OpenMP

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Goal

- learn OpenMP, by far the most widespread standard API for shared memory parallel programming
- learn that various schedulers execute your parallel programs differently

OpenMP

- *de fact* standard model for programming shared memory machines
- C/C++/Fortran + parallel directives + APIs
  - by `#pragma` in C/C++
  - by comments in Fortran
- many free/vendor compilers, including GCC

OpenMP reference

- official home page: `http://openmp.org/`
- specification: `http://openmp.org/wp/openmp-specifications/`
- latest version is 4.5 (`http://www.openmp.org/mp-documents/openmp-4.5.pdf`)
- section numbers below refer to those in OpenMP spec 4.0 (`http://www.openmp.org/mp-documents/OpenMP4.0.0.pdf`)

GCC and OpenMP

- `http://gcc.gnu.org/wiki/openmp`
- gcc 4.2 → OpenMP spec 2.5
- gcc 4.4 → OpenMP spec 3.0 (task parallelism)
- gcc 4.7 → OpenMP spec 3.1
- gcc 4.9 → OpenMP spec 4.0 (SIMD)

Compiling/running OpenMP programs with GCC

- compile with `-fopenmp`

```
$ gcc -Wall -fopenmp program.c
```

- run the executable specifying the number of threads with `OMP_NUM_THREADS` environment variable

```
$ OMP_NUM_THREADS=1 ./a.out  # use 1 thread
$ OMP_NUM_THREADS=4 ./a.out  # use 4 threads
```

- see 2.5.1 "Determining the Number of Threads for a parallel Region" for other ways to control the number of threads

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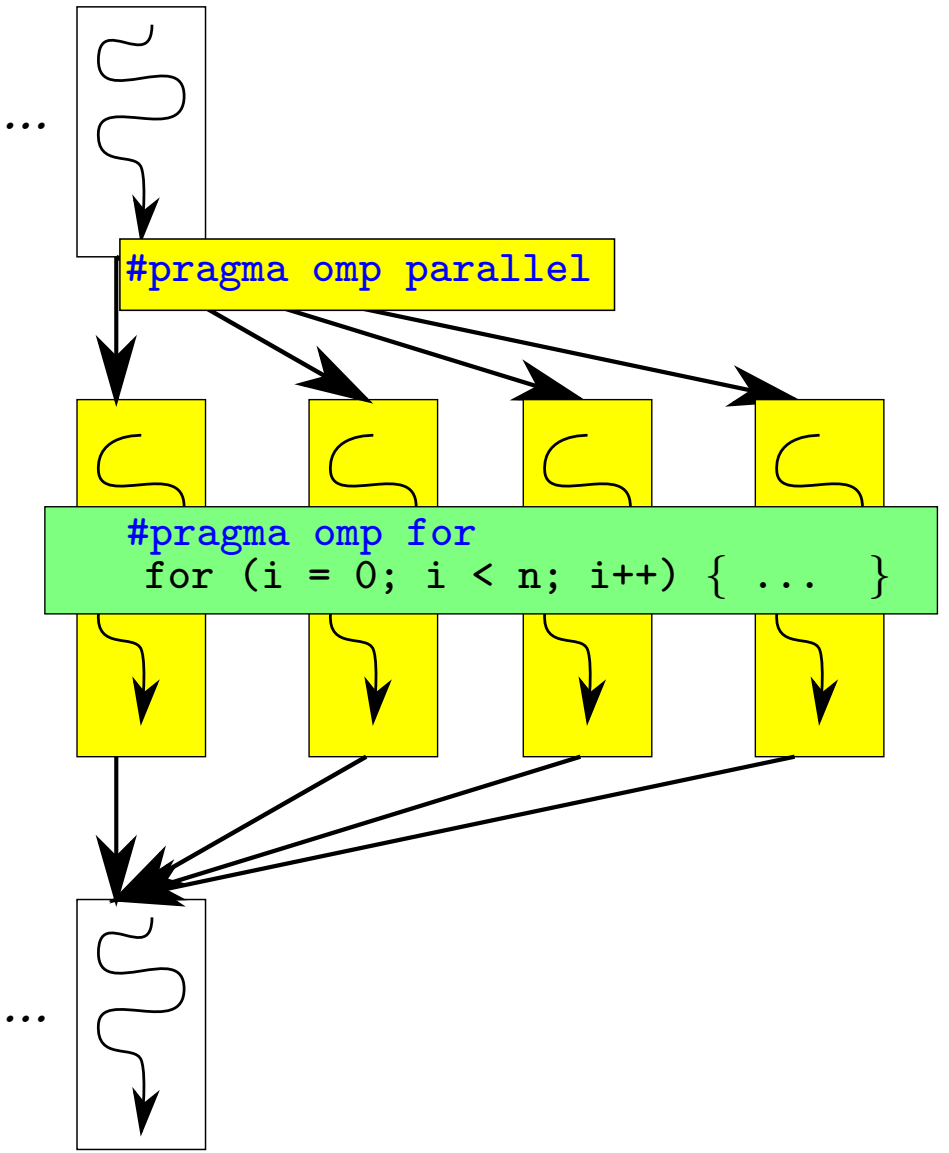
Two pragmas you must know first

- `#pragma omp parallel` to launch a team of threads (2.5)
- then `#pragma omp for` to distribute iterations to threads (2.7.1)

