Parallelism (PAR)

Short tutorial on OpenMP

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Part I

OpenMP Basics

Outline

- OpenMP overview
- OpenMP model
- Creating threads and accessing data
- Some API calls
- Thread synchronization
- Memory consistency

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- OpenMP model
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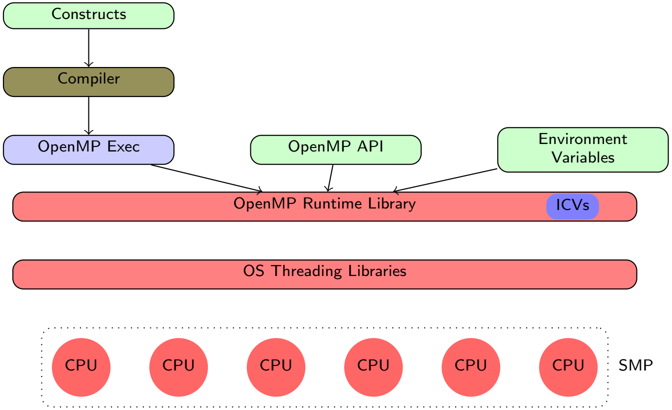
What is OpenMP?

- It's an API extension to the C, C++ and Fortran languages to write parallel programs for shared memory machines
  - Current version is 4.0 (July 2013)
  - Supported by most compiler vendors
    - Intel, IBM, PGI, Sun, Cray, Fujitsu, HP, GCC,...
- Maintained by the Architecture Review Board (ARB), a consortium of industry and academia
- This mini-tutorial just covers part of the specification, for the complete reference please consult the documentation online

http://www.openmp.org

OpenMP components



OpenMP components

Constructs

These form the major elements of OpenMP programming

- Create threads
- Share the work amongst threads
- Synchronize threads and memory

Library routines

To control and query the parallel execution environment (internal control variables - ICVs)

Environment variables

The execution environment can also be set before the program execution is started

OpenMP directives syntax

In C/C++

Through a compiler directive:

```
#pragma omp construct [clauses]
```

- OpenMP syntax is ignored if the compiler does not recognize OpenMP

Structured block

Most directives apply to:

- A block of one or more statements
- One entry point, one exit point
  - No branching in or out allowed

Headers/Macros

C/C++ only

- omp.h contains the API prototypes and data types definitions
- The _OPENMP is defined by OpenMP enabled compiler
  - Allows conditional compilation of OpenMP

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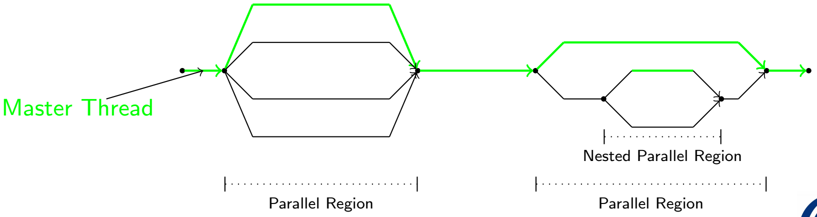
Execution model

Fork-join model

- OpenMP uses a fork-join model
  - The master thread spawns a team of threads that joins at the end of the parallel region
  - Threads in the same team can collaborate to do work



Memory model

- OpenMP defines a relaxed memory model
  - Threads can see different values for the same variable
  - Memory consistency is only guaranteed at specific points
  - Luckily, the default points are usually enough
    - If not ... there is a mechanism to guarantee it! (described at the end of Part I)
- Variables can be shared or private to each thread

Outline

- OpenMP overview
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- Some API calls
- Thread synchronization
- Memory consistency

The parallel construct

Directive

```
#pragma omp parallel [clauses]
    structured block
```

where some of the `clauses` are:

- `num_threads(`*`expression`*`)`
- `if(`*`expression`*`)`
- shared(*var-list*)
- private(*var-list*)
- firstprivate(*var-list*)
- reduction(*operator:var-list*)

Coming shortly!

