Course admin stuff

- Coursework 1 is under way
  - 102 people signed up in github

- Where to find it
  - Spec is on github: https://github.com/HPCE/hpce-2017-cw1
  - Submission for this coursework is via blackboard
    - Submission is open

Expectations for coursework

- Coursework is not lab [1]
  - You have to manage when, where, and how long you spend on it
  - 100% coursework does not mean easy [1]

- You are expected to be reasonably independent
  - This is a masters level course

[1] – Though the earlier parts kind of are.

Working together

- The software community has a tradition of sharing
  - Many open-source projects, some of which you will rely on
  - Lots of forums for discussing problems: stack-overflow, ...

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- Approach this work in the same way
  - You may encounter the same problems as other students
  - Discuss solutions with each other, help each other out
  - One-on-one discussions, github issues, whatever
    - https://github.com/HPCE/hpce-2015-cw1/blob/master/background-bugs.md
  - Give credit or thanks if appropriate: be excellent to each other

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  - Give credit or thanks if appropriate: be excellent to each other

- But you have to balance co-operation and competition
  - The later courseworks require good ideas and strategies
  - Up to you to protect your IP.

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  - Some similarity of structure is expected, but there are limits
  - Students are amusingly bad at obfuscation
  - You need to be able to explain any code you submit in the oral
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- If necessary you ***may*** use code from third-party sources
  - e.g. open-source projects, samples, stack overflow, ...
  - Origin and extent must be very clearly shown
  - Need to be able to justify why it was used
  - Should be aware of potential licensing implications

More practical: image processing

- *Gamma correction*: adjust light/dark
  - $p_{[x,y]} = \text{pow}(p_{[x,y]}, \text{gamma})$

γ = 2

γ = 1

γ = 0.5

```
void process_frame(
    float gamma,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
){
    for(unsigned x=   0u; x<width; x++){
        for(unsigned y=0; y<height; y++){
            double fIn = frameIn[y*width + x] * (1.0/256.0);

            double fOut = pow( fIn, gamma );

            frameOut[y*width + x] = (uint8_t)floor(fOut * 256.0);
        }
    }
}
```

```
void process_frame(
    float gamma,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
){
    tbb::parallel_for(0u,   width, [&](unsigned x){
        for(unsigned y=0; y<height; y++){
            double fIn = frameIn[y*width + x] * (1.0/256.0);

            double fOut = pow( fIn, gamma );

            frameOut[y*width + x] = (uint8_t)floor(fOut * 256.0);
        }
    });
}
```

```
void process_frame(
    float gamma,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
){
    auto f =                          [&](unsigned x){
        for(unsigned y=0; y<height; y++){
            double fIn = frameIn[y*width + x] * (1.0/256.0);

            double fOut = pow( fIn, gamma );

            frameOut[y*width + x] = (uint8_t)floor(fOut * 256.0);
        }
    };

    tbb::parallel_for(0u,   width,
        f
    );
}
```

f is a variable, but we let compiler decide on its type

Capture variables by reference (can modify outer variables)

Lambda parameters, just like function parameter.

```
void process_frame(
    float gamma,
    unsigned width, unsigned height,
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            double fOut = pow( fIn, gamma );

            frameOut[y*width + x] = (uint8_t)floor(fOut * 256.0);
        }
    };

    tbb::parallel_for(0u,   width,
        f
    );
}
```

```
void process_frame(
    float gamma,
    unsigned width, unsigned height,
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){
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            double fIn = frameIn[y*width + x] * (1.0/256.0);

            double fOut = pow( fIn, gamma );

            frameOut[y*width + x] = (uint8_t)floor(fOut * 256.0);
        }
    };

    for(unsigned i=   0u; i<width; i++){
        f(i);
    }
}
```

Quantisation via dithering

- Dithering: cumulative error due to quantisation is tracked

Quantisation via error dithering

```
void process_frame(
    unsigned levels,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
)
{
    for(unsigned x=0; x<width; x++){
        double error=0.0;
        for(unsigned y=0; y<height; y++){
            double fIn = frameIn[y*width + x] * (1.0/255.0);

            double fTrue = fIn + error;

            double fQuant = round( fTrue * levels ) / levels;

            frameOut[y*width + x] = (uint8_t)floor(fQuant * 255.0);

            error = fTrue - fQuant;
        }
    }
}
```

Quantisation via error dithering

```
void process_frame(
    unsigned levels,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
)
{
    for(unsigned x=0; x<width; x++){
        double error=0.0;
        for(unsigned y=0; y<height; y++){
            double fIn = frameIn[y*width + x] * (1.0/255.0);

            double fTrue = fIn + error;

            double fQuant = round( fTrue * levels ) / levels;

            frameOut[y*width + x] = (uint8_t)floor(fQuant * 255.0);

            error = fTrue - fQuant;
        }
    }
}
```

Loop carried dependency through error

Parallelising the inner loop

```
void process_frame(
    unsigned levels,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
)
{
    for(unsigned x=0; x<width; x++){
        double error=0.0;
        tbb::parallel_for(0u, height, [&](unsigned y){
            double fIn = frameIn[y*width + x] * (1.0/255.0);

            double fTrue = fIn + error;

            double fQuant = round( fTrue * levels ) / levels;

            frameOut[y*width + x] = (uint8_t)floor(fQuant * 255.0);

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        });
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```

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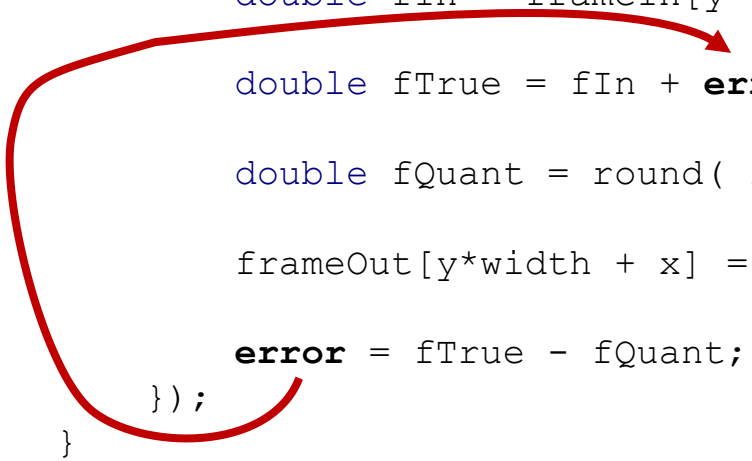
            double fIn = frameIn[y*width + x] * (1.0/255.0);

            double fTrue = fIn + error;

            double fQuant = round( fTrue * levels ) / levels;

            frameOut[y*width + x] = (uint8_t)floor(fQuant * 255.0);

            error = fTrue - fQuant;
        });
    }
}
```



Parallelising the outer loop

```
void process_frame(
    unsigned levels,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
)
{
    tbb::parallel_for(0u, width, [&](unsigned x){
        double error=0.0;
        for(unsigned y=0; y<height; y++){
            double fIn = frameIn[y*width + x] * (1.0/255.0);

            double fTrue = fIn + error;

            double fQuant = round( fTrue * levels ) / levels;

            frameOut[y*width + x] = (uint8_t)floor(fQuant * 255.0);

            error = fTrue - fQuant;
        }
    });
}
```

A solution for the inner loop?

```
void process_frame(
    unsigned levels,
    unsigned width, unsigned height,
    const uint8_t *frameIn,
    uint8_t *frameOut
)
{
    std::vector<double> error(height, 0.0);

    for(unsigned x=0; x<width; x++){
        tbb::parallel_for(0u, height, [&](unsigned y){
            double fIn = frameIn[y*width + x] * (1.0/255.0);
            assert( (fIn>=0) && (fIn<=1.0));

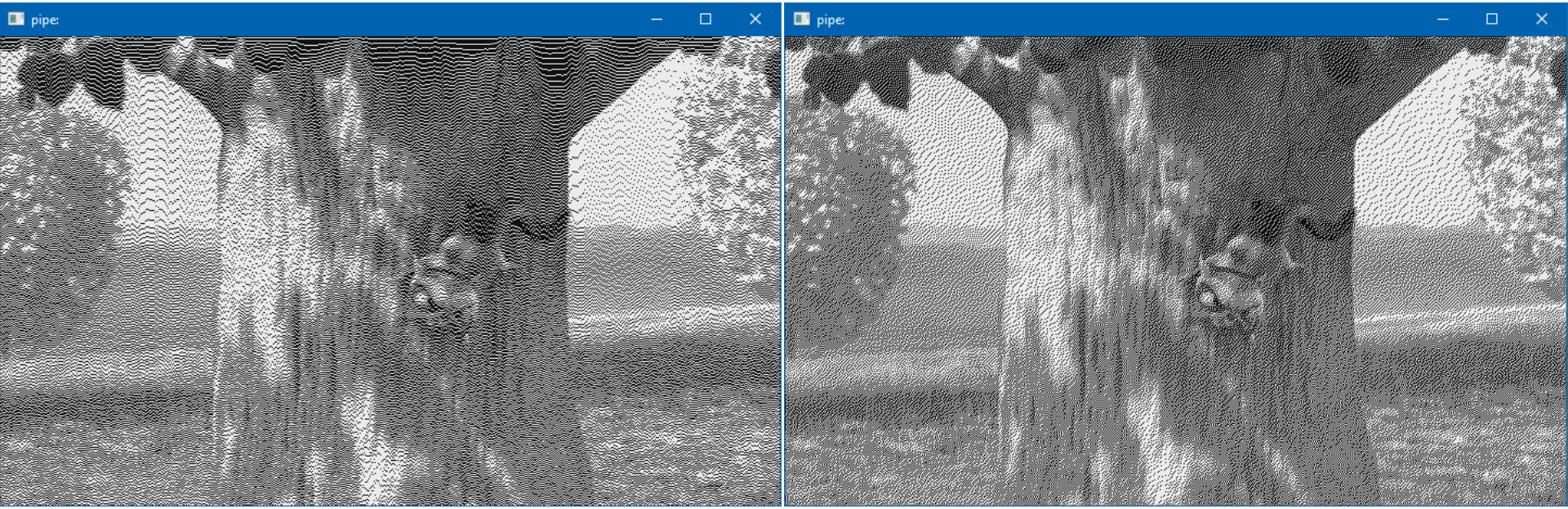
            double fTrue = fIn + error[y];

            double fQuant = round( fTrue * levels ) / levels;

            frameOut[y*width + x] = (uint8_t)floor(fQuant * 255.0);

            error[y] = fTrue - fQuant;
        });
    }
}
```

