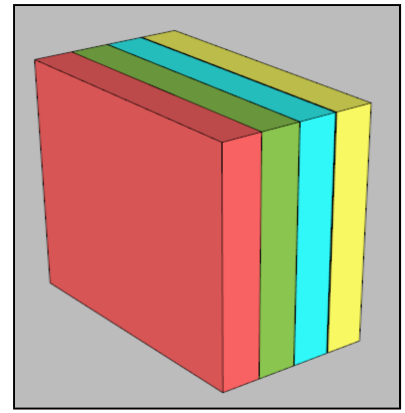




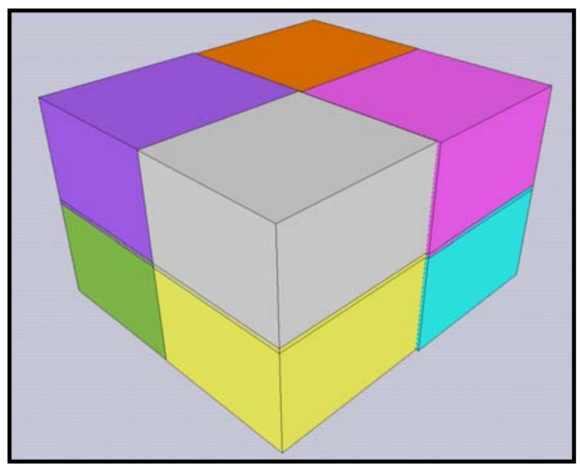
3D Block, *, *



3D *,Block, *



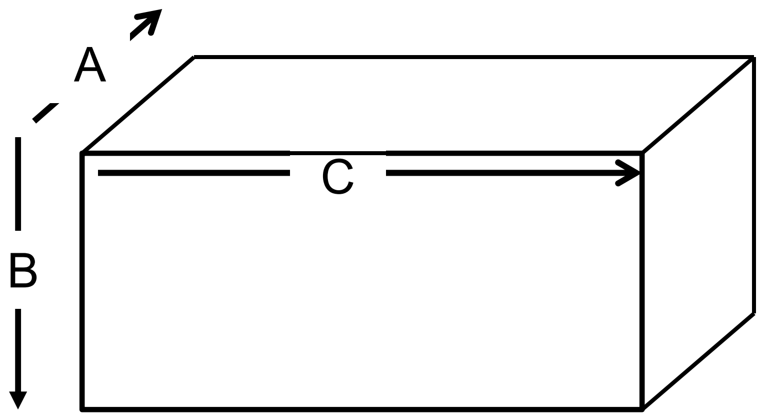
3D *,*,Block



3D Block, Block, Block

Direction Issue: Decomposition Order Matters (think cache)

float Array[A][B][C];



In 3D problems, this is often (but not always) thought of as:

float Array[NZ][NY][NX];

3D Compute-to-Communicate Ratio

Compute : Communicate ratio = $N^3 : 6N^2 = N : 6$

where N is the dimension of compute nodes per core

In 3D the Compute : Communicate ratio is sometimes referred to as *Volume-to-Surface*