We'll see it later

The parallel construct

Specifying the number of threads

- The `nthreads-var` ICV is used to determine the number of threads to be used for encountered parallel regions
  - It is a list of positive integer values, its first element specifying the number of processors for the next nesting level
  - When a `parallel` construct is encountered, and the generating task's `nthreads-var` list contains multiple elements, the generated task(s) inherit the value of `nthreads-var` as the list obtained by deletion of the first element
  - If the generating task's `nthreads-var` list contains a single element, the generated task(s) inherit that list as the value of `nthreads-var`

The parallel construct

Specifying the number of threads

- The `nthreads-var` list can be defined from the execution command line by setting the `OMP_NUM_THREADS` environment variable
  - Example: `setenv OMP_NUM_THREADS 4,3,2`
- After that, the `threads-var` list can be modified through:
  - the `omp_set_num_threads` API, which sets the value of the first element of the current list
  - the `num_threads` clause, which causes the implementation to ignore the ICV and use the value of the clause for that region.

The `if` clause

Avoiding parallel regions

- Sometimes we only want to run in parallel under certain conditions
  - E.g., enough input data, not running already in parallel, ...
- The `if` clause allows to specify an *expression*. When evaluates to false the `parallel` construct will only use 1 thread
  - Note that still creates a new team and data environment

The parallel construct

```
void main () {
  #pragma omp parallel
    ...
  omp_set_num_threads(2);
  #pragma omp parallel
    ...
  #pragma omp parallel num_threads(random()%4+1) if(0)
    ...
}
```

How many threads are used in each parallel region above?

Data-sharing attributes

Shared

When a variable is marked as `shared`, the variable inside the construct is the same as the one outside the construct

- In a parallel construct this means all threads see the same variable
  - but not necessarily the same value
- Usually need some kind of synchronization to update them correctly
  - OpenMP has consistency points at synchronizations
- By default, variables are implicitly `shared`

Data-sharing attributes

Private

When a variable is marked as `private`, the variable inside the construct is a new variable of the same type with an undefined value

- In a parallel construct this means all threads have a different variable
- Can be accessed without any kind of synchronization

Data-sharing attributes

Firstprivate

When a variable is marked as `firstprivate`, the variable inside the construct is a new variable of the same type but it is initialized to the original variable value

- In a parallel construct this means all threads have a different variable with the same initial value
- Can be accessed without any kind of synchronization

Data-sharing attributes

```
int x=1;
#pragma omp parallel XXXXXX num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

What does appear on the screen if `XXXXXX` is `shared(x)`, `private(x)` or `firstprivate(x)`?

Example: computation of PI

```
static long num_steps = 100000;
double step;
void main ()
{
    int i;
    double x, pi, sum = 0.0;

    step = 1.0/(double) num_steps;

    for (i=1;i<= num_steps; i++){
        x = (i-0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = step * sum;
}
```

Example: computation of PI (not equivalent to sequential!)

```
static long num_steps = 100000;
double step;
#include <omp.h>
#define NUM_THREADS 2
void main ()
{
   int i, id;
   double x, pi, sum=0.0;

   step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
#pragma omp parallel private(x, i)
   for (i=1;i<= num_steps; i++){
      x = (i-0.5)*step;
      sum = sum + 4.0/(1.0+x*x);
   }

   pi = sum * step;
}
```

Outline

Some useful routines

int omp_get_num_threads()	Returns the number of threads in the current team. 1 if outside a parallel region
int omp_get_thread_num()	Returns the id of the thread in the current team. id between 0 and omp_get_num_threads()-1
void omp_set_num_threads()	Sets the number of threads to be used in parallel regions at the next nesting level
int omp_get_max_threads()	Returns the number of threads that could be used in parallel regions at the next nesting level
double omp_get_wtime()	Returns the number of seconds since an arbitrary point in the past

Example: computation of PI (data race!)

```
static long num_steps = 100000;
double step;
#include <omp.h>
#define NUM_THREADS 2
void main ()
{
   int i, id;
   double x, pi, sum=0.0;

   step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel private(x, i, id)
   {
      id = omp_get_thread_num();
      for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
         x = (i-0.5)*step;
         sum = sum + 4.0/(1.0+x*x);
      }
   }
   pi = sum * step;
}
```

Example: computation of PI (measuring execution time)

```
static long num_steps = 100000;
double step;
#include <omp.h>
#define NUM_THREADS 2
void main ()
{
    int i, id;
    double x, pi, sum=0.0;
    double TimeStart, TimeEnd;

