Implementation of Parallelization

SIMD/SIMT & Multithreading: Numba (with CUDA), OpenMP, Python Threading & PThreads

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Outline

OpenMP®

(SIMD/SIMT & Threads)

OpenMP - Goals

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Portability public API, implementations for C, C++, Fortran

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- Supported/shipped with various compilers for various platforms (e.g. Intel and GNU compilers for Linux), i.e. to compile simply add option:

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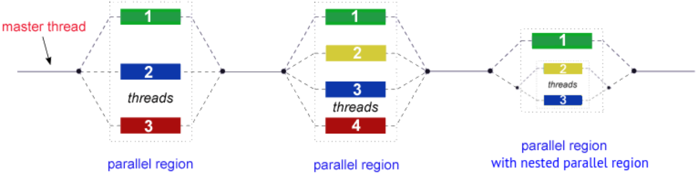

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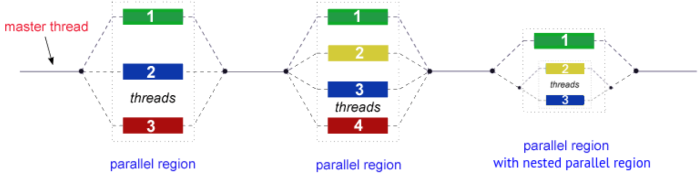

- comprised of 3 API components:
  - Compiler Directives
  - Runtime Library routines
  - Environment Variables

OpenMP - Compiler Directives

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We will focus here on C/C++ syntax, FORTRAN syntax slightly different:

```
#pragma omp [simd/target] <directive name> [<clauses>]   (C/C++)
!$OMP [SIMD/TARGET] [END] <directive name> [<clauses>]   (Fortran)
```

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!$OMP [SIMD/TARGET] [END] <directive name> [<clauses>]   (Fortran)
```

Used for:

- Defining parallel regions: requesting vectorization or spawning threads
- Specifying strip-mining / inter-thread distribution strategy of loop iterations or sections of code
- Serializing sections of code (e.g. for access to I/O or shared variables)
- Synchronizing threads

You can find a reference sheet for the C/C++ API for OpenMP 4.0 in the source code archive for this workshop.

OpenMP/SIMD: Example

```
void test(const float* A, const float* B, float* C) {
   #pragma omp simd
   for (int j = 0;j < N; j++) {
     for (int i = 0;i < N; i++) {
       C[i] = A[i] + B[i];
     }
   }
}
```

OpenMP/SIMD: Example

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void test(const float* A, const float* B, float* C) {
   #pragma omp simd
   for (int j = 0;j < N; j++) {
     for (int i = 0;i < N; i++) {
       C[i] = A[i] + B[i];
     }
   }
}
```

```
icc -fiopenmp -no-vec -qopt-report=5 <src file>
```

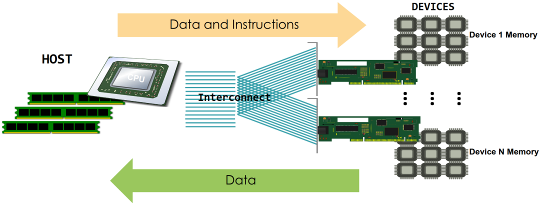
```
LOOP BEGIN at test-vec.c(25,4)
   remark #15540: loop was not vectorized: auto-vectorization is disabled with
-no-vec flag
LOOP END

LOOP BEGIN at test-vec.c(12,15) inlined into test-vec.c(29,4)
   remark #15305: vectorization support: vector length 4
   remark #15309: vectorization support: normalized vectorization overhead 0.500
   remark #15301: OpenMP SIMD LOOP WAS VECTORIZED
   remark #15475: --- begin vector cost summary ---
   remark #15476: scalar cost: 8
   remark #15477: vector cost: 1.000
   remark #15478: estimated potential speedup: 7.990
   remark #15488: --- end vector cost summary ---
   remark #25015: Estimate of max trip count of loop=25000

   LOOP BEGIN at test-vec.c(13,6) inlined into test-vec.c(29,4)
      remark #25456: Number of Array Refs Scalar Replaced In Loop: 1
   LOOP END
LOOP END
```

OpenMP/GPU - Target Offloading

- OpenMP target offloading was introduced in OpenMP 4.0 and further enhanced in later versions.




```
icx -fiopenmp [-offload=nvptx-none] <src file>
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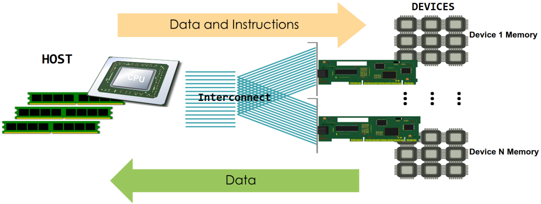


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gcc -fopenmp [-foffload=nvptx-none] <src file>
```
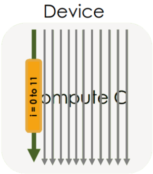

- allows to run code on one or multiple “external” devices e.g. graphics cards

OpenMP/GPU - Worksharing

```
#pragma omp target
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}
```

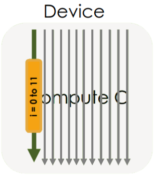


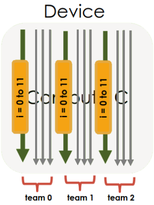
- `target` clause marks section to be executed on external device(s)

OpenMP/GPU - Worksharing

```
#pragma omp target
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}
```

```
#pragma omp target teams
num_teams(3)
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}
```





- `target` clause marks section to be executed on external device(s)
- each `team` is (a group of) thread(s) executing the `target` code block concurrently
- work in code block can be distributed among teams (coarse-grained parallelism); no synchronization between teams (!)
- work in team(s) can be spread between many threads (fine-grained parallelism; cf. OpenMP/Threads)

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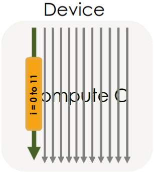