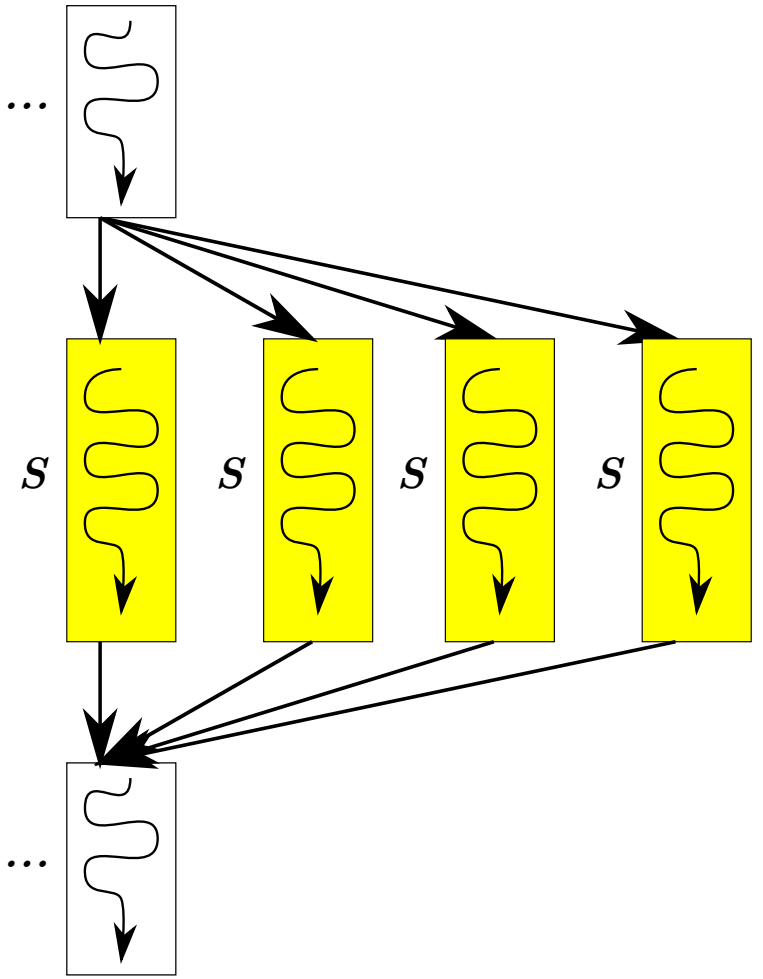
Note: all OpenMP pragmas have the common format: `#pragma omp ...`



#pragma parallel

- basic syntax:

```
1   ...
2   #pragma omp parallel
3     S
4   ...
```



- basic semantics:
  - create a team of `OMP_NUM_THREADS` threads
  - the current thread becomes the *master* of the team
  - *S will be executed by each member of the team*
  - the master thread waits for all to finish S and continue

`parallel` pragma example

```
1 #include <stdio.h>
2 int main() {
3   printf("hello\n");
4 #pragma omp parallel
5   printf("world\n");
6   return 0;
7 }
```

```
1 $ OMP_NUM_THREADS=1 ./a.out
2 hello
3 world
4 $ OMP_NUM_THREADS=4 ./a.out
5 hello
6 world
7 world
8 world
9 world
```

Remarks : what does `parallel` do?

- you may assume an OpenMP thread ≈ OS-supported thread (e.g., Pthread)
- that is, if you write this program

```
1 int main() {
2 #pragma omp parallel
3   worker();
4 }
```

and run it as follows,

```
1 $ OMP_NUM_THREADS=50 ./a.out
```

you will get 50 OS-level threads, each doing `worker()`

How to distribute work among threads?

- `#pragma omp parallel` creates threads, *all executing the same statement*
- it's not a means to parallelize work, *per se*, but just a means to create a number of similar threads (SPMD)
- so how to distribute (or partition) work among them?
  1. do it yourself
  2. use *work sharing* constructs

Do it yourself: functions to get the number/id of threads

- `omp_get_num_threads()` (3.2.2) : the number of threads *in the current team*
- `omp_get_thread_num()` (3.2.4) : the current thread's id (0, 1, ...) in the team
- they are primitives with which you may partition work yourself by whichever ways you prefer
- e.g.,

```
1 #pragma omp parallel
2 {
3   int t  = omp_get_thread_num();
4   int nt = omp_get_num_threads();
5   /* divide n iterations evenly amont nt threads */
6   for (i = t * n / nt; i < (t + 1) * n / nt; i++) {
7     ...
8   }
9 }
```

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Work sharing constructs

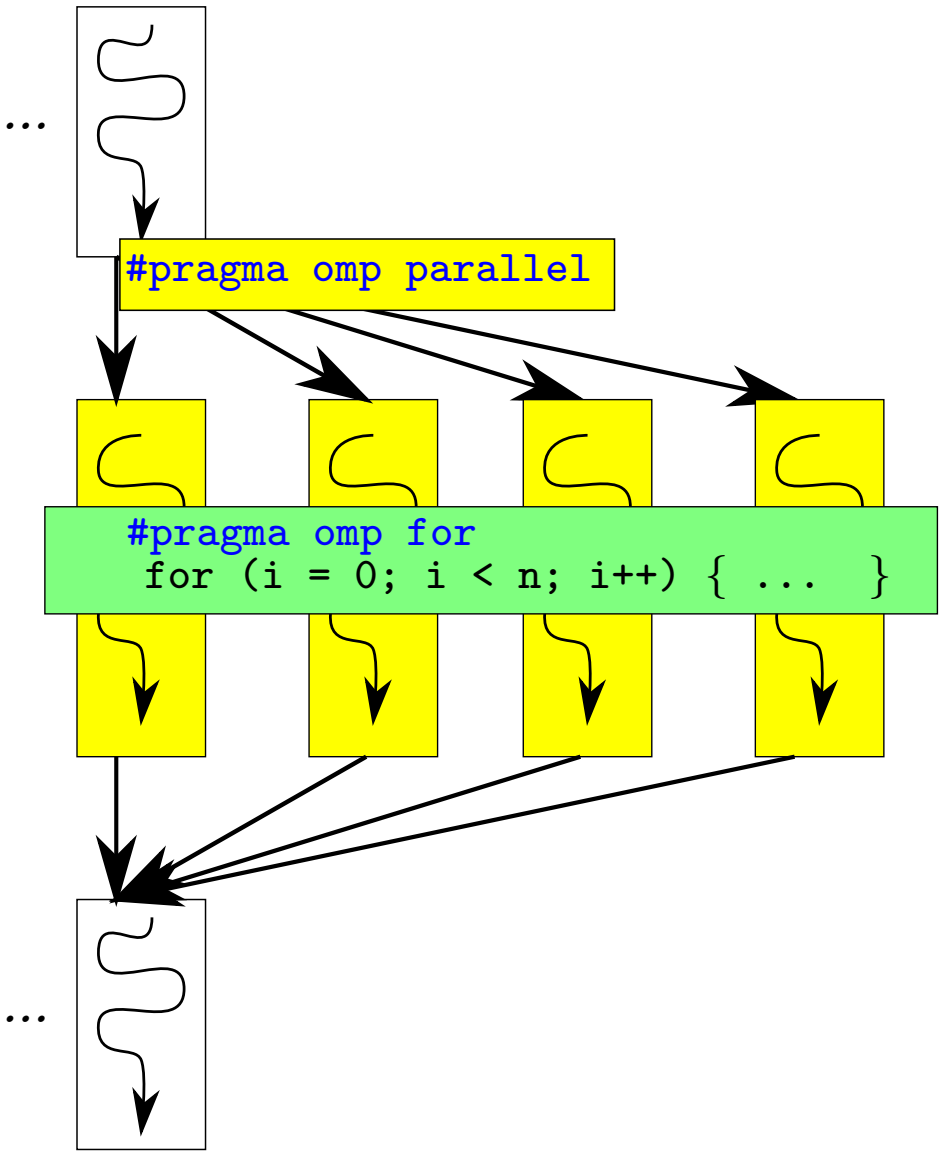
- in theory, `parallel` construct is all you need to do things in parallel
- but it's too inconvenient
- OpenMP defines ways to *partition* work among threads *(work sharing constructs)*
  - for
  - task
  - section