    TimeStart = omp_get_wtime();
    step = 1.0/(double) num_steps;
    omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel private(x, i, id)
    {
    ...
    }
    pi = sum * step;
    TimeEnd = omp_get_wtime();
    printf("Wall clock time = %.20f\n", TimeEnd-TimeStart);
}
```

Outline

Why synchronization?

OpenMP is a shared memory model

- Threads communicate by sharing variables
- Unintended sharing of data causes race conditions (i.e. the execution outcome may change as the threads are scheduled differently)
- Threads need to synchronize to impose some ordering in their sequence of actions

Some OpenMP synchronization mechanisms:

- `barrier`
- `critical`
- `atomic`
- Use of locks through API

Thread Barrier

The barrier construct

#pragma `omp barrier`

- Threads cannot proceed past a barrier point until all threads reach the barrier AND all previously generated work is completed
- Some constructs have an implicit `barrier` at the end
  - E.g., the `parallel` construct

Barrier

Example

```
#pragma omp parallel
{
    foo();
#pragma omp barrier
    bar();
}
```

Forces all foo occurrences too happen before all bar occurrences

Implicit barrier at the end of the parallel region

Exclusive access: critical construct

```
#pragma omp critical [(name)]
    structured block
```

- Provides a region of mutual exclusion where only one thread can be working at any given time
- By default all critical regions are the same
- Multiple mutual exclusion regions by providing them with a name
  - Only those with the same name synchronize

Example: computation of PI

```
...
void main ()
{
   int i, id;
   double x, pi, sum=0.0;

   step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel private(x, i, id)
   {
      id = omp_get_thread_num();
      for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
         x = (i-0.5)*step;
         #pragma omp critical
         sum = sum + 4.0/(1.0+x*x);
      }
   }
   pi = sum * step;
}
```

Critical construct

```
int x=1,y=0;
#pragma omp parallel num_threads(4)
{
#pragma omp critical (x)
    x++;
#pragma omp critical (y)
    y++;
}
```

Different names: One thread can update *x* while another updates *y*

Exclusive access: atomic construct

```
#pragma omp atomic [update | read | write]
    expression
```

- Ensures that a specific storage location is accessed atomically, avoiding the possibility of multiple, simultaneous reading and writing threads
  - Atomic updates: `x += 1`, `x = x - foo()`, `x[index[i]]++`
  - Atomic reads: `value = *p`
  - Atomic writes: `*p = value`
- Only protects the read/operation/write
- Usually more efficient than a `critical` construct
- Other clauses and forms for `atomic` are allowed in the specification

First example: computation of PI

```
...
void main ()
{
   int i, id;
   double x, pi, sum=0.0;

   step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel private(x, i, id)
   {
      id = omp_get_thread_num();
      for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
         x = (i-0.5)*step;
         #pragma omp atomic
         sum = sum + 4.0/(1.0+x*x);
      }
   }
   pi = sum * step;
}
```

The reduction clause

Reduction is a very common pattern where all threads accumulate values into a single variable

```
reduction(operator:list)
```

- Valid operators are: +,-,*,|,||,&,&&,^
- The compiler creates a `private` copy of each variable in list that is properly initialized to the identity value
- At the end of the region, the compiler ensures that the `shared` variable is properly (and safely) updated with the partial values of each thread, using the specified operator

First example: computation of PI

```
...
void main ()
{
   int i, id;
   double x, pi, sum;

   step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel private(x, i, id) reduction(+:sum)
   {
      id = omp_get_thread_num();
      for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
         x = (i-0.5)*step;
         sum = sum + 4.0/(1.0+x*x);
      }
   }
   pi = sum * step;
}
```

Locks

OpenMP provides lock primitives for low-level synchronization

`omp_init_lock`	Initialize the lock
`omp_set_lock`	Acquires the lock
`omp_unset_lock`	Releases the lock
`omp_test_lock`	Tries to acquire the lock (won't block)
`omp_destroy_lock`	Frees lock resources

Locks

Example

```
#include <omp.h>
void foo ()
{
    omp_lock_t lock;

    omp_init_lock(&lock);
    #pragma omp parallel
    {
        omp_set_lock(&lock);
        // mutual exclusion region
        omp_unset_lock(&lock);
    }
    omp_destroy_lock(&lock);
}
```

Lock must be initialized before being used

Only one thread at a time here

Outline

The flush construct

Relaxed consistency memory model

- A thread's temporary view of memory is not required to be consistent with memory at all times
- A value written to a variable can remain in the thread's temporary view until it is forced to memory at a later time
- Likewise, a read from a variable may retrieve the value from the thread's temporary view, unless it is forced to read from memory

The flush construct