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    C[i] = A[i] + B[i];
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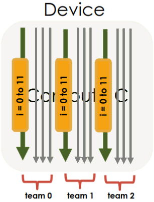
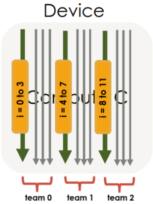



```
#pragma omp target teams
distribute num_teams(3)
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}
```



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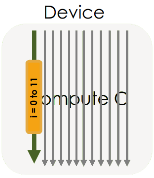


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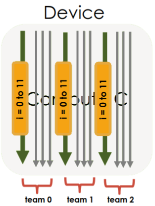


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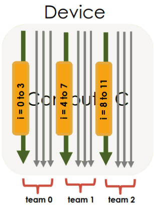
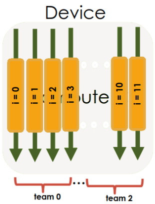



```
#pragma omp target teams
distribute parallel for
num_teams(3)
for (int i = 0; i < 12; ++i)
{
    C[i] = A[i] + B[i];
}
```



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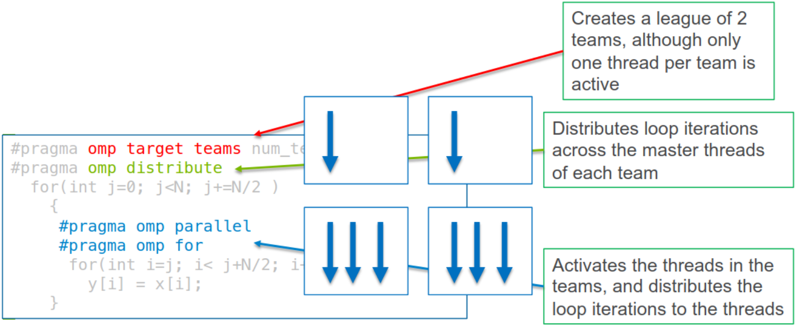
OpenMP/GPU - Worksharing (cont.)



- distribution/parallelisation can be done separately (e.g. on different for loops) or combined (composite directive)

OpenMP/GPU - Data transfer/synchronization

```
  int A[N][N], B[N][N], C[N][N];
  /*
    initialize arrays
  */
#pragma omp target
  {
    for (int i = 0; i < N; ++i) {
      for (int j = 0; j < N; ++j) {
        C[i][j] = A[i][j] + B[i][j];
      }
    }
  } // end target
```

- static arrays are implicitely copied to devices into allocated memory at the beginning of `target` block andcopied back at end; scalars are made private to each thread and initialised with its current value

OpenMP/GPU - Data transfer/synchronization

```
int A[N][N], B[N][N], C[N][N];
/*
  initialize arrays
*/
#pragma omp target map(to: A, B) map(from: C)
{
  for (int i = 0; i < N; ++i) {
    for (int j = 0; j < N; ++j) {
      C[i][j] = A[i][j] + B[i][j];
    }
  }
} // end target
```

```
int *A, *B, *C;
/*
  allocate arrays of size N and initialize
*/
#pragma omp target map(to: A[0:N], B[0:N])
map(from: C[0:N])
{
  for (int i = 0; i < N; ++i) {
    for (int j = 0; j < N; ++j) {
      C[i][j] = A[i][j] + B[i][j];
    }
  }
} // end target
```

- static arrays are implicitely copied to devices into allocated memory at the beginning of `target` block andcopied back at end; scalars are made private to each thread and initialised with its current value
- dynamic arrays have to be explicitly allocated & mapped into device with `map` clause and index range

OpenMP/GPU - Data transfer/synchronization

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        C[i][j] = A[i][j] + B[i][j];
      }
    }
  } // end target
```

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  int *A, *B, *C;
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  */
#pragma omp target map(to: A[0:N], B[0:N])
map(from: C[0:N])
  {
    for (int i = 0; i < N; ++i) {
      for (int j = 0; j < N; ++j) {
        C[i][j] = A[i][j] + B[i][j];
      }
    }
  } // end target
```

- static arrays are implicitely copied to devices into allocated memory at the beginning of `target` block andcopied back at end; scalars are made private to each thread and initialised with its current value
- dynamic arrays have to be explicitly allocated & mapped into device with `map` clause and index range
- map types: `to`, `from`, `tofrom`, `alloc`, `release`, `delete`

OpenMP/GPU - Data transfer/synchronization (cont.)

- copying data back and forth for every target section not efficient

```
#pragma omp target map(to: A, B) map(from: C)
  {
    for (int i = 0; i < N; ++i) {
      for (int j = 0; j < N; ++j) {
        C[i][j] = A[i][j] + B[i][j];
      }
    }
  }

/*
Some computation using C (no changes to A, B or C)
*/

#pragma omp target map(to: A, B, C) map(from: D)
  {
    for (int i = 0; i < N; ++i) {
      for (int j = 0; j < N; ++j) {
        D[i][j] = A[i][j] + B[i][j] C[i][j];
      }
    }
  }
```

OpenMP/GPU - Data transfer/synchronization (cont.)

- copying data back and forth for every target section not efficient
- better to use `target data` clause around all target sections/kernels sharing data and sychronise between host and devices only what/when necessary using `update` clause

```
#pragma omp target data map(to: A, B) map(alloc: C, D)
{

#pragma omp target
  {
    for (int i = 0; i < N; ++i) {
      for (int j = 0; j < N; ++j) {
        C[i][j] = A[i][j] + B[i][j];
      }
    }
  }
#pragma omp target update from(C)
/*
Some changes to A (no changes to B or C)
*/
#pragma omp target update to(A)

#pragma omp target map(from: D)
  {
    for (int i = 0; i < N; ++i) {
      for (int j = 0; j < N; ++j) {
        D[i][j] = A[i][j] + B[i][j] C[i][j];
      }
    }
  }
}//end target-data
```

OpenMP/Threads - Runtime Library Routines

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- These routines are provided by the openmp library are used to configuring and monitoring the multithreading during execution: e.g.
  `omp_get_num_threads` returns number of threads in current team
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- There are further routines for locks for synchronization/access control (see later)
- as well as timing routines for recording elapsed time for each thread.