`#pragma omp for` (work-sharing for)

- basic syntax:

```
1  #pragma omp for
2  for(i=...; i...; i+=...){
3    S
4  }
```

- basic semantics:
  the threads in the team divde the iterations among them
- but how? ⇒ scheduling



`#pragma omp for` restrictions

- not arbitrary for statement is allowed after a `for` pragma
- strong syntactic restrictions apply, so that *the iteration counts can easily be identified at the beginning* of the loop
- roughly, it must be of the form:

```
1  #pragma omp for
2  for(i = init; i < limit; i += incr)
3    S
```

  except `<` and `+=` may be other similar operators

- *init*, *limit*, and *incr* must be loop invariant

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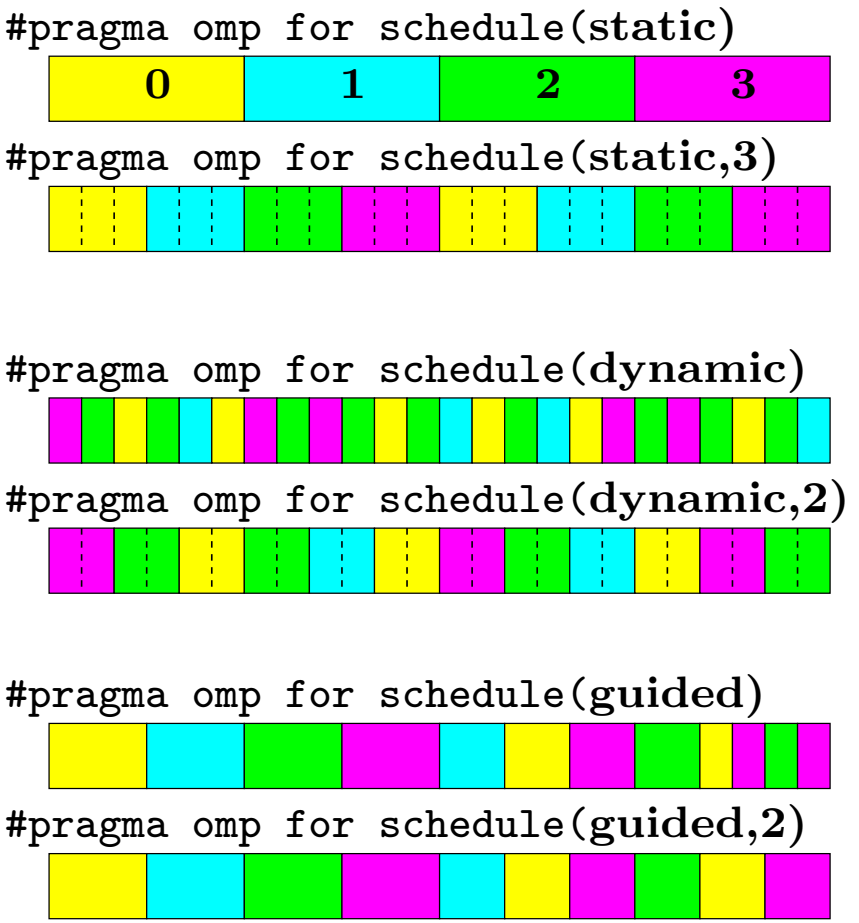
Scheduling (2.7.1)

- `schedule` clause in work-sharing for loop determines how iterations are divided among threads
- There are three alternatives (`static`, `dynamic`, and `guided`)

static, dynamic, and guided

- `schedule(static[,chunk])`: predictable round-robin
- `schedule(dynamic[,chunk])`: each thread repeats fetching *chunk* iterations
- `schedule(guided[,chunk])`: threads grab many iterations in early stages; gradually reduce iterations to fetch at a time
- *chunk* specifies the minimum granularity (iteration counts)



Other scheduling options and notes

- `schedule(runtime)` determines the schedule by `OMP_SCHEDULE` environment variable. e.g.,

```
$ OMP_SCHEDULE=dynamic,2 ./a.out
```

- `schedule(auto)` or no `schedule` clause choose an implementation dependent default

Parallelizing loop nests by `collapse`

- `collapse(`l`)` can be used to partition nested loops. e.g.,

```
1 #pragma omp for collapse(2)
2 for (i = 0; i < n; i++)
3   for (j = 0; j < n; j++)
4     S
```

  will partition n^2 iterations of the doubly-nested loop

- `schedule` clause applies to nested loops as if the nested loop is an equivalent flat loop
- restriction: the loop must be *"perfectly nested"* (the iteration space must be a rectangular and no intervening statement between different levels of the nest)