2D error diffusion



- Attempt to diffuse error both across and down image
- Reduce tendency towards banding effects

```
void process_frame(
    unsigned levels, unsigned width, unsigned height,
    double *frame
)
{
    for(unsigned x=0; x<width-1; x++){
        for(unsigned y=0; y<height-1; y++){
            double fIn = frame[y*width + x];

            double fQuant = round( fIn * levels ) / levels;
            frame[y*width + x] = fQuant;

            double error = fIn - fQuant;
            frame[  y    * width + x+1] += error * 0.4;
            frame[ (y+1) * width + x  ] += error * 0.4;
            frame[ (y+1) * width + x+1] += error * 0.2;
        }
    }
}
```

- More difficult loop carried dependency

```
void process_frame(
    unsigned levels, unsigned width, unsigned height,
    double *frame
)
{
    for(unsigned x=0; x<width-1; x++){
        for(unsigned y=0; y<height-1; y++){
            double fIn = frame[y*width + x];

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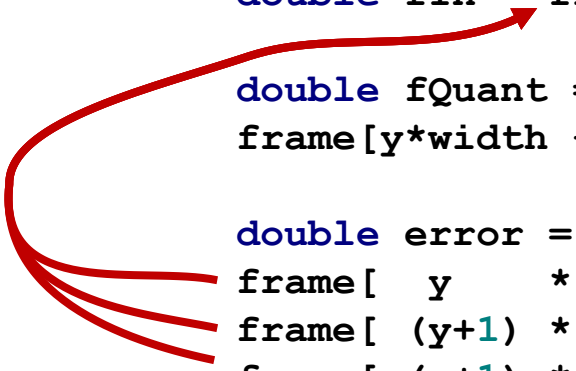
        }
    }
}
```



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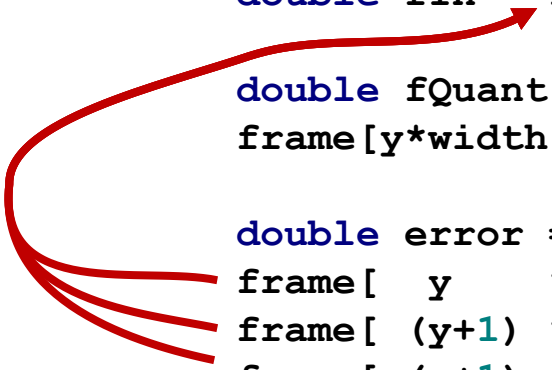