OpenMP/Threads - Environment variables

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- Like for most programs in the UNIX world, environmental variables are used to store configurations needed for running the program. In OpenMP, they are used for setting e.g. the number of threads per team (`OMP_NUM_THREADS`), maximum number of threads (`OMP_THREAD_LIMIT`) or the scheduler policy (`OMP_SCHEDULE`).

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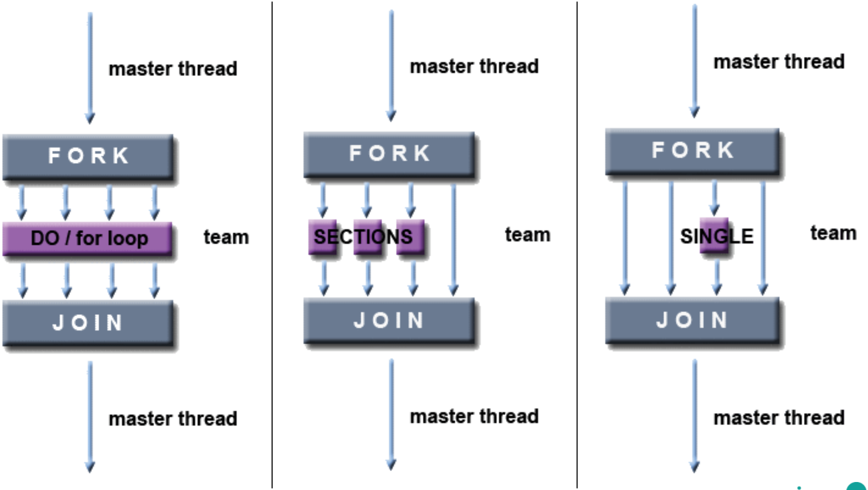
- While most of these settings can also be done using clauses in the compiler directives of runtime library routines, environmental variables provide a user an easy way to change these crucial settings without the need of an additional config file (parsed by your program) or even rewritting/recompiling the openmp-enhanced program.

OpenMP/Threads - Worksharing



OpenMP/Threads - Worksharing: Examples

```c
#include <omp.h>
#define N 1000
#define CHUNKSIZE 100

main(int argc, char *argv[]) {

int i, chunk;
float a[N], b[N], c[N];

/* Some initializations */
for (i=0; i < N; i++)
  a[i] = b[i] = i * 1.0;
chunk = CHUNKSIZE;

#pragma omp parallel shared(a,b,c,chunk) private(i)
  {

  #pragma omp for schedule(dynamic,chunk) nowait
  for (i=0; i < N; i++)
    c[i] = a[i] + b[i];

  }   /* end of parallel region */

}
```

```c
#include <omp.h>
#define N 1000

main(int argc, char *argv[]) {

int i;
float a[N], b[N], c[N], d[N];

/* Some initializations */
for (i=0; i < N; i++) {
  a[i] = i * 1.5;
  b[i] = i + 22.35;
  }

#pragma omp parallel shared(a,b,c,d) private(i)
  {

  #pragma omp sections nowait
    {

    #pragma omp section
    for (i=0; i < N; i++)
      c[i] = a[i] + b[i];

    #pragma omp section
    for (i=0; i < N; i++)
      d[i] = a[i] * b[i];

    }  /* end of sections */

  }  /* end of parallel region */

}
```

```c
#include <omp.h>
#define N       1000
#define CHUNKSIZE   100

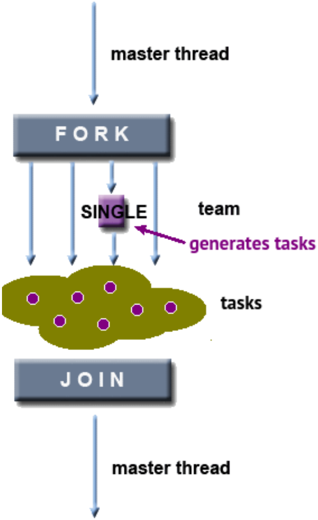
main(int argc, char *argv[]) {

int i, chunk;
float a[N], b[N], c[N];

/* Some initializations */
for (i=0; i < N; i++)
  a[i] = b[i] = i * 1.0;
chunk = CHUNKSIZE;

#pragma omp parallel for \
  shared(a,b,c,chunk) private(i) \
  schedule(static,chunk)
  for (i=0; i < n; i++)
    c[i] = a[i] + b[i];
}
```

OpenMP/Threads - advanced Worksharing



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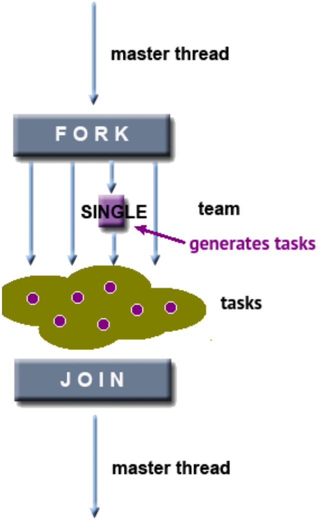

- defines explicit tasks similar to sections that are generated (usually by a single task) and then deferred to any thread in the team via a queue/scheduler

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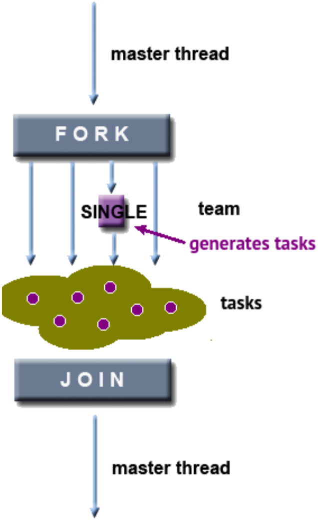