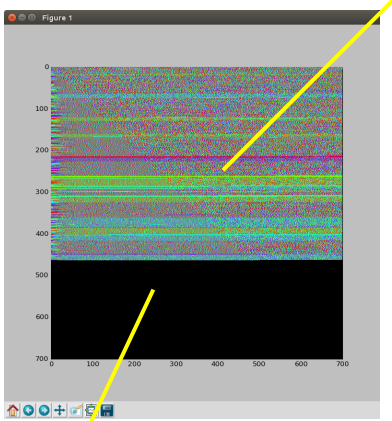
Visualizing schedulers

- seeing is believing. let's visualize how loops are distributed among threads
- write a simple doubly nested loop and run it under various scheduling options

```
1  #pragma omp for collapse(2) schedule(runtime)
2  for (i = 0; i < 1000; i++)
3    for (j = 0; j < 1000; j++)
4      unit_work(i, j);
```

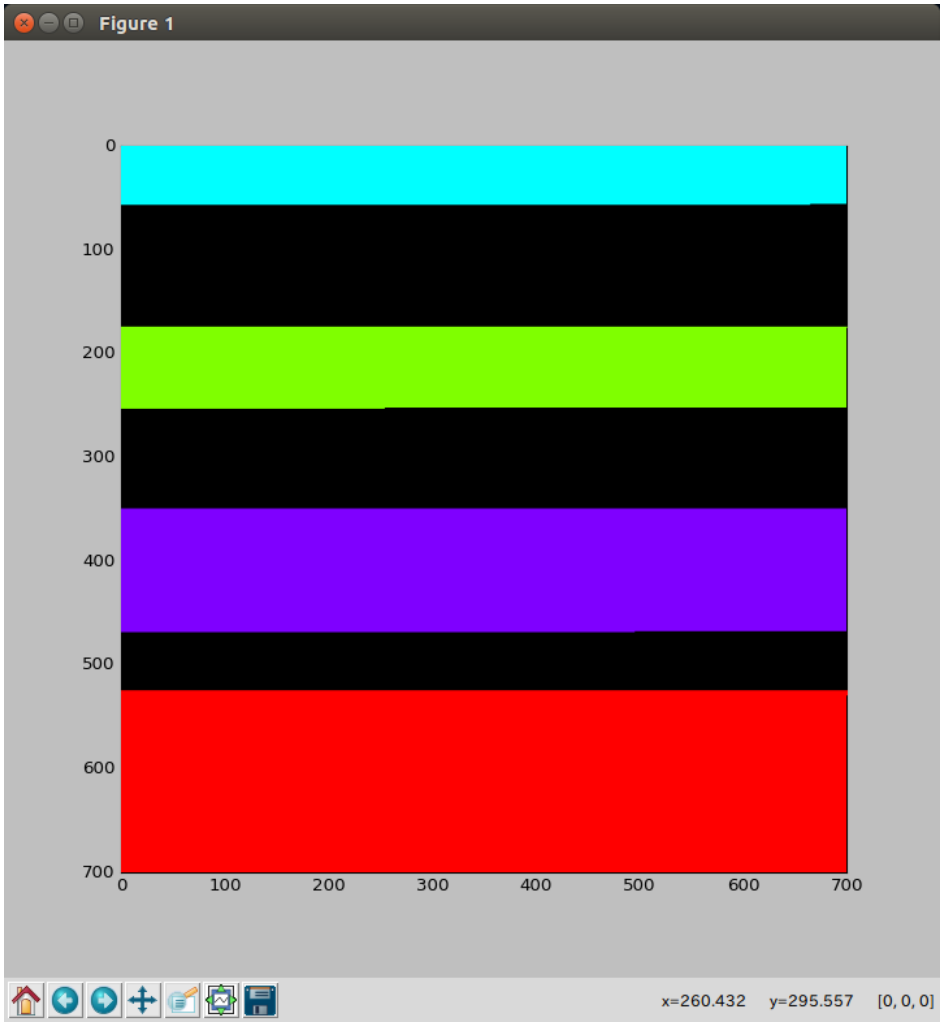
- load per point is systematically skewed:
  - ≈ 0 in the lower triangle
  - drawn from $[100, 10000]$ (clocks) in the upper triangle