- More difficult loop carried dependency
- Have a write before read dependency
  - Current loop iteration reads from (x,y)
  - Writes (x,y+1), (x+1,y), and (x+1,y+1)
  - Three constraints per node

```
void process_frame(
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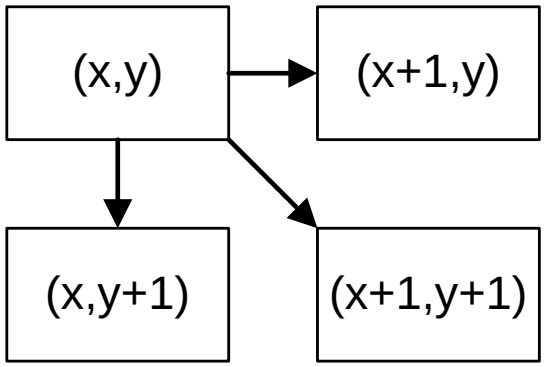
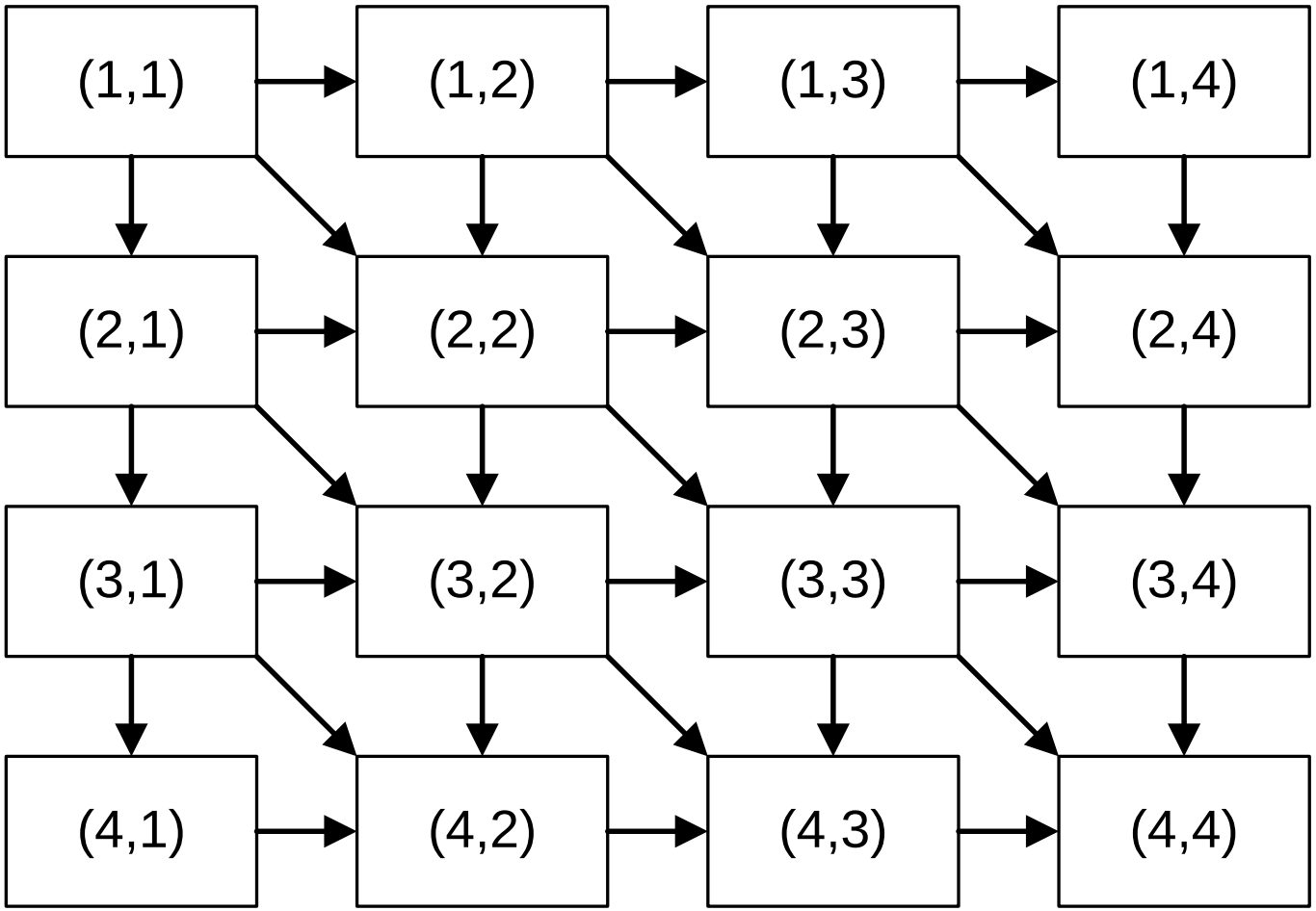
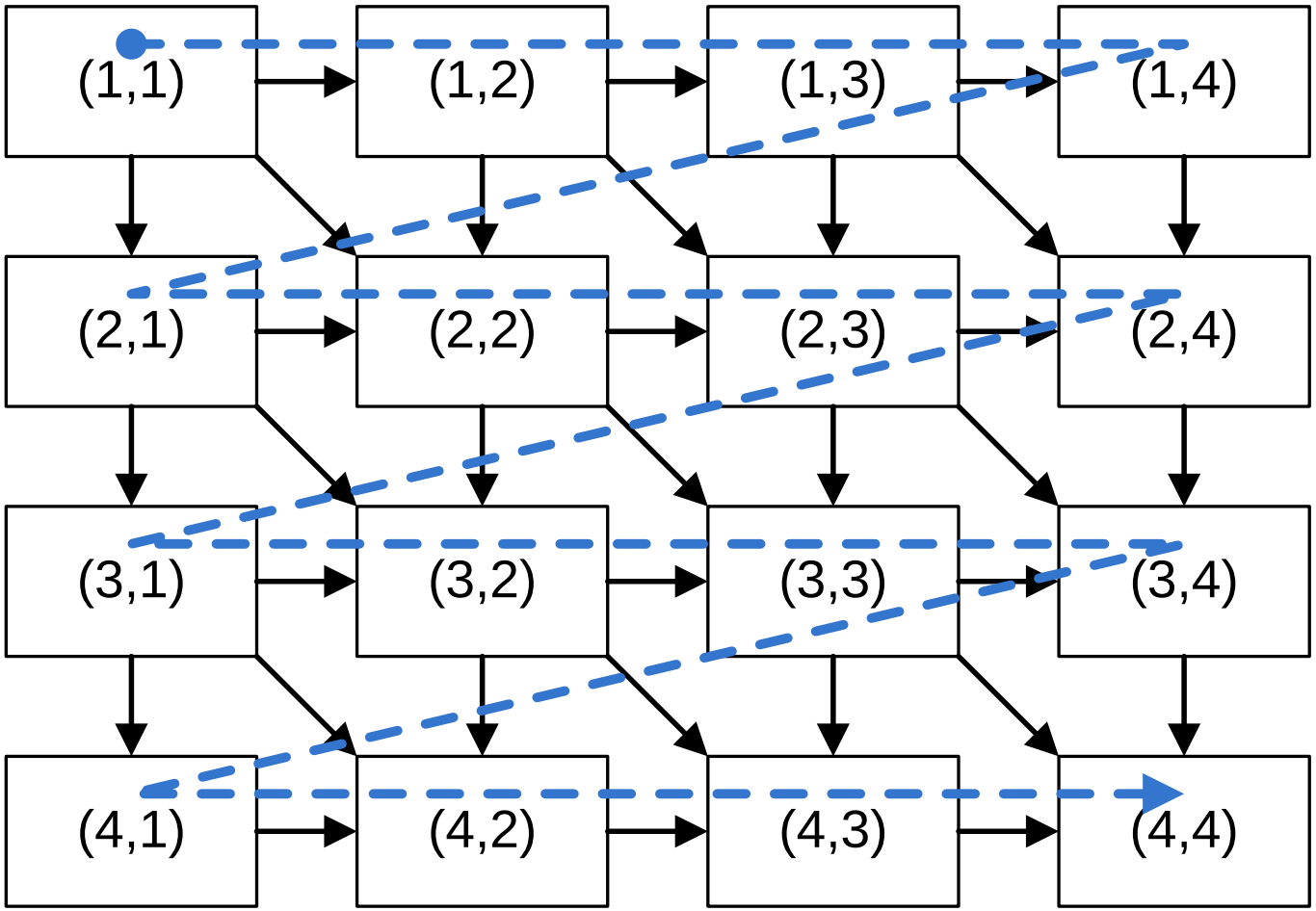


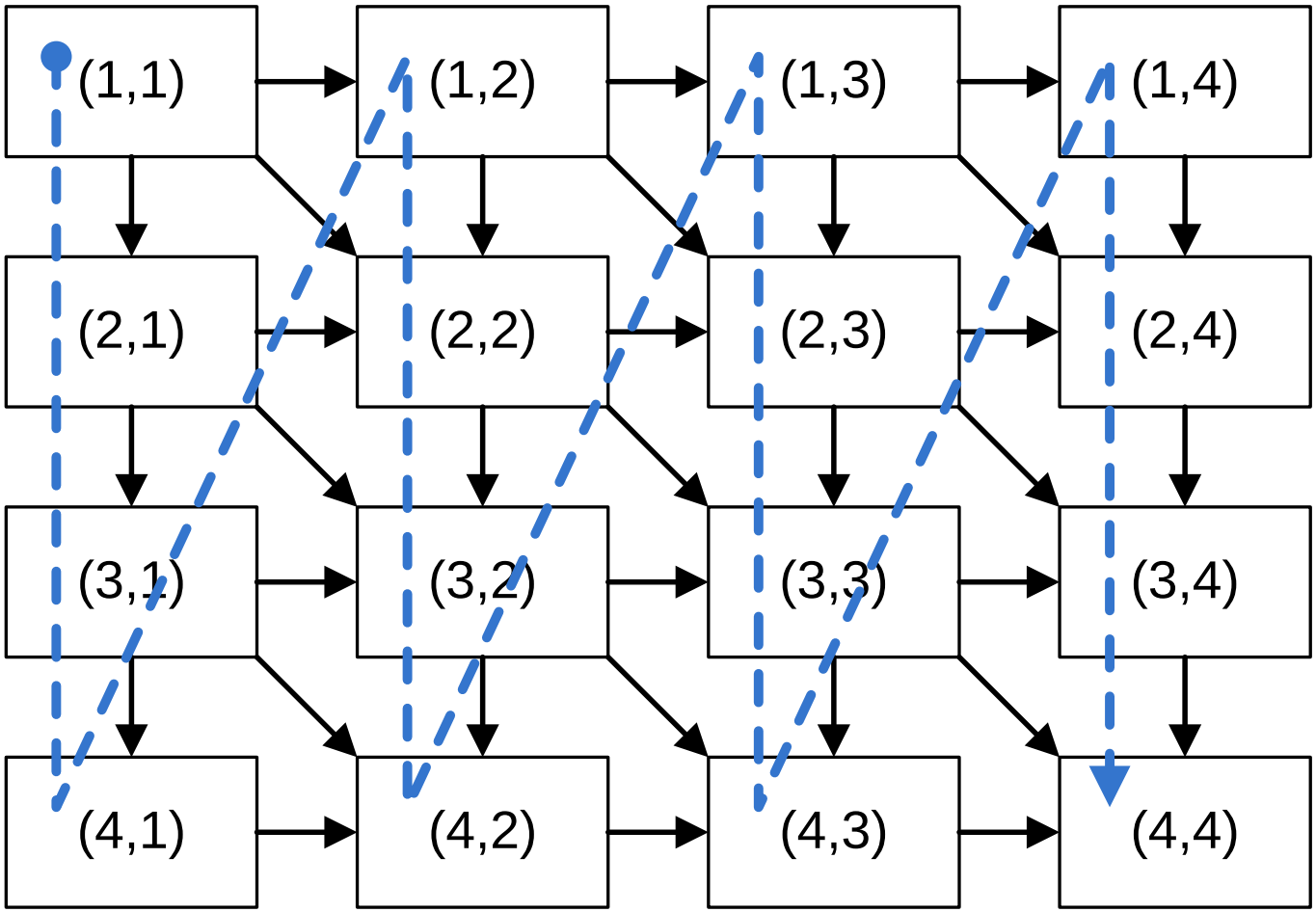
Generalise to the full grid



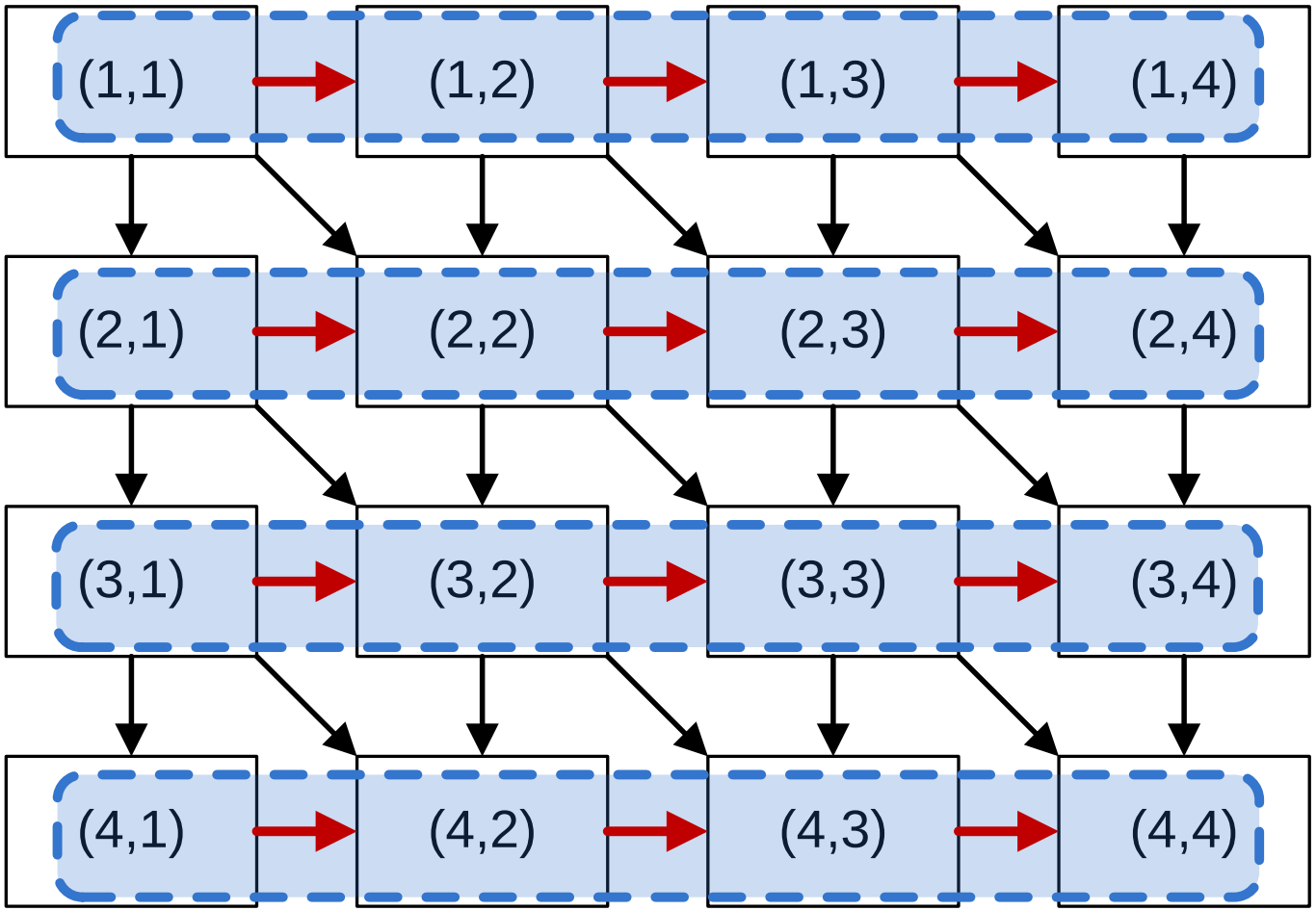
Serial execution: y then x



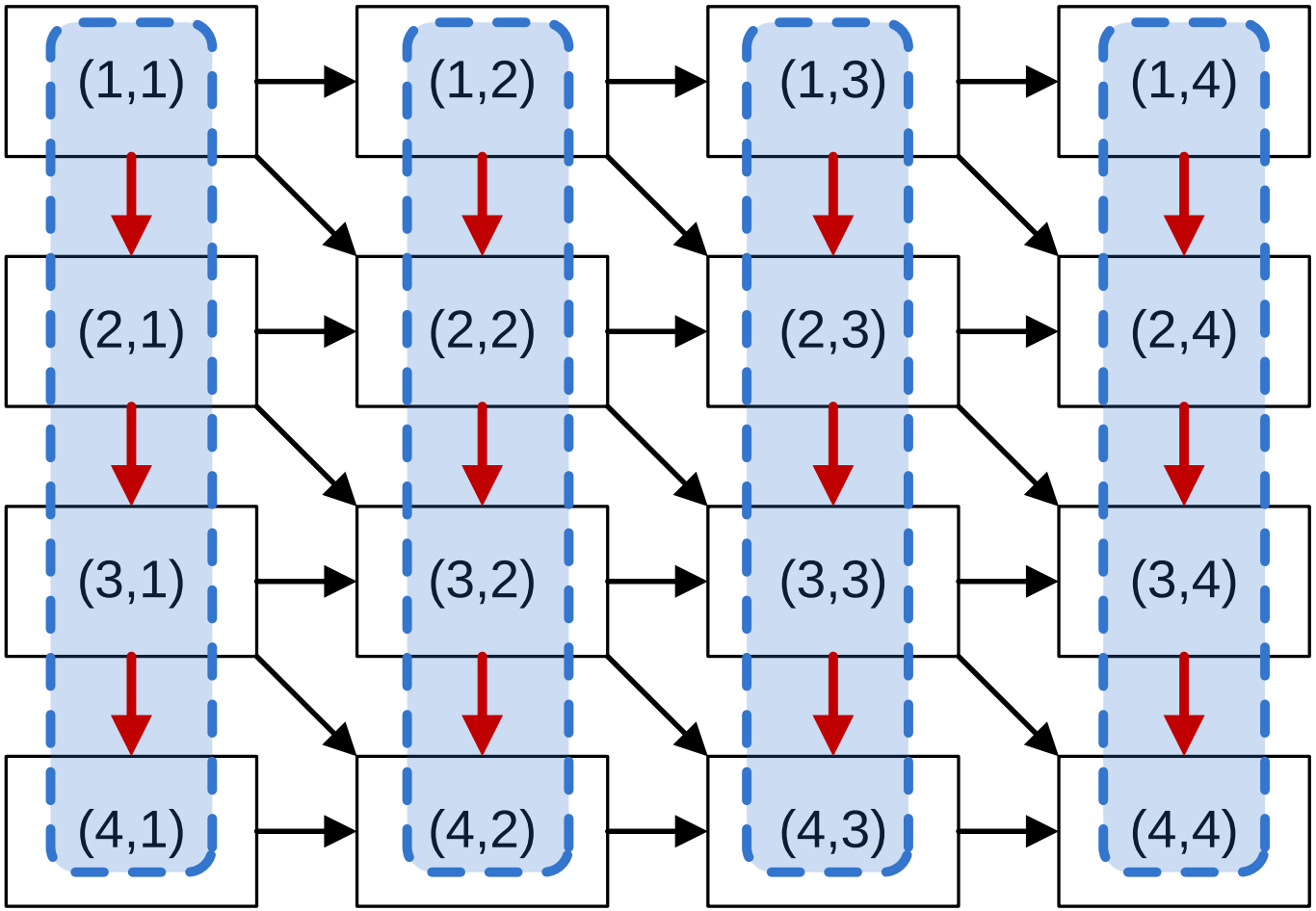
Serial execution: x then y



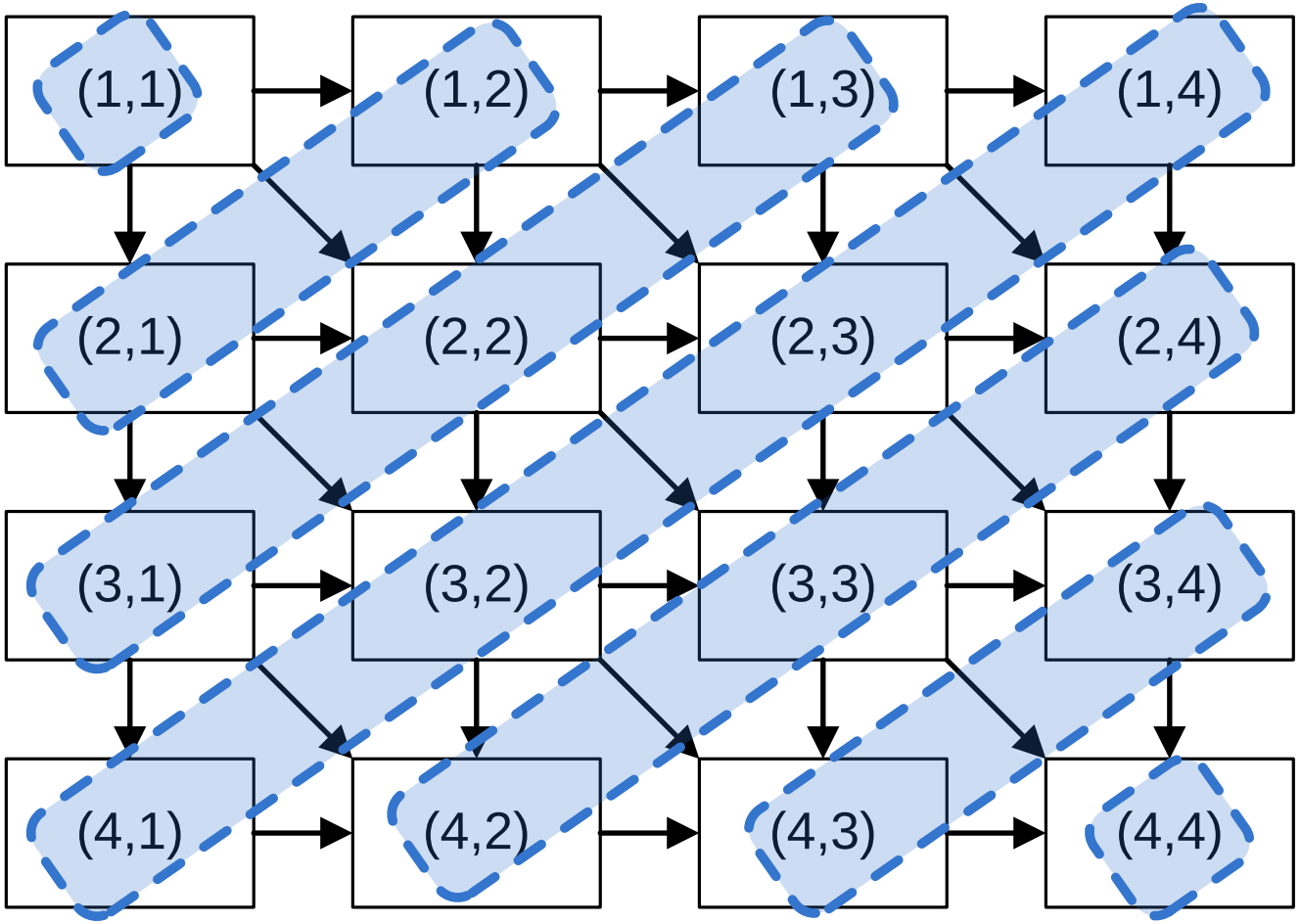
Parallelisation: can’t do it along x



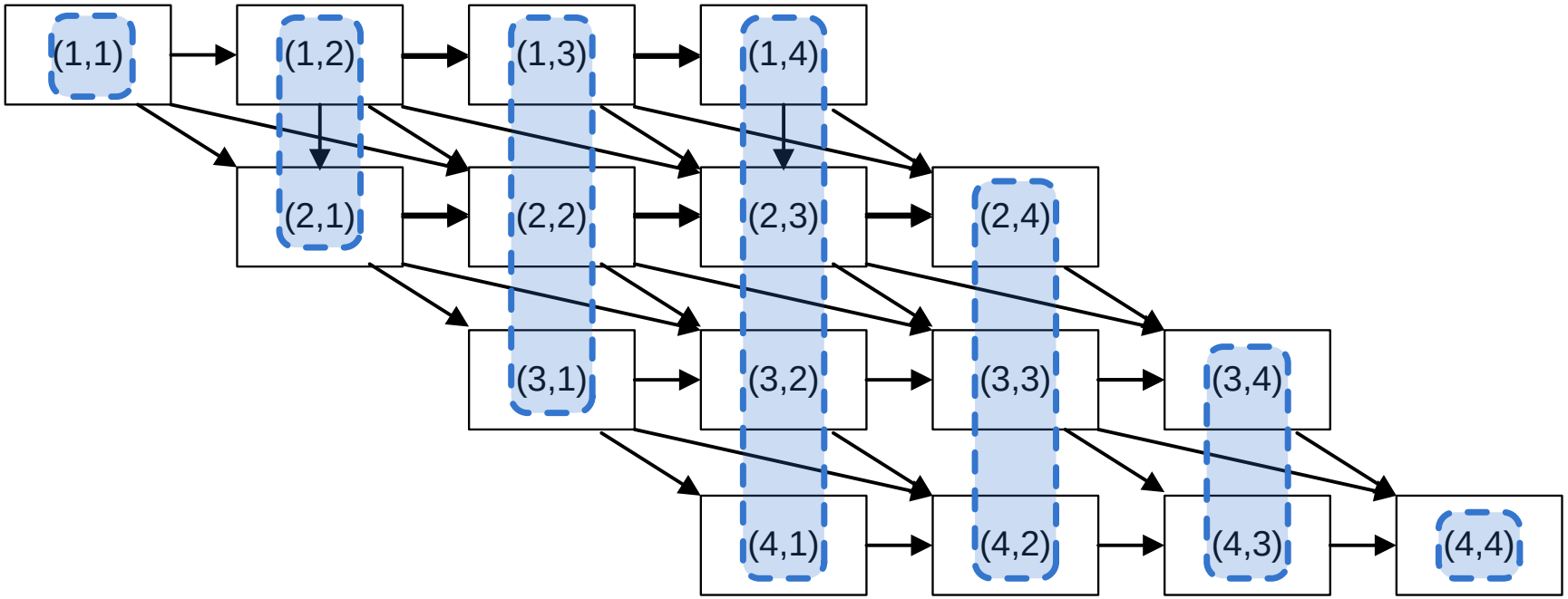
Parallelisation: can’t do it along y



Skewing the loops