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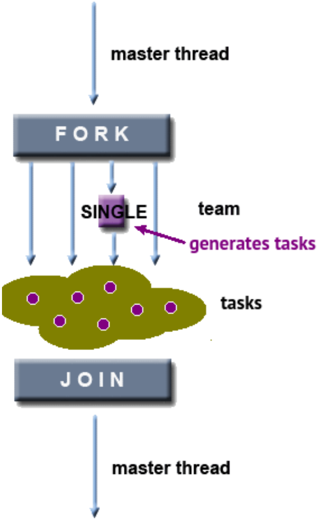
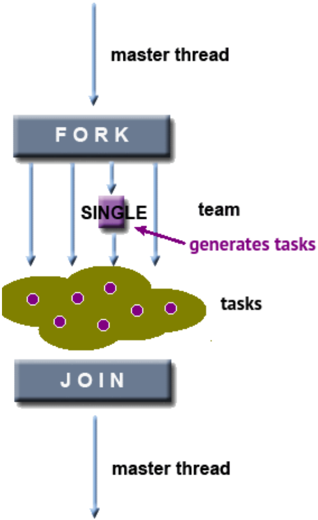


- defines explicit tasks similar to sections that are generated (usually by a single task) and then deferred to any thread in the team via a queue/scheduler
- tasks are not necessarily tied to a single thread, can be e.g. postponed or migrated to other threads
- allows for defining dependencies among tasks (e.g. task X has to finish before any thread can work on task Y)

OpenMP/Threads - advanced Worksharing: Example




```
#include <omp.h>

float sum(const float *a, size_t n)
{
    // base cases
    if (n == 0) {
        return 0;
    }
    else if (n == 1) {
        return 1;
    }

    // recursive case
    size_t half = n / 2;
    float x, y;

    #pragma omp parallel shared(x,y)

    #pragma omp single nowait
    {
        #pragma omp task shared(x)
        x = sum(a, half);
        #pragma omp task shared(y)
        y = sum(a + half, n - half);
        #pragma omp taskwait
        x += y;
    }
    return x;
}
```

OpenMP/Threads - Synchronization / Flow control

In the 'Introduction to Parallelization', we discussed the need of controlling the execution of threads at certain points to e.g. synchronize them to exchange intermediate results or to protect resources from getting accessed simultaneously with non-deterministic outcome ('race condition'). OpenMP provides two ways to do this:

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OpenMP provides two ways to do this:

- Compiler Directives:
  - (for general parallel regions) e.g. `cancel`,`single`,`master`,`critical`,`atomic`, `barrier`
  - (for loops) `ordered`
  - (for tasks) `taskwait`, `taskyield`

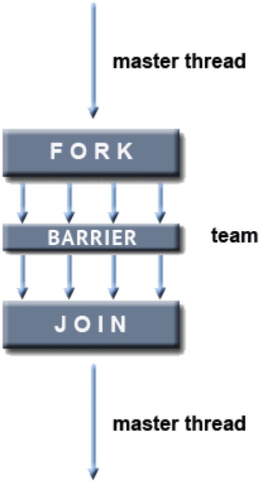
OpenMP/Threads - Synchronization / Flow control

In the 'Introduction to Parallelization', we discussed the need of controlling the execution of threads at certain points to e.g. synchronize them to exchange intermediate results or to protect resources from getting accessed simultaneously with non-deterministic outcome ('race condition').
OpenMP provides two ways to do this:

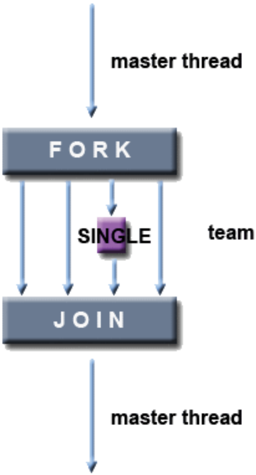
- Compiler Directives:
  - (for general parallel regions) e.g. `cancel`,`single`,`master`,`critical`,`atomic`, `barrier`
  - (for loops) `ordered`
  - (for tasks) `taskwait`, `taskyield`
- Runtime Library Routines: `omp_set_lock`,`omp_unset_lock`,`omp_test_lock`

OpenMP/Threads - Synchronization / Flow control (RESTRICTION)

BARRIER

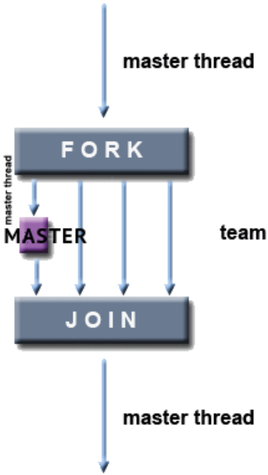


SINGLE



implicit BARRIER

MASTER

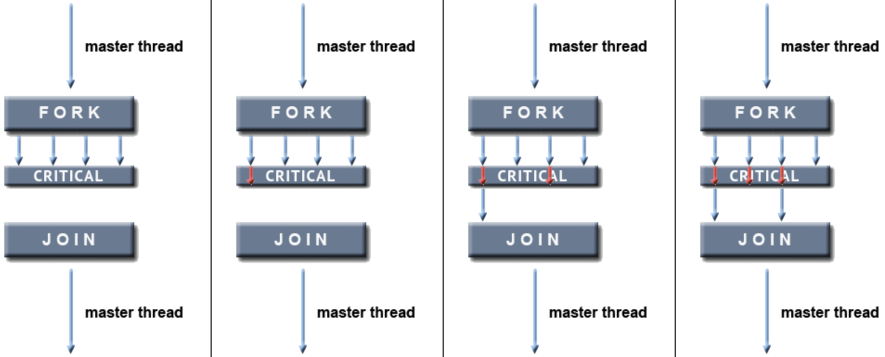


NO implicit BARRIER

OpenMP/Threads - Synchronization / Flow control (MUTEX)

`CRITICAL` / `ATOMIC`

	#1 executes #3 entered	#1 exited #3 executes	#3 exited #2 executes



- `CRITICAL`,`ATOMIC` exclusive for ALL threads, not just team
- `CRITICAL` regions can be named, regions with same name treated as same region

OpenMP/Threads - Memory management (CLAUSES)

- Certain clauses for compiler directives allow us to specify how data is shared (e.g. `shared`, `private`, `threadprivate`) and how they are initialized (e.g.`firstprivate`, `copyin`)