load $\sim [100, 10000]$ clocks

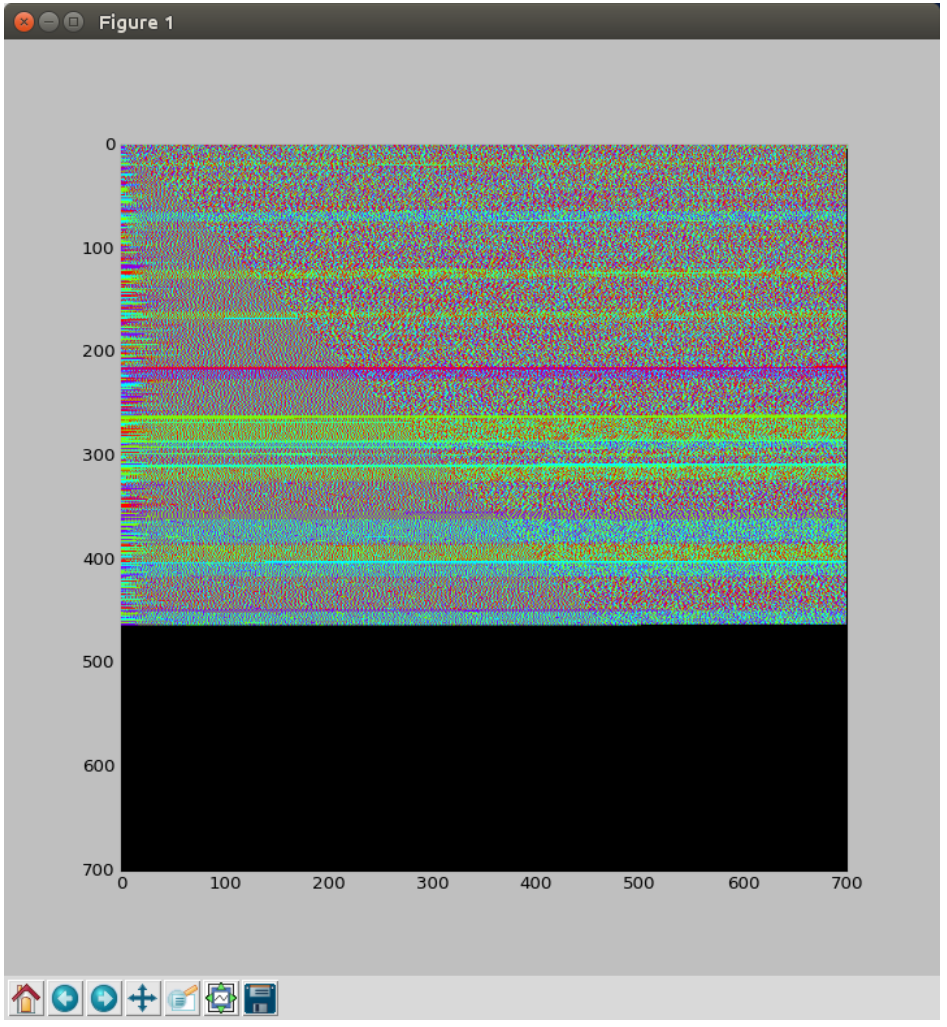


load ≈ 0

Visualizing schedulers



static



dynamic

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Task parallelism in OpenMP

- OpenMP's initial focus was simple parallel loops
- since 3.0, it supports task parallelism
- but why it's necessary?
- aren't `parallel` and `for` all we need?

Limitation of `parallel for`

- what if you have a parallel loop inside another

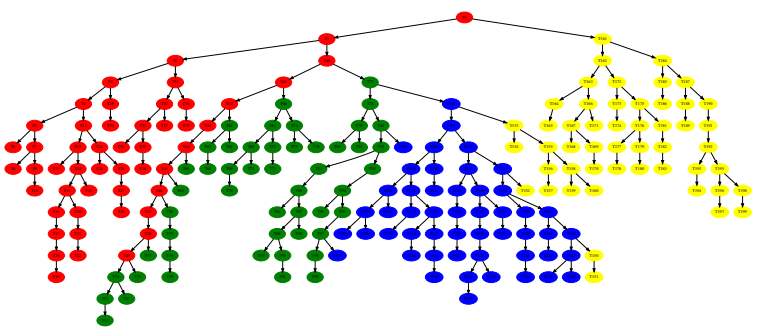
```
1 for ( ... ) {
2   ...
3   for ( ...) ...
4 }
```

- perhaps inside a separate function?

```
1 main() {
2   for ( ... ) {
3     ...
4     g();
5   }
6 }
7 g() {
8   for (...) ...
9 }
```

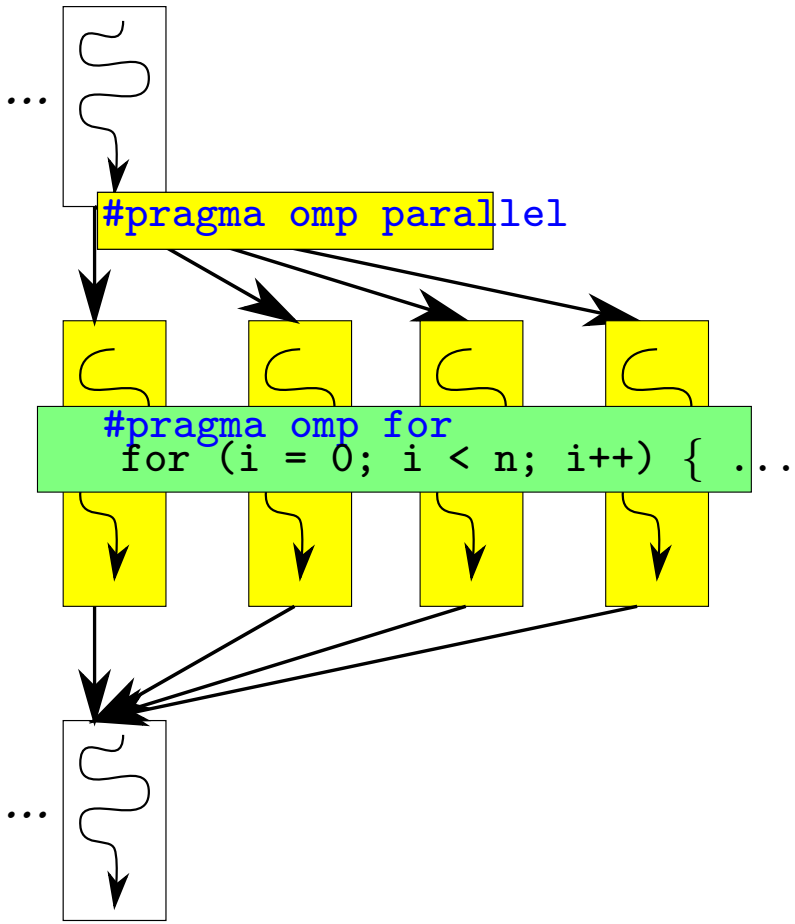
- what for parallel recursions?

```
1 qs() {
2   if (...) { ... }
3   else {
4     qs();
5     qs();
6   }
7 }
```



`parallel for` can't handle nested parallelism

- OpenMP generally ignores nested `parallel` pragma when enough threads have been created by the outer `parallel` pragma, for good reasons
- the fundamental limitation is its simplistic work-sharing mechanism
- tasks address these issues, by allowing tasks to be created at arbitrary points of execution (and a mechanism to distribute them across cores)



Task parallelism in OpenMP

- syntax:
  - create a task ≈ TBB's `task_group::run`

```
1 #pragma omp task
2   S
```