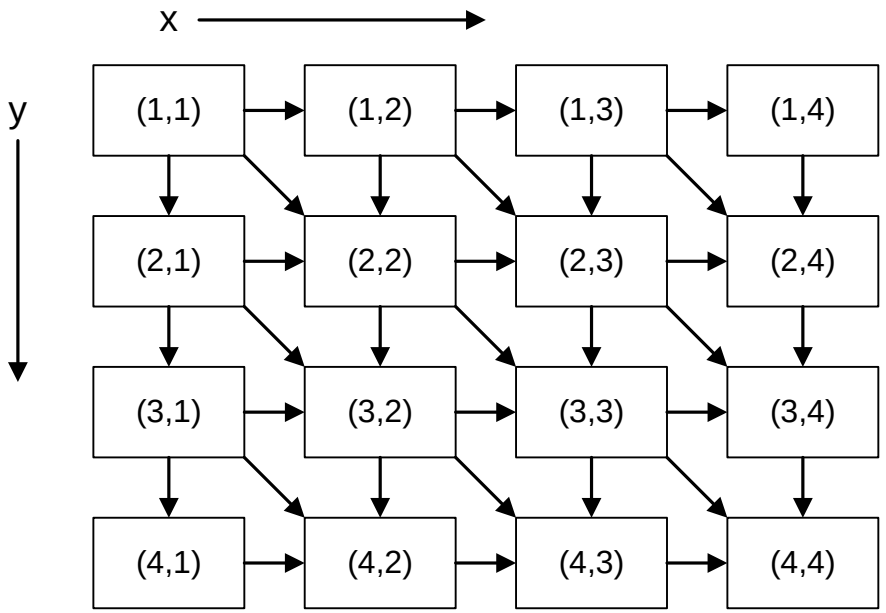


Or viewed another way



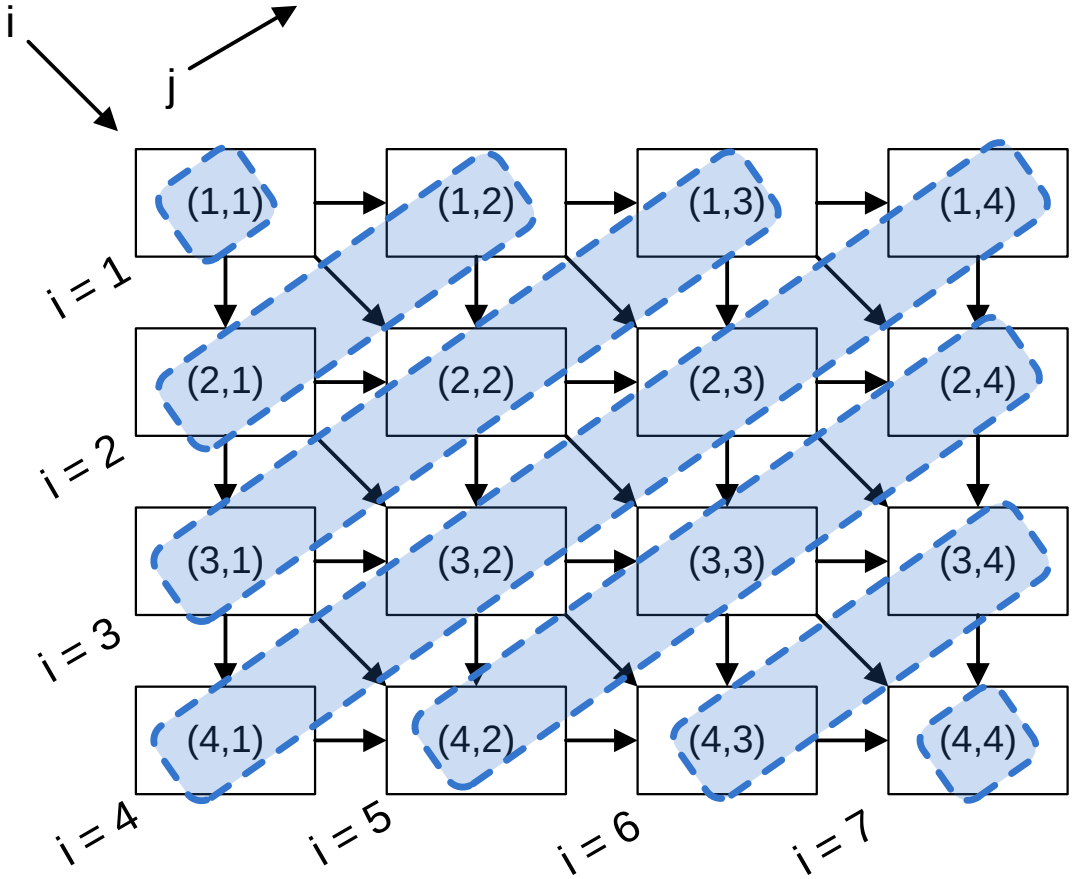
Iteration spaces

- We already have iteration as a primitive
  - for loops : bounded iteration over known range
  - while loops : possibly unbounded iteration (though maybe not)
- Iteration spaces assign unique labels to distinct iterations



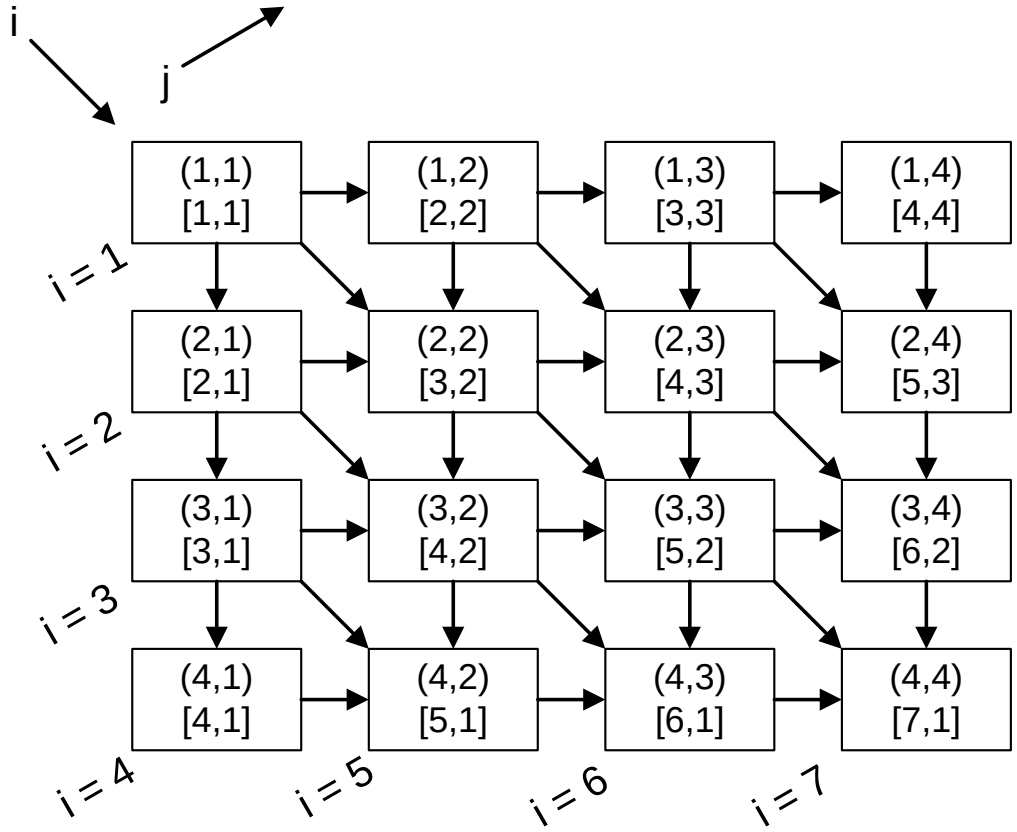
Transforming iteration spaces

- We now want to map (x,y) to a new iteration space [i,j]
  - A different set of loop variables that expose parallel operations



Transforming iteration spaces

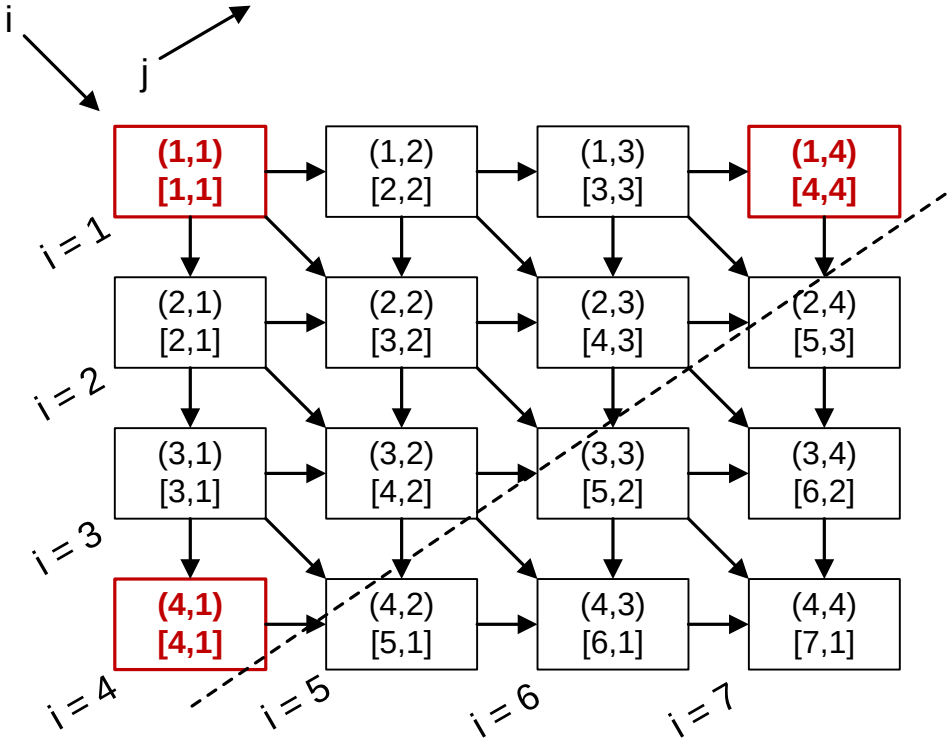
- Mapping must be distinct: all (x,y) go to a different [i,j]



Solving for the equations

- Mapping must be distinct: all (x,y) go to a different [i,j]