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- Similarly, the `reduction` clause provides an elegant way to gather private data from the threads when joining them

OpenMP/Threads - Memory management (CLAUSES)

- Similarly, the `reduction` clause provides an elegant way to gather private data from the threads when joining them

```
#include <omp.h>

 main(int argc, char *argv[])  {

 int   i, n, chunk;
 int a[100], b[100], result;

 n = 100;
 chunk = 10;
 result = 0.0;
 for (i=0; i < n; i++) {
   a[i] = i;
   b[i] = i*2;
   }

 #pragma omp parallel for       \
   default(shared) private(i)   \
   schedule(static,chunk)       \
   reduction(+:result)

   for (i=0; i < n; i++)
     result = result + (a[i] * b[i]);

 printf("result= %d\n",result);
}
```

OpenMP/Threads - Memory management (FLUSHING DATA)

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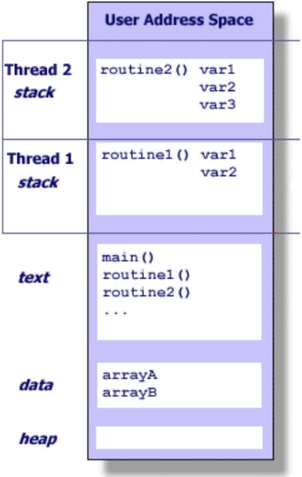
OpenMP/Threads - Memory management (FLUSHING DATA)

- even if shared, sometimes variable may not be updated in the "global" view, e.g. if kept in a register or cache of a CPU instead of the shared memory
- while many directives (e.g. `for`, `section`, `critical`) implicitly flush variable to synchronize them with other threads, sometimes explicit flushing using the `flush` may be necessary.

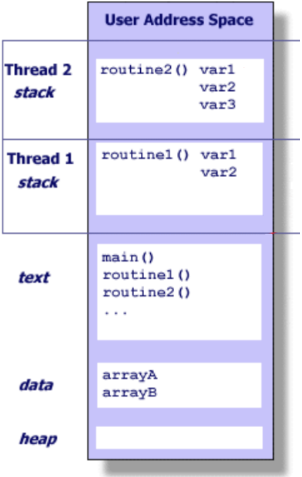
OpenMP/Threads - Memory management (STACK)



OpenMP/Threads - Memory management (STACK)

- OpenMP standard does not specify a default stack size for each thread. So depends on the compiler e.g.

Compiler	Approx Stack Limit
icc/ifort (Linux)	4 MB
gcc/gfort (Linux)	2 MB



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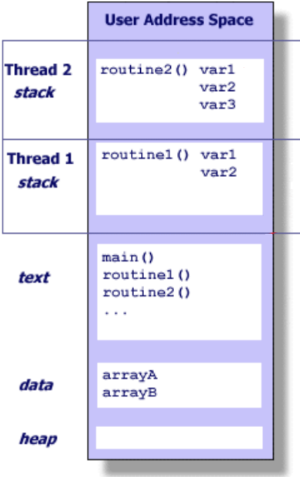

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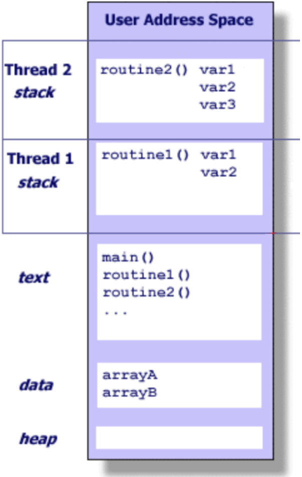
- if stack allocation exceeded, may result in seg fault or (worse) data corruption.
- Env. variable `OMP_STACKSIZE` allows to set stacksize prior to execution. So if your program needs an significant amount of data on the stack, make sure to adapt the stacksize this way!



OpenMP/Threads - Cython wrappers

- Cython is currently using OpenMP as its (only) backend for its parallelisation.
- It provides some wrappers for it that can be used directly in cython's parallelisation module:

```
from cython.parallel import parallel
from cython.cimports.openmp import omp_set_dynamic, omp_get_num_threads

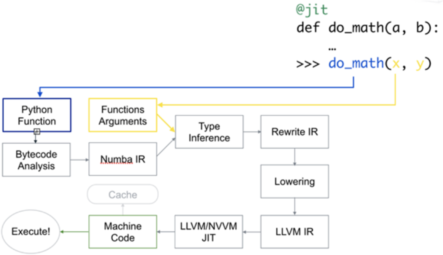
num_threads = cython.declare(cython.int)

omp_set_dynamic(1)
with cython.nogil, parallel():
    num_threads = omp_get_num_threads()
    # ...
```

Python/Numba(CUDA)

Python/Numba: JIT

- Numba is an open-source “just-in-time” (JIT) compiler for Python
- Translates subset of Python code into faster machine code (using platform-independent LLVM optimizer)



- works with wide range of platforms, architectures (both CPU and GPU) and libraries (e.g. CPython, NumPy)
- it can also parallelize code

Python/Numba: vectorize

- facilitates usage of (compiled) NumPy universal functions (`ufuncs`) i.e. functions that operate element-wise on ndarrays.

```
from numba import vectorize, float64

@vectorize([float64(float64, float64)])
def f(x, y):
    return x + y
```

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@vectorize([float64(float64, float64)])
def f(x, y):
    return x + y
```

- if no signature(s) provided, new ufunc will be compiled at call-time when new signature encountered (dynamic universal functions)

Python/Numba for CUDA GPUs

- Numba supports CUDA GPU programming by directly compiling a restricted subset of Python code into CUDA kernels and device functions following the CUDA execution model
- minimal changes required to run python code on GPU instead:

```
from numba import cuda

@cuda.jit
def my_kernel(io_array):
    """
    Code for kernel.
    """
    # code here; updates to io_array

import numpy

# Create the data array - usually initialized some other way
data = numpy.ones(256)

# Set the number of threads in a block
threadsperblock = 32

# Calculate the number of thread blocks in the grid
blockspergrid = (data.size + (threadsperblock - 1)) // threadsperblock