  - wait for tasks ≈ TBB's `task_group::wait`

```
1 #pragma omp taskwait
```

OpenMP task parallelism template

- don't forget to create a `parallel` region
- don't also forget to enter a `master` region, which says only the master executes the following statement and others "stand-by"

```
1  int main() {
2  #pragma omp parallel
3  #pragma omp master
4  // or #pragma omp single
5    ms(a, a + n, t, 0);
6  }
```

- and create tasks in the master region

```
1  void ms(a, a_end, t, dest) {
2    if (n == 1) {
3      ...
4    } else {
5      ...
6  #pragma omp task
7      ms(a, c,     t,      1 - dest);
8  #pragma omp task
9      ms(c, a_end, t + nh, 1 - dest);
10 #pragma omp taskwait
11     ...
12 }
```

Visualizing task parallel schedulers

- the workload is exactly the same as before

```
1  #pragma omp for collapse(2) schedule(runtime)
2  for (i = 0; i < 1000; i++)
3    for (j = 0; j < 1000; j++)
4      unit_work(i, j);
```

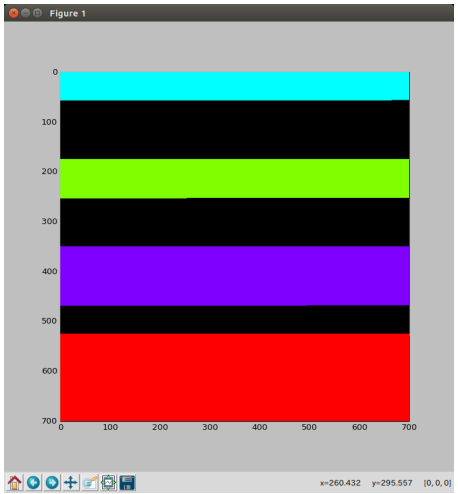
- but we rewrite it into recursions

```
1  void work_rec(rectangle b) {
2    if (small(b)) {
3      ...
4    } else {
5      rectangle c[2][2];
6      split(b, c); // split b into 2x2 sub-rectangles
7      for (i = 0; i < 2; i++) {
8        for (i = 0; i < 2; i++) {
9  #pragma omp task
10         work_rec(b[i][j]);
11       }
12     }
13 #pragma omp taskwait
14   }
```

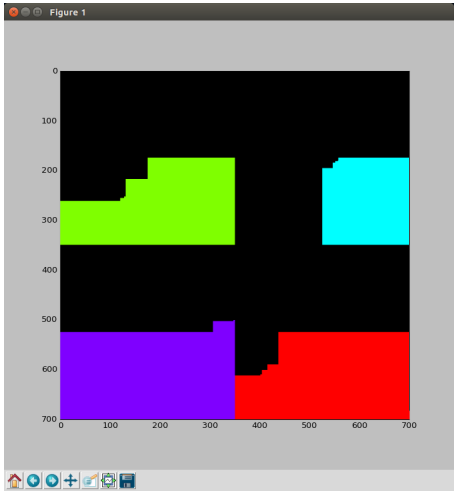
load $\sim [100, 10000]$ clock

load ≈ 0

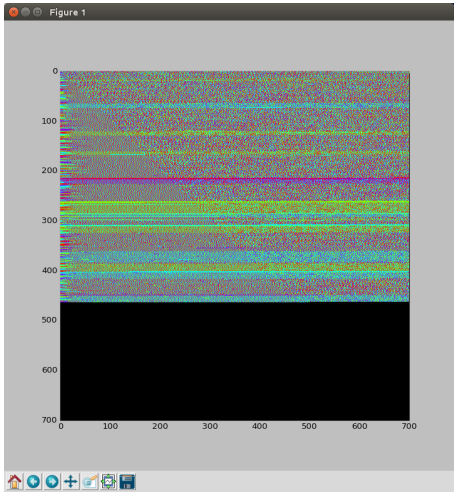
Visualizing schedulers



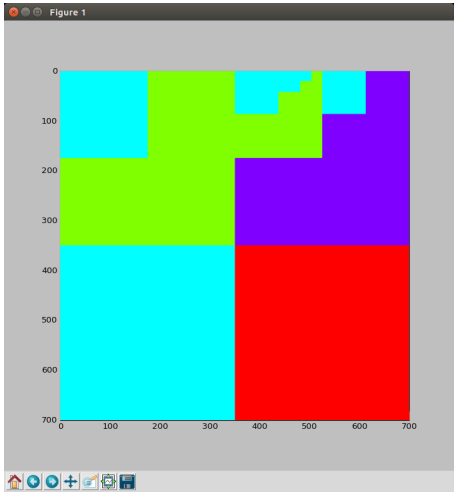
static



2D recursive (midway)



dynamic



2D recursive (end)

A note on current GCC task implementation

- the overhead seems high and the scalability seems low, so it's not very useful now
- TBB, Cilk, and MassiveThreads-backed TBB are all much better
- Intel implementation of OpenMP tasks is good too
- we'll come back to the topic of efficient implementation of task parallelism later

Pros/cons of schedulers

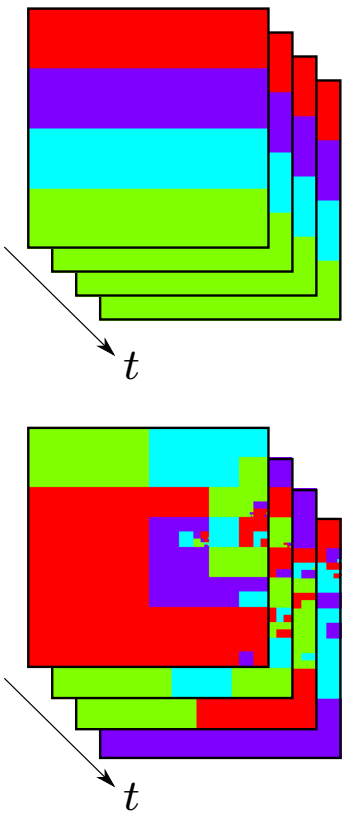
- `static:`
  - partitioning iterations is simple and does not require communication
  - may cause load imbalance (leave some threads idle, even when other threads have many work to do)
  - mapping between work $\leftrightarrow$ thread is deterministic and predictable (why it's important?)
- `dynamic:`
  - no worry about load imbalance, if chunks are sufficiently small
  - partitioning iterations needs communication (no two threads execute the same iteration) and may become a bottleneck
  - mapping between iterations and threads is non-deterministic
  - OpenMP's dynamic scheduler is inflexible in partitioning loop nests