```
for(unsigned i=0; i<n-1; i++){
    for(int j=i; j>=0; j--){
        unsigned x=i;
        unsigned y=i-j;
```



Back to the code!

```
void process_frame(unsigned levels,unsigned width,unsigned height,double *frame)
{
    unsigned n=std::min(width,height);

    for(unsigned i=0; i<n-1; i++){
        for(int j=i; j>=0; j--){
            unsigned x=i;
            unsigned y=i-j;

            double fIn = frame[y*width + x];

            double fQuant = round( fIn * levels ) / levels;

            frame[y*width + x] = fQuant;

            double error = fIn - fQuant;
            frame[  y    * width + x+1] += error * 0.4;
            frame[ (y+1) * width + x  ] += error * 0.4;
            frame[ (y+1) * width + x+1] += error * 0.2;
        }
    }
}
```

Note: this only handles *half* the iteration space

Parallel! Correct?

```
void process_frame(unsigned levels,unsigned width,unsigned height,double *frame){
    unsigned n=std::min(width,height);

    for(unsigned i=0; i<n-1; i++){
        tbb::parallel_for(0u, i+1, [&](unsigned rev_j){
            int j=i-(int)rev_j;
            unsigned x=i;
            unsigned y=i-j;

            double fIn = frame[y*width + x];

            double fQuant = round( fIn * levels ) / levels;

            frame[y*width + x] = fQuant;

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        });
    }
}
```

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TBB

Goals of TBB

- In-process shared-memory parallelism
  - Can directly pass pointers to data-structures between tasks
- Sophisticated design-patterns
  - Data-parallelism and pipeline-parallelism and task parallelism ...
- Robust ***and*** efficient constructs to support design-patterns
  - Try to make it difficult to write programs that don't work
- Efficient scheduling of tasks to CPUs
  - Try to automatically match active tasks to number of cores
- Good interoperability with the existing world
  - Can be used within existing applications and code bases

Threaded Building Blocks : parallel_for

```
void erode(
  unsigned w, unsigned h,
  const uint8_t *pSrc,
  uint8_t *pDst
){
  for(unsigned y=1; y<h-1; y++){

    for(unsigned x=1;x<w-1;x++){
      uint8_t acc=pSrc[y*w+x];
      acc=std::min(acc, pSrc[y*w+x-1]);
      acc=std::min(acc, pSrc[y*w+x+1]);
      acc=std::min(acc, pSrc[y*(w-1)+x]);
      acc=std::min(acc, pSrc[y*(w+1)+x]);
      pDst[y*w+x]=acc;
    }