# Now start the kernel
my_kernel[blockspergrid, threadsperblock](data)

# Do something with the updated data
...
```

Python/Numba(CUDA) - Threads/Blocks

- block size (`threadsperblock`) and grid size (`blockspergrid`) can have higher dimensionality if needed to decompose problem
- factors for choosing block size:
  - size of data array (decomposition of problem)
  - size of shared memory per block (since blocks share local memory on SMs)
  - maximum number of threads per block supported (e.g. 1024)
  - maximum number of threads per block per SM (e.g. 2048)
  - maximum number of blocks per SM (e.g. 32)
  - number of threads per warp (32)

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  - maximum number of threads per block per SM (e.g. 2048)
  - maximum number of blocks per SM (e.g. 32)
  - number of threads per warp (32)
- Rules of thumb:
  - multiple of warp size (32)
  - good place to start is 128-521 and use benchmarking to find optimal value

Python/Numba(CUDA) - Thread positioning

- in order to perform an operation, a thread must now its position in the grid of all the other threads (e.g. to know on which data to operate)

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- numba provides fields to obtain position of thread in block and block in grid within kernel

```
@cuda.jit
def my_kernel(io_array):
    # Thread id in a 1D block
    tx = cuda.threadIdx.x
    # Block id in a 1D grid
    ty = cuda.blockIdx.x
    # Block width, i.e. number of threads per block
    bw = cuda.blockDim.x
    # Compute flattened index inside the array
    pos = tx + ty * bw
    if pos < io_array.size:  # Check array boundaries
        io_array[pos] *= 2 # do the computation
```

Python/Numba(CUDA) - Thread positioning

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- numba provides fields to obtain position of thread in block and block in grid within kernel
- also provides function `grid(dim)` to return directly thread position in grid of any dimensionality

```
@cuda.jit
def my_kernel2(io_array):
    pos = cuda.grid(1)
    if pos < io_array.size:
        io_array[pos] *= 2 # do the computation
```

Python/Numba(CUDA) - Memory management

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- not always efficient, expecially as it always copies data back (cf. OpenMP's data mapping / `tofrom`)

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- not always efficient, expecially as it always copies data back (cf. OpenMP's data mapping / `tofrom`)
- manual memory management:

`d_arr = numba.cuda.device_array(shape, dtype)` allocate an empty device ndarray. Similar to numpy.empty()

`d_ary = numba.cuda.to_device(arr)` allocate and transfer a NumPy ndarray to device

`arr = d_ary.copy_to_host([arr])` copies device array data to provided/newly created host array

Python/Numba(CUDA) - Shared memory / Thread synchronization

- threads **in the same block** can share limited amount of faster memory (done within kernel): `shared_array = cuda.shared.array(shape,type)`
- share has to be known at "compile" time e.g. constant defined outside kernel

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- share has to be known at "compile" time e.g. constant defined outside kernel
- if multiple threads are updating same data elements in shared memory within their kernels, synchronization needed!
- `cuda.syncthreads()` synchronizes all threads **in the same block** i.e. acts as a barrier that all threads have to reach before progressing in their kernel

Python/threading

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  Simplicity
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  Portability
  : *Threading* module available for both Python2 & 3, a various different implementations (`CPython`, `PyPy`, `Jython`, etc.) and for a wide range of platforms/OS

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  Portability *Threading* module available for both Python2 & 3, a various different implementations (`CPython`, `PyPy`, `Jython`, etc.) and for a wide range of platforms/OS
- There are inherit design choices made for the most popular Python implementations that limit the utility of multithreading (see later)

Python/threading - Thread management: Creation & Term.

- Python threads are created explicitly by creating an instance of the `Thread` class
  (`threading.Thread(target=...[,args=...][,name=...],...)`)
  - `target` is the name of a function to be invoked by the Thread's `run()` method
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- They terminate when finishing their starting routine or, if 'daemonic' once the main program finishes with only daemon threads left
- Basic threads **cannot** be terminated by other threads (but you can implement a subclass with this property if needed)
- you can explicitly wait for a Thread to finish by invoking its *join()* method.
- there is also a `Timer` class, that allows to set up a delayed thread.

Python/threading - Thread management: Example 1

```
import threading
import time
import random

def do_something():

   time.sleep(random.randrange(1,5))
   print('%s RUNNING\n' % (threading.current_thread().name))

if __name__ == '__main__':

    threads = []

    for i in range(10):
        my_thread = threading.Thread(target=do_something)
        threads.append(my_thread)

    for t in threads:
        t.start()

    for t in threads:
        t.join()

    print('Done')
```

Python/threading: Synchronization / Flow control

- certain structures allow you to control and synchronize the execution of the threads:

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  `Lock/RLock` To secure a *critical* region, locks can be used. They can be held by either a single thread or no thread at all. Should a thread try to acquire a lock on a resource that is already locked, that thread will basically pause until the lock is released. RLocks allow same thread to lock multiple times.

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  `Condition` Allows to keep threads waiting until explicitely notified and associated lock released

  `Semaphore` Allows to limit access to locked are to a number of threads at a time

Python/threading: Example 2 (Barrier)

```
import threading
import time
import random

num = 4
bar = threading.Barrier(num)

def do_something():

   time.sleep(random.randrange(2, 20))
   print('%s REACHED the barrier\n' % (current_thread().name))
   try:
       bar.wait()
   except:
       pass
   finally:
       print('%s PASSED the barrier\n' % (current_thread().name))

if __name__ == '__main__':

    threads = []

    for i in range(10):
        my_thread = threading.Thread(target=do_something,args=())
        my_thread.start()

    time.sleep(30)
    print("Release stuck threads by breaking barrier…")
    bar.abort()
```

Python/threading: Example 3 (Lock/RLock)

```
import threading

total = 0
lock = threading.Lock()

def update_total(amount):