Pros/cons of schedulers

- `recursive (divide and conquer + tasks):`
  - no worry about load imbalance, as in dynamic
  - distributing tasks needs communication, but efficient implementation techniques are known
  - mapping between work and thread is non-deterministic, as in dynamic
  - you can flexibly partition loop nests in various ways (e.g., keep the space to square-like)
  - need boilerplate coding efforts (easily circumvented by additional libraries; e.g., TBB's `blocked_range2d` and `parallel_for`)

Deterministic and predictable schedulers

- programs often execute the same for loops many times, with the same trip counts, and with the same iteration touching a similar region
- such *iterative* applications may benefit from reusing data brought into cache in the previous execution of the same loop
- a deterministic scheduler achieves this benefit



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Data sharing

- `parallel`, `for`, `task` pragma accept clauses specifying which variables should be shared among threads or between the parent/child tasks
- 2.14 "Data Environments"
  - `private`
  - `firstprivate`
  - `shared`
  - `reduction` (only for `parallel` and `for`)
  - `copyin`

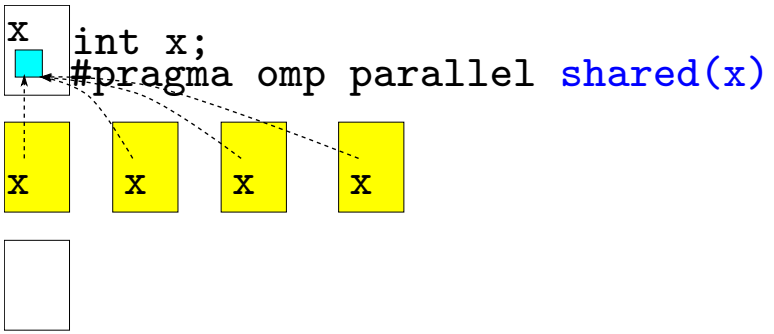
Data sharing example

```
1  int main() {
2    int S;   /* shared */
3    int P;   /* made private below */
4  #pragma omp parallel private(P) shared(S)
5    {
6      int L; /* automatically private */
7      printf("S at %p, P at %p, L at %p\n",
8             &S, &P, &L);
9    }
10   return 0;
11 }
```

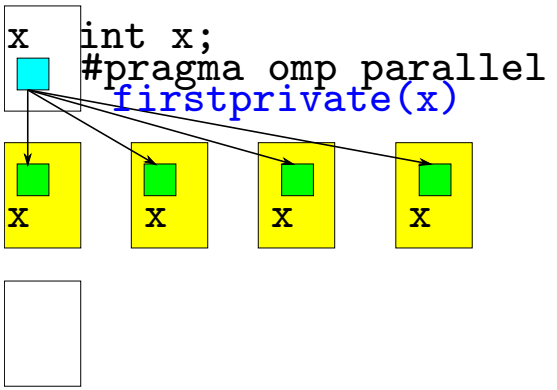
```
1  $ OMP_NUM_THREADS=2 ./a.out
2  S at 0x..777f494, P at 0x..80d0e28, L at 0x..80d0e2c
3  S at 0x..777f494, P at 0x..777f468, L at 0x..777f46c
```

Data sharing behavior

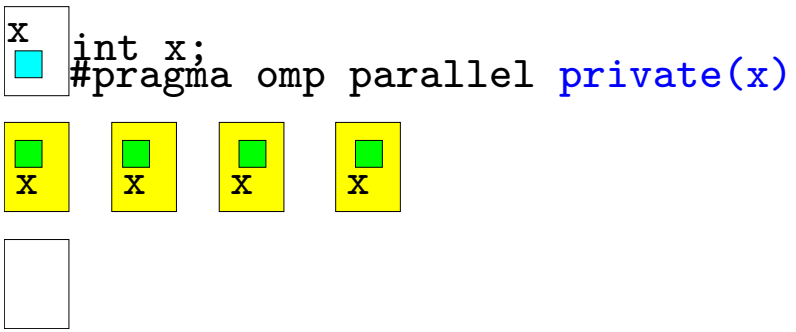
shared



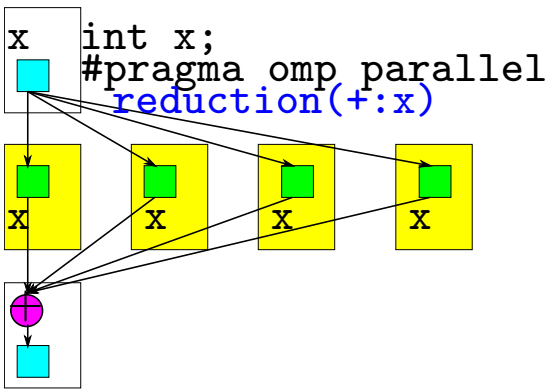
firstprivate



private



reduction

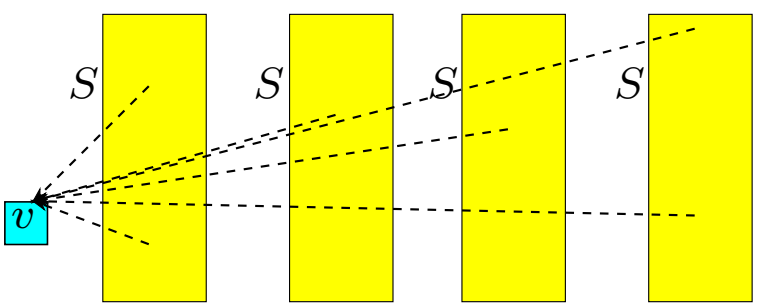


Reduction

- in general, "reduction" refers to an operation to combine many values into a single value. e.g.,
  - $v = v_1 + \cdots + v_n$
  - $v = \max(v_1, \cdots, v_n)$
  - ...
- simply sharing the variable (v) does not work (race condition)
- even if you make updates atomic, it will be slow (by now you should know how slow it will be)

```
1  v = 0.0;
2  for (i = 0; i < n; i++) {
3    v += f(a + i * dt) * dt;
4  }
```