  }
}
```

```
void erode_tbb(
  unsigned w, unsigned h,
  const uint8_t *pSrc,
  uint8_t *pDst
){
  tbb::parallel_for( 1u, h-1, [=](unsigned y){

    for(unsigned x=1;x<w-1;x++){
      uint8_t acc=pSrc[y*w+x];
      acc=std::min(acc, pSrc[y*w+x-1]);
      acc=std::min(acc, pSrc[y*w+x+1]);
      acc=std::min(acc, pSrc[y*(w-1)+x]);
      acc=std::min(acc, pSrc[y*(w+1)+x]);
      pDst[y*w+x]=acc;
    }

  });
}
```

Template Functions

```
#include <iostream>

template<class T>
void F(T x)
{
    std::cout<<x<<"\n";
}

int main(int, char *[])
{
    F(124.456);
    F("wibble");
    return 0;
}
```

- Template functions do not have a fixed input type

```
template<class T>
void F(T &x, int n)
{
    x.Quack(n);
}
```

- Template functions do not have a fixed input type
- Templates rely on static “duck typing”
  - “*If it walks like a duck, and quacks like a duck, let’s call it a duck*”
  - As long as the input type can do everything you want, it will compile

```
template<class T>
void F(T &x, int n)
{
   x.Quack(n);
}

struct HowardTheDuck
{
   void Quack(int n)
   {
       for(int i=0;i<n;i++)
           std::cout<<"Quack";
   }
};

struct DaffyTheDuck
{
   void Quack(int n)
   {
       for(int i=0;i<n;i++)
           PlaySound("quack.wav");
   }
};
```

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```
template<class T>
void F(T &x, int n)
{
   x.Quack(n);
}

struct HowardTheDuck
{
   void Quack(int n)
   {
       for(int i=0;i<n;i++)
           std::cout<<"Quack";
   }
};

struct DaffyTheDuck
{
   void Quack(int n)
   {
       for(int i=0;i<n;i++)
           PlaySound("quack.wav");
   }
};
```

- Template functions do not have a fixed input type
- Templates rely on static “duck typing”
  - “*If it walks like a duck, and quacks like a duck, let’s call it a duck*”
  - As long as the input type can do everything you want, it will compile

```
int main(int, char *[])
{
   HowardTheDuck howard;
   DaffyTheDuck daffy;
   F(howard, 2); // prints "QuackQuack"
   F(daffy, 1);  // plays quack sound once
   return 0;
}
```

All about C++ lambdas

- Lambda functions are similar to matlab @ functions
  - Define pieces of code which can be treated as variables
  - Can capture parts of the environment in a closure

C++

```
auto f = [](int x){ return x*2; };

int x = f(4);
```

Matlab

```
f = @(x)( x*2 );

x = f(4);
```

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```

Matlab

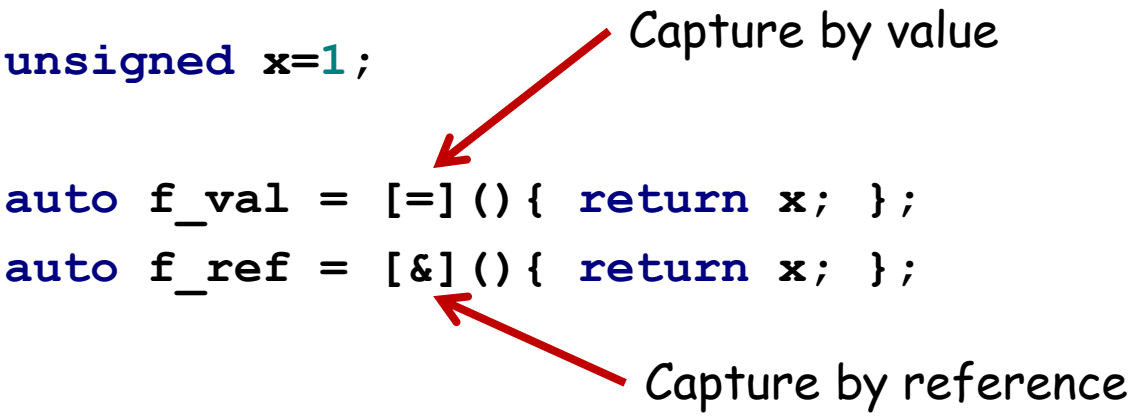
```
f = @(x)( x*2 );

x = f(4);
```

- C++ requires type annotations, as it is statically typed
  - The `auto` keyword means "*the type of the expression to the right*"
  - e.g.: `auto x=1.1;` means x has type `double`

Choosing your environment

- Lambdas can capture the environment in two ways
  - *Capture by value*: value of a variable fixed when lambda created
  - *Capture by reference*: variable is a reference to original



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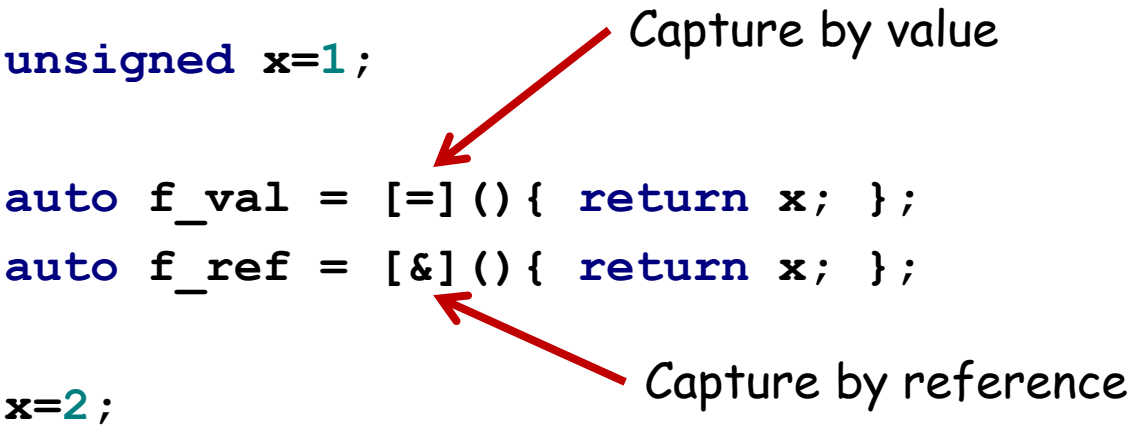

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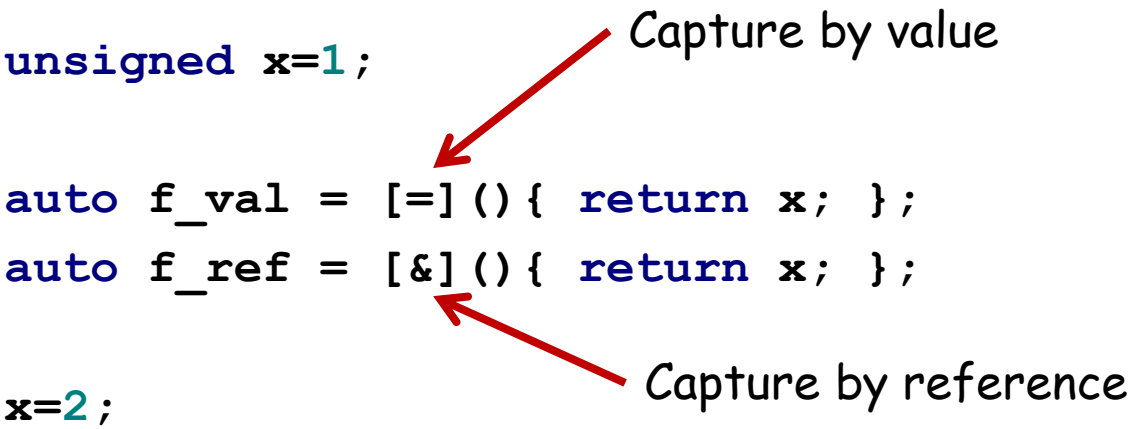

Some `tbb::parallel_for` implementations

- It’s useful to think about how parallel for can be built

- There are many possible ways to do `parallel_for`
  - Not all valid implementations are actually parallel
  - Not all parallel implementations are actually valid

Sequential implementation

- We are allowed to just do it sequentially
- Any correct TBB program should work with this version

```
namespace tbb{

template<class TI, class TF>
void parallel_for(const TI &begin, const TI &end, const TF &f)
{
   for( TI i=begin ; i < end ; i++){
       f(i);
   }
}

}; // namespace tbb
```

Alternative sequential implementation

- The iterations can happen in any order
- **But**: must call each iteration once *and only* once

```
namespace tbb{

template<class TI, class TF>
void parallel_for(const TI &begin, const TI &end, const TF &f)
{
    TI i=end;
    do{
        i=i-1;
        f(i);
    }while(i!=begin);
}

}; // namespace tbb
```

Under the hood : `std::thread`

- `std::thread` is the C++ mechanism for creating threads
- Platform independent layer over low-level OS functions
- Designed to try to stop you doing anything too bad
  - But still very easy to have things go wrong: avoid if possible!

```
#include <thread> // Standard C++ header

void say_hello()
{ std::cout<<"Hello world"<<std::endl; }

int main(int argc, char *argv[])
{
   std::thread worker(say_hello); // Spawn new thread
   worker.join();  // Block till it finishes
   return 0;
}
```

Parallel implementation on `std::thread`

```
template<class TI, class TF>
void parallel_for(const TI &begin, const TI &end, const TF &f)
{
   std::vector<std::thread> threads;

   // Spin off threads for each iteration
   for(TI i=begin; i < end; i++){
       auto f_i = [&f,i](){  f(i);  } // Lambda to execute f(i)

       threads.push_back( std::thread( f_i ) ); // Start new thread
   }

   // Make sure all threads have finished
   for(unsigned i=0;i<threads.size();i++){
       threads[i].join();  // Wait until task has finished
   }
}
```

Scalability of `std::thread` version

- Let us assume some simple timing behaviour
  - t_s : time taken to create and spawn one thread
  - t_f : time taken to execute the function f

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  - t_s : time taken to create and spawn one thread
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  - OS is using time-slicing to assign threads to CPUs
  - There are P actual processor cores

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- Also assume some system properties
  - OS is using time-slicing to assign threads to CPUs
  - There are P actual processor cores
- What is the expected behaviour for large `n=end-begin` ?