    #Updates the total

    global total
    lock.acquire()
    try:
        total += amount
    finally:
        lock.release()
    print (total)

if __name__ == '__main__':
    for i in range(10):
        my_thread = threading.Thread(
            target=update_total, args=(5,))
        my_thread.start()
```

Python/threading: Example 3 (Lock/RLock)

```
import threading

total = 0
lock = threading.Lock()

def update_total(amount):

    #Updates the total

    global total
    with lock:
        total += amount
    print (total)

if __name__ == '__main__':
    for i in range(10):
        my_thread = threading.Thread(
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```

```python
import threading

total = 0
lock = threading.RLock()

def do_something(amount):

    with lock:
        update_total(amount)


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    global total
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        total += amount
    print (total)

if __name__ == '__main__':
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        my_thread = threading.Thread(
            target=do_something, args=(5,))
        my_thread.start()
```

Python/threading: Example 4 (Condition/Semaphore)

```
import threading
import time

def create(cond):

    while True:
        time.sleep(3)
        print('%s: New item PRODUCED\n' %
                    (threading.current_thread().name))

        with cond:
           cond.notify()
           time.sleep(3)
           print('%s: Item AVAILABLE\n' %
                    (threading.current_thread().name))

def consume(cond):

    while True:
        with cond:
           print('%s: WAITING for new item ...\n' %
                    (threading.current_thread().name))
           cond.wait()
           print('%s: CONSUMING item\n' %
                    (threading.current_thread().name))
        time.sleep(10)

if __name__ == '__main__':

    cond = threading.Condition()

    thread_producer = threading.Thread(target=create, name='producer',
                                       args=(cond,))
    thread_consumer1 = threading.Thread(target=consume, args=(cond,))
    thread_consumer2 = threading.Thread(target=consume, args=(cond,))

    thread_creator.start()
    thread_consumer1.start()
    thread_consumer2.start()
```

Python/threading: Example 4 (Condition/Semaphore)

```python
import threading
import time

def create(cond):

    while True:
        time.sleep(3)
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        with cond:
            cond.notify()
            time.sleep(3)
            print('%s: Item AVAILABLE\n' %
                    (threading.current_thread().name))

def consume(cond):

    while True:
        with cond:
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            cond.wait()
            print('%s: CONSUMING item\n' %
                    (threading.current_thread().name))
        time.sleep(10)

if __name__ == '__main__':

    cond = threading.Condition()

    thread_producer = threading.Thread(target=create, name='producer',
                                      args=(cond,))
    thread_consumer1 = threading.Thread(target=consume, args=(cond,))
    thread_consumer2 = threading.Thread(target=consume, args=(cond,))

    thread_creator.start()
    thread_consumer1.start()
    thread_consumer2.start()
```

```python
import threading
import time

total = 2
sem = threading.Semaphore(total)

def do_something():

    with sem:
        print(threading.currentThread().getName() + '\n')
        time.sleep(5)

if __name__ == '__main__':
    for i in range(10):
        my_thread = threading.Thread(
            target=do_something, args=(5,))
        my_thread.start()
```

Python/threading: Memory management

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  `Queue` The `Queue` class provides a FIFO structure that allow e.g. *producer* threads to pass on data to *consumer* threads

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- alternatively, there are additional structures to communicate (results) *safely* between threads:

  `Queue` The `Queue` class provides a FIFO structure that allow e.g. *producer* threads to pass on data to *consumer* threads

  `Event` `Event` objects allow are simply binary structures to send signals across threads

Python/threading: Example 4 (Queue/Event)

```
import threading
import queue
import time

def create(data, q):

    for item in data:

        […]

        q.put(item)

def consume(q):

    while True:
        data = q.get()

        […]

        q.task_done()

if __name__ == '__main__':
    q = queue.Queue()
    data = range(10)

    thread_creator = threading.Thread(target=create, args=(data, q))
    thread_consumer = threading.Thread(target=consume, args=(q,))
    thread_consumer.daemon = True

    thread_creator.start()
    thread_consumer.start()

    time.sleep(2)
    q.join()
    print("Done")
```

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import time

def create(data, q):

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        […]

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    thread_consumer.start()

    time.sleep(2)
    q.join()
    print("Done")
```

```python
import threading
import queue

def create(data, q):

    for item in data:

        […]

        q.put(item)

def consume(q, evt):

    while True:
        try:
            data = q.get(timeout=5)
        except:
            evt.set()

        […]

if __name__ == '__main__':
    q = queue.Queue()
    evt = threading.Event()
    data = range(10)

    thread_creator = threading.Thread(target=create, args=(data,q,))
    thread_consumer = threading.Thread(target=consume, args=(q,evt,))
    thread_consumer.daemon = True

    thread_creator.start()
    thread_consumer.start()