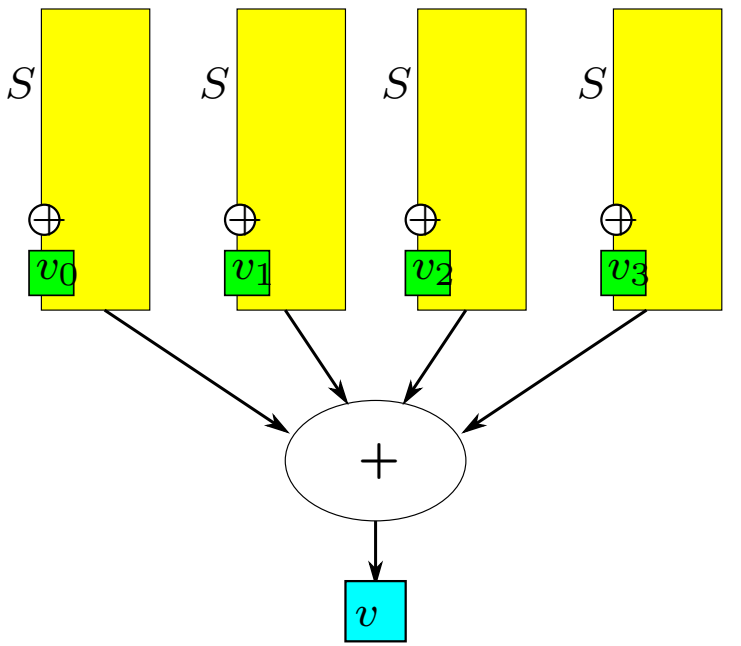
```
1  v = 0.0;
2  #pragma omp parallel shared(v)
3  #pragma omp for
4  for (i = 0; i < n; i++) {
5  #pragma omp atomic
6    v += f(a + i * dt) * dt;
7  }
```



Reduction clause in OpenMP

- a more efficient strategy is to
  - let each thread reduce on its private variable, and
  - when threads finish, combine their partial results into one
- `reduction` clause in OpenMP does just that

```
1  v = 0.0;
2  #pragma omp parallel shared(v)
3  #pragma omp for reduce(+:v)
4  for (i = 0; i < n; i++) {
5    v += f(a + i * dt) * dt;
6  }
```



Simple reduction and user-defined reduction (2.7.1)

- reduction syntax:

```
1 #pragma omp parallel reduction(op:var,var,...)
2     S
```

  - builtin reductions
    - *op* is one of `+`, `*`, `-`, `&`, `^`, `|`, `&&`, and `||`
    - (Since 3.1) `min` or `max`
  - (Since 4.0) a user-defined reduction name

- user-defined reduction syntax:

```
1 #pragma omp declare reduction (name : type : combine statement)
```

User-defined reduction example

```
1  typedef struct {
2    int x; int y;
3  } point;
4  point add_point(point p, point q) {
5    point r = { p.x + q.x, p.y + q.y };
6    return r;
7  }
8  // declare reduction "ap" to add two points
9  #pragma omp declare reduction(ap:  point:  omp_out=add_point(omp_out,
           omp_in))
10
11 int main(int argc, char ** argv) {
12   int n = atoi(argv[1]);
13   point p = { 0.0, 0.0 };
14   int i;
15 #pragma omp parallel for reduction(ap : p)
16   for (i = 0; i < n; i++) {
17     point q = { i, i };
18     p = add_point(p, q);
19   }
20   printf("%d %d\n", p.x, p.y);
21   return 0;
22 }
```

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SIMD constructs

- `simd` pragma
  - allows an explicit vectorization of for loops
  - syntax restrictions similar to `omp for` pragma apply
- `declare simd` pragma
  - instructs the compiler to generate vectorized versions of a function
  - with it, loops with function calls can be vectorized

`simd` pragma

- basic syntax (similar to `omp for`):

```
1 #pragma omp simd clauses
2 for (i = ...; i < ...; i += ...)
3     S
```

- clauses
  - `aligned(`*var,var,...*`:`*align*`)`
  - `uniform(`*var,var,...*`)` says variables are loop invariant
  - `linear(`*var,var,...*`:`*stride*`)` says variables have the specified stride between consecutive iterations

`declare simd` pragma

- basic syntax (similar to `omp for`):

```
1 #pragma omp declare simd clauses
2 function definition
```

- clauses
  - those for `simd` pragma
  - `notinbranch`
  - `inbranch`

SIMD pragmas, rationales

- most automatic vectorizers give up vectorization in many cases
  1. conditionals (lanes may branch differently)
  2. inner loops (lanes may have different trip counts)
  3. function calls (function bodies are not vectorized)
  4. iterations may not be independent
- `simd` and `declare simd` directives should eliminate obstacles 3 and 4 and significantly enhance vectorization opportunities

A note on current GCC OpenMP SIMD implementation

- as of now (version 4.9), GCC `simd` and `declare simd` $\approx$ existing auto vectorizer $-$ dependence analysis
- `declare simd` functions are first converted into a loop over all vector elements and then passed to the loop vectorizer

```
1 #pragma omp declare simd
2 float f(float x, float y) {
3   return x + y;
4 }
```

$\rightarrow$

```
1 float8 f(float8 vx, float8 vy) {
2   float8 r;
3   for (i = 0; i < 8; i++) {
4     float x = vx[i], y = vy[i]
5     r[i] = x + y;
6   }
7   return r;
8 }
```

- the range of vectorizable loops in current GCC (4.9) implementation seems very limited
  - innermost loop with no conditionals
  - doubly nested loop with a very simple inner loop