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// Spin off threads for each iteration
for(TI i=begin; i < end; i++){
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Under-utilised: $t_f / (P-1) < t_s$

- Each execution of *f* takes t_f time
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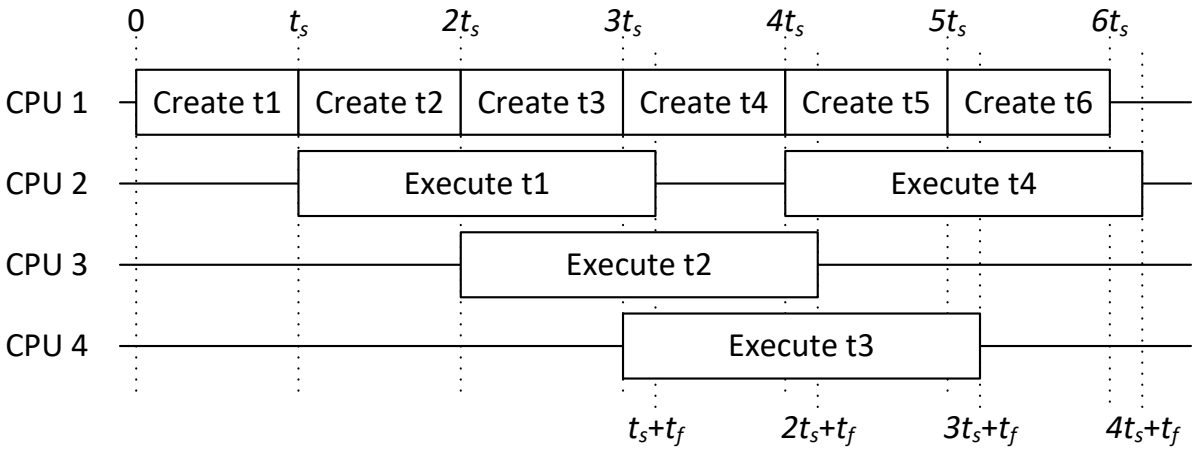

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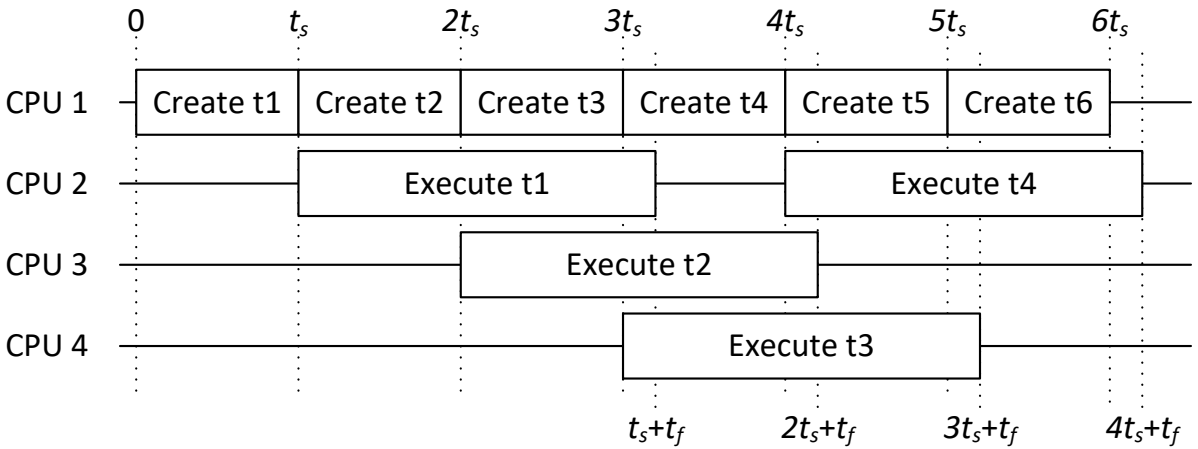
- Under-utilised when P-1 workers are faster than creator



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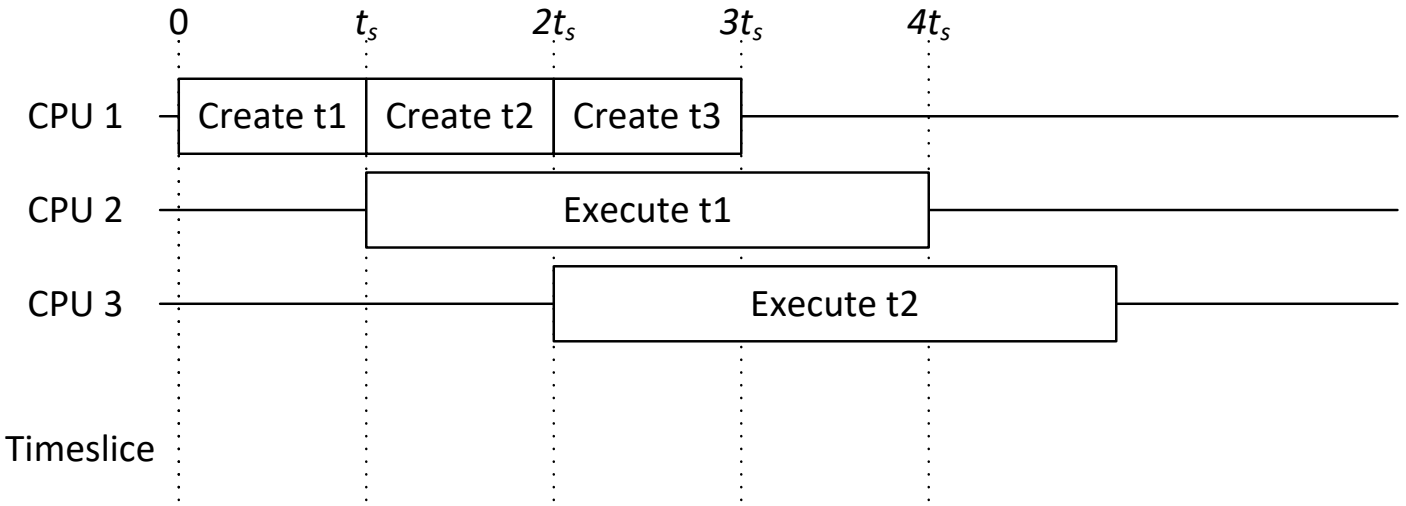

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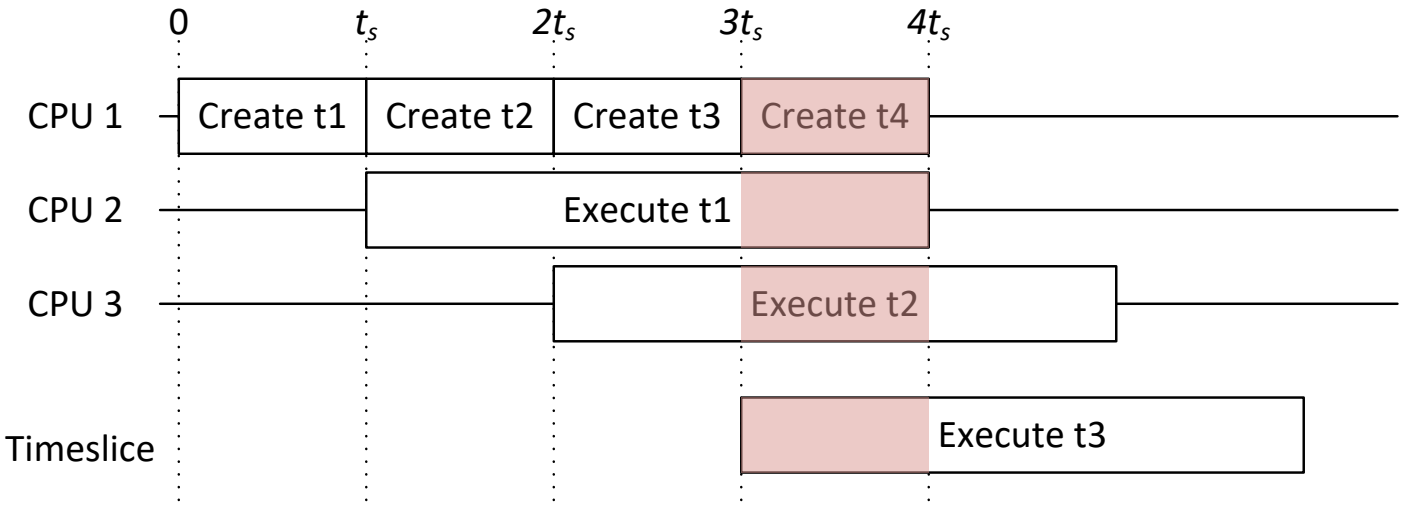
  - We have P+1 tasks, but just P processors: slow down by P/(P+1)



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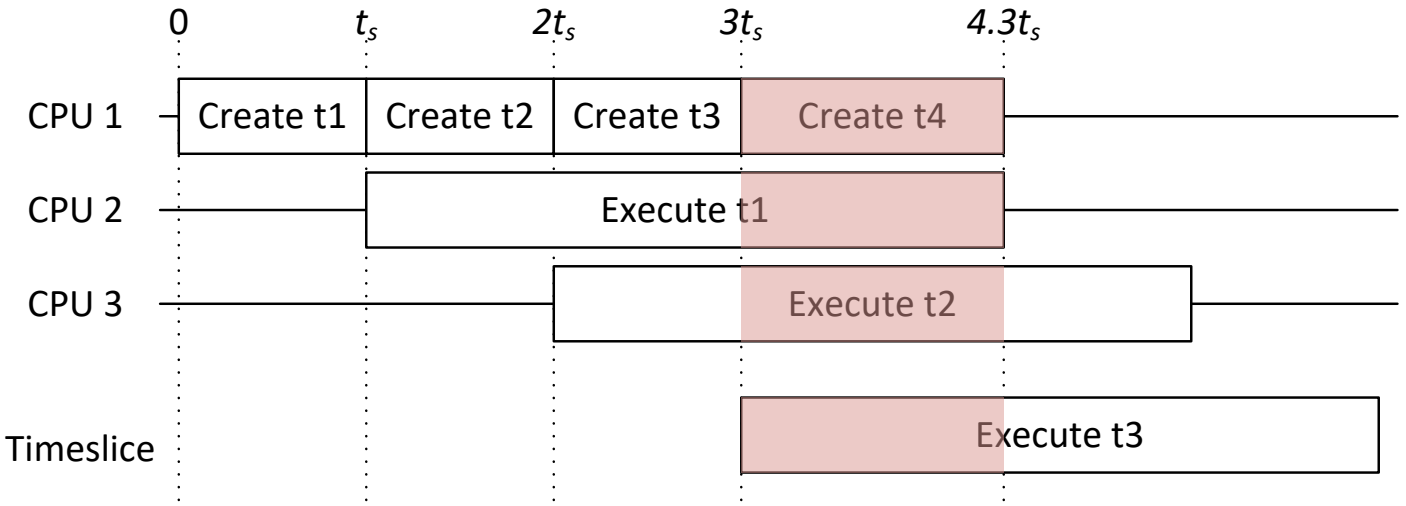