    evt.wait()
    print("Done")
```

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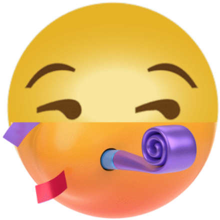
Python - Multithreading: Caveats (2025 update)



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CPython 3.13/14 finally has the option to disable the GIL!

POSIX Threads

PThreads - History/Goals

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- first defined in IEEE POSIX standard 1003.1c in 1995, but undergoes continuous evolution/revision
- historically implementations focused on Unix as OS, but implementations also exist now for others e.g. for Windows

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- To enable these included libraries, use e.g.

`icc -pthread` for INTEL (Linux)
`gcc -pthread` for GNU (Linux)

PThreads - API

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- The subroutines defined in the API can be classified into four major groups:

  Thread management
  : For creating new threads, checking their properties and joining/destroying them and the end of their lifecycle (`pthread_`,`pthread_attr_`)

  Mutexes
  : For creating mutex locks to control excess to exclusive resources (`pthread_mutex_`,`pthread_mutexattr_`)

  Condition variables
  : routines for managing condition variable to allow for easy communication between threads that share a mutex (`pthread_cond_`,`pthread_condattr_`)

  Semaphores
  : Like in Python, there are semaphores. A semaphore is a signalling mechanism and a thread that is waiting on a semaphore can be signaled by another thread and use a counter to limit access.

  Synchronization
  : barriers, read/write locks (`pthread_barrier_`,`pthread_rwlock_`)

PThreads - Thread management: Creation & Termination

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- POSIX threads (`pthread_t`) are created explicitly using the `pthread_create(thread,attr,start_routine,arg)` where
  - `attr` is a thread attribute structure containing settings for creating/running thread
  - `start_routine` is a procedure that works as a starting point for the thread
  - `arg` is a pointer to the argument for the starting routine (can be pointing to a single data element, an array or a custom data structure)

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  - start_routine is a procedure that works as a starting point for the thread
  - arg is a pointer to the argument for the starting routine (can be pointing to a single data element, an array or a custom data structure)
- They terminate when finishing their starting routine, calling pthread_exit(status) to return a status flag, by another thread by calling pthread_cancel(thread) with thread pointing to them or the host process finishing first (without pthread_exit() call)

PThreads - Thread management: Example 1

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS     5

void *PrintHello(void *threadid)
{
   long tid;
   tid = (long)threadid;
   printf("Hello World! It's me, thread #%ld!\n", tid);
   pthread_exit(NULL);
}

int main (int argc, char *argv[])
{
   pthread_t threads[NUM_THREADS];
   int rc;
   long t;
   for(t=0; t<NUM_THREADS; t++){
      printf("In main: creating thread %ld\n", t);
      rc = pthread_create(&threads[t], NULL, PrintHello, (void *)t);
      if (rc){
         printf("ERROR; return code from pthread_create() is %d\n", rc);
         exit(-1);
      }
   }

   /* Last thing that main() should do */
   pthread_exit(NULL);
}
```

PThreads - Thread management: Joining & Detaching

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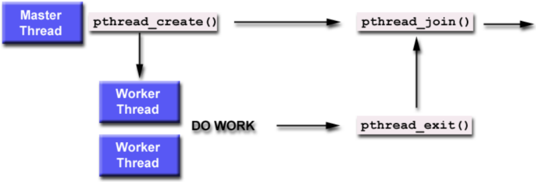

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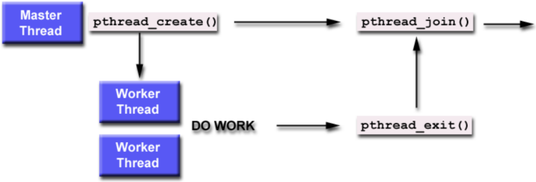

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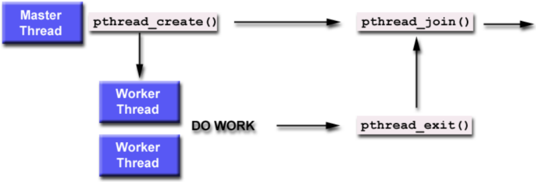

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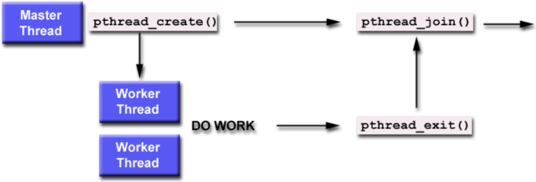

- threads can be declared "joinable" on creation
- data (Thread Control Block) remains in memory after completion of a thread until `pthread_join` is called on this dead thread and the clean-up is triggered
- "detached" threads do not keep such (potentially unnecessary) data, i.e. get cleaned up directly on completion

PThreads - Mutexes

- Mutexes work in similar way as the OpenMP and Python locks: once claimed by one thread, other threads encountering it will be hold until the mutex released again.

PThreads - Joining & Mutexes: Example

```
#define NUMTHRDS 4
#define VECLEN 100000
   DOTDATA dotstr;
   pthread_t callThd[NUMTHRDS];
   pthread_mutex_t mutexsum;

void *dotprod(void *arg)
{
   […]

   mysum = 0;
   for (i=start; i<end ; i++)
    {
      mysum += (x[i] * y[i]);
    }

   pthread_mutex_lock (&mutexsum);
   dotstr.sum += mysum;
   printf("Thread %ld did %d to %d:  mysum=%f global sum=
%f\n",offset,start,end,mysum,dotstr.sum);
   pthread_mutex_unlock (&mutexsum);

   pthread_exit((void*) 0);
}

int main (int argc, char *argv[])
{
long i;
double *a, *b;
void *status;
pthread_attr_t attr;

a = (double*) malloc (NUMTHRDS*VECLEN*sizeof(double));
b = (double*) malloc (NUMTHRDS*VECLEN*sizeof(double));
```

```
[…]

pthread_mutex_init(&mutexsum, NULL);

/* Create threads to perform the dotproduct  */
pthread_attr_init(&attr);
pthread_attr_setdetachstate(&attr, PTHREAD_CREATE_JOINABLE);

for(i=0;i<NUMTHRDS;i++)
  {
  /* Each thread works on a different set of data.
   * The offset is specified by 'i'. The size of
   * the data for each thread is indicated by VECLEN.
   */
   pthread_create(&callThd[i], &attr, dotprod, (void *)i);
   }

pthread_attr_destroy(&attr);
/* Wait on the other threads */

for(i=0;i<NUMTHRDS;i++) {
  pthread_join(callThd[i], &status);
  }
/* After joining, print out the results and cleanup */

printf ("Sum =  %f \n", dotstr.sum);
free (a);
free (b);
pthread_mutex_destroy(&mutexsum);
pthread_exit(NULL);
}
```

PThreads - Condition variables

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- instead of claiming a lock, it allows threads to wait (`pthread_cond_wait()`) until another thread send a signal (`pthread_cond_signal()`) through the condition variable to continue.

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- Since there are no "team" structure like in OpenMP, on creation a number of threads is defined, that has to reach the barrier before any of them is allowed to pass.

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- As for OpenMP, POSIX does not dictate the (default) stack size for a thread and thus can vary greatly.
- So better explicitly allocate enough stack to provide portability and avoid segmentation faults or data corruption
- use `pthread_attr_setstacksize` to set the desired stacksize in the attribute object used for creating the thread.