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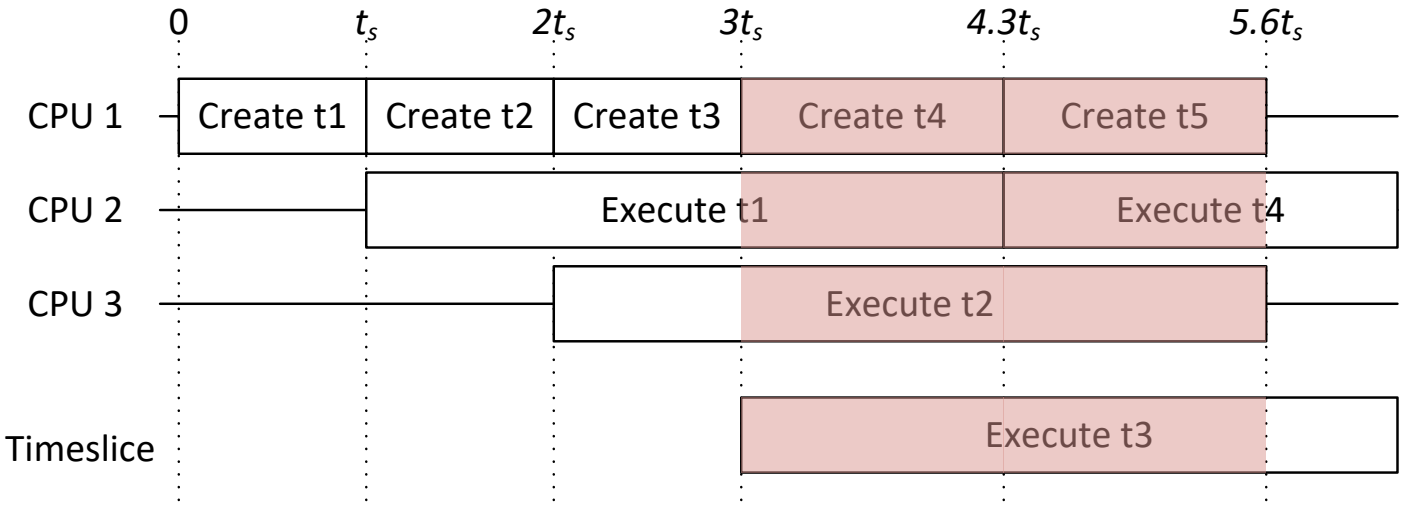

We are either under- or over-utilised

- *Underutilised*: limited by creation speed of work
  - Cannot exploit all the CPUs even though there is more work
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  - There is overhead when switching between OS threads
  - Each thread needs to warm up cache again
  - Increases memory pressure

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  - There is overhead when switching between OS threads
  - Each thread needs to warm up cache again
  - Increases memory pressure

- Worst case: continual slow-down
  - The cost of creating threads is partially borne by kernel
  - User code may slow down more than kernel code under load
  - Number of workers slowly goes up; completion rate goes down

Solving under-utilisation

```
template<class TI, class TF>
void parallel_for(const TI &begin, const TI &end, const TF &f)
{
    if(begin+1 == end){
        f(begin);
    }else{
        TI mid=(begin+end)/2;

        std::thread left(  // Spawn the left thread in parallel
            [&](){  parallel_for(begin, mid, f);    }
        );

        // Perform the right segment on our thread
        parallel_for(mid, end, f);

        // wait for the left to finish
        left.join();
    }
}
```

Creation of work using trees

- Tree starts on one thread

[0..4)

```
template<class TI, class TF>
void parallel_for(
     const TI &begin,const TI &end,
     const TF &f)
{
  if(begin+1 == end){
    f(begin);
  }else{
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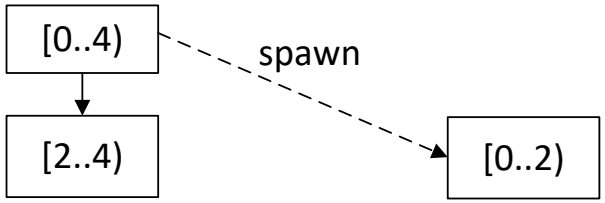
    std::thread left(
      [&](){  parallel_for(begin, mid, f);    }
    );
    parallel_for(mid, end, f);
    left.join();
  }
}
```

Creation of work using trees

- Tree starts on one thread
- Create thread to branch

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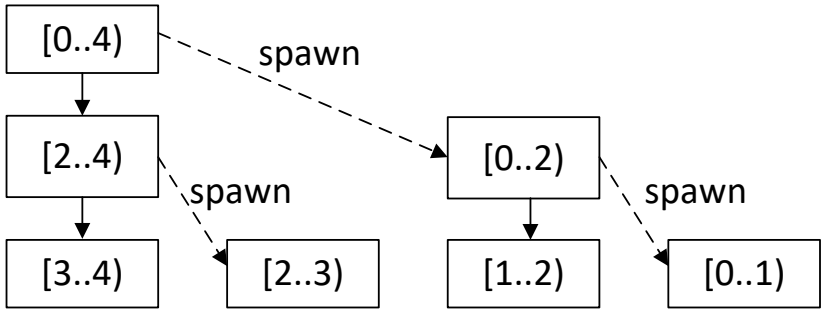


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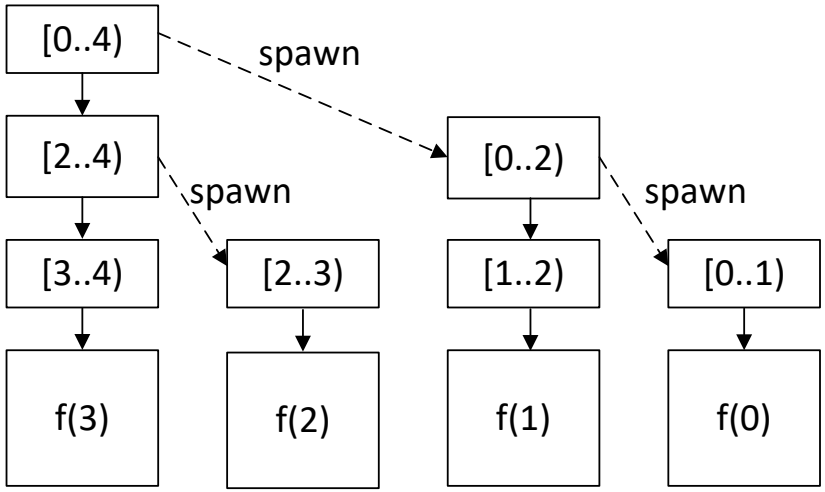


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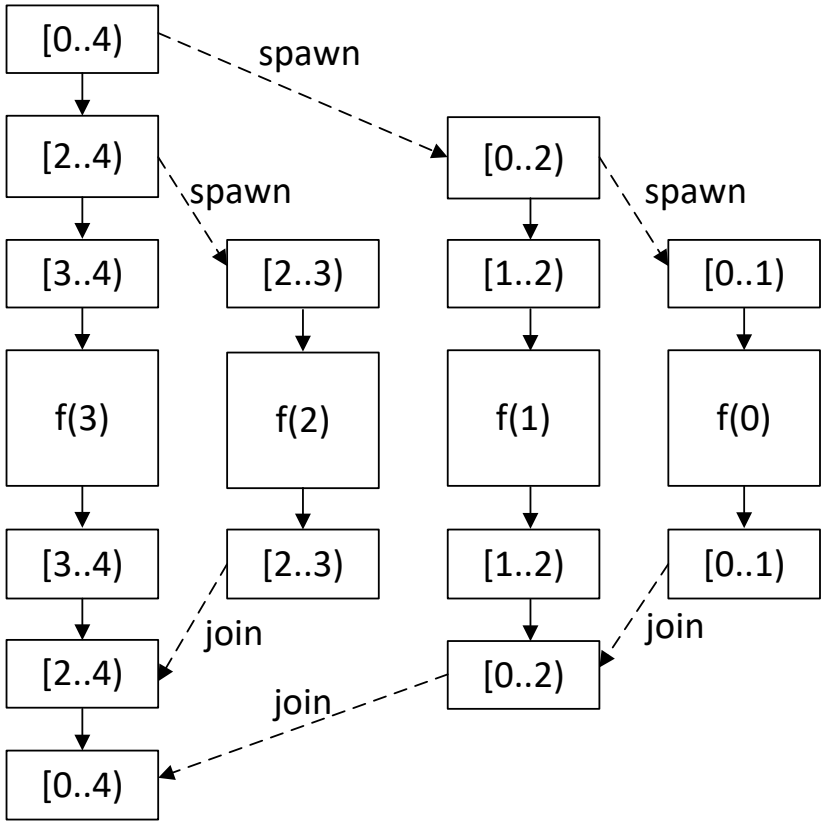
- Create thread to branch
- Execute function at leaves
- Join back up to the root

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Properties of fork / join trees

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- Growth of threads is **exponential** with time
- Can put significant pressure on the OS thread scheduler
  - Context switching 1000s of threads is very inefficient
- Each thread requires significant resources
  - Need kernel handles, stack, thread-info block, ...
  - Can’t allocate more than a few thousand threads per process

Re-examining the goals

- What we want is parallel_for:

  "*Iterations **may** execute in parallel*"

- std::thread gives us something different:

  "*The new thread **will** execute in parallel*"

Re-examining the goals

- What we want is parallel_for:

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- std::thread gives us something different:

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- Our thread based strategy is too eager to go parallel
- We want to go just parallel enough, then stay serial

Tasks versus threads

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- TBB has a number of high-level ways to use tasks
  - But there is a single low-level underlying task primitive

Overview of task groups

- A task group collects together a number of child tasks
  - The task creating the group is called the parent
  - One or more child tasks are created and `run()` by the parent
  - Child tasks ***may*** execute in parallel
  - Parent task must `wait()` for all child tasks before returning

parallel_for using `tbb::task_group`

```
#include "tbb/task_group.h"

template<class TI, class TF>
void parallel_for(const TI &begin, const TI &end, const TF &f)
{
   if(begin+1 == end){
     f(begin);
   }else{
     auto left=[&](){  parallel_for(begin, (begin+end)/2,  f); }
     auto right=[&](){ parallel_for((begin+end)/2, end,    f); }

     // Spawn the two tasks in a group
     tbb::task_group group;
     group.run(left);
     group.run(right);

     group.wait(); // Wait for both to finish
   }
}
```

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- Some important differences between tasks and threads
  - Threads ***must*** execute in parallel
  - A thread may continue after its creator exits
  - Threads must be joined individually