```
#pragma omp flush (list)
```

- It enforces consistency between the temporary view and memory for those variables in list
- Synchronization (implicit or explicit) constructs have an associated flush operation

Part II

Loop Parallelism in OpenMP

Outline

- The worksharing concept
- Loop worksharing
- The single construct

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- The worksharing concept
- Loop worksharing
- The single construct

The worksharing concept

Worksharing constructs divide the execution of a code region among the members of a team

- Threads cooperate to do some work
- Better way to split work than using thread-ids
- Lower overhead than using `tasks` (next section)
  - But, less flexible

In OpenMP, there are four worksharing constructs:

- loop worksharing
- single ← We'll see it later
- sections
- workshare ← Not used much ... we'll skip them

Outline

- The worksharing concept
- Loop worksharing
- The single construct

Loop parallelism

The for construct

```
#pragma omp for [clauses]
    for( init-expr ; test-expr ; inc-expr )
```

where some possible clauses are:

- private
- firstprivate
- reduction
- `schedule(`*`schedule-kind`*`)`
- `nowait`
- `collapse(`*`n`*`)`

The for construct

The iterations of the loop(s) associated to the construct are divided among the threads of the team.

- Loop iterations must be independent
- Loops must follow a form that allows to compute the number of iterations
- Valid data types for inductions variables are: integer types, pointers and random access iterators (in C++)
  - The induction variable(s) are automatically privatized
- The default data-sharing attribute is `shared`

It can be merged with the `parallel` construct:

```
#pragma omp parallel for
```

First example: computation of PI

```
#include <omp.h>
static long num_steps = 100000;
double step;
#define NUM_THREADS 2

void main ()
{
   int i, id;
   double x, pi, sum;

   step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
   #pragma omp parallel for private(x) reduction(+:sum)
   for (i=1; i<=num_steps; i++) {
         x = (i-0.5)*step;
         sum = sum + 4.0/(1.0+x*x);
   }
   pi = sum * step;
}
```

The schedule clause

The `schedule` clause determines which iterations are executed by each thread.

- If no `schedule` clause is present then is implementation defined

There are several possible options as schedule:

- `static[,chunk]`
- `dynamic[,chunk]`
- `guided[,chunk]`

The schedule clause

`static`

The iteration space is broken in chunks of approximately size $N/num\_threads$. Then these chunks are assigned to the threads in a Round-Robin fashion.

`static,N` (also called interleaved)

The iteration space is broken in chunks of size N. Then these chunks are assigned to the threads in a Round-Robin fashion.

Characteristics of static schedules

- Low overhead
- Good locality (usually)
- Can have load imbalance problems

The schedule clause

`dynamic,N`

Threads dynamically grab chunks of N iterations until all iterations have been executed. If no chunk is specified, $N = 1$.

`guided,N`

Variant of `dynamic`. The size of the chunks decreases as the threads grab iterations, but it is at least of size N. If no chunk is specified, $N = 1$.

Characteristics of dynamic schedules

- Higher overhead
- Not very good locality (usually)
- Can solve imbalance problems

The nowait clause

When a worksharing has a `nowait` clause then the implicit `barrier` at the end of the loop is removed.

- This allows to overlap the execution of non-dependent loops/tasks/worksharings

```
#pragma omp for nowait
for ( i = 0; i < n ; i++ )
   v[i] = 0;
#pragma omp for
for ( i = 0; i < n ; i++ )
   a[i] = 0;
```

First and second loop are independent so we can overlap them

The nowait clause

Useful to overlap the execution of two (or more) consecutive loops if they have the same static schedule and all have the same number of iterations.

```
#pragma omp for schedule(static,2) nowait
for ( i = 0; i < n ; i++ )
   v[i] = 0;
#pragma omp for schedule(static,2)
for ( i = 0; i < n ; i++ )
   a[i] = v[i]*v[i];
```

The collapse clause

Allows to distribute work from a set of *n* nested loops.

- Loops must be perfectly nested
- The nest must traverse a rectangular iteration space

```
#pragma omp for collapse(2)
for ( i = 0; i < N; i++ )
   for ( j = 0; j < M; j++ )
      foo (i,j);
```

i and *j* loops are folded and iterations distributed among all threads. Both *i* and *j* are privatized

Outline

- The worksharing concept
- Loop worksharing
- The single construct

Giving work to just one thread

The single construct

```
#pragma omp single [clauses]
    structured block
```

- where clauses can be:
  - private
  - firstprivate
  - nowait
- Only one thread of the team executes the structured block
- There is an implicit barrier at the end

Part III

Task Parallelism in OpenMP

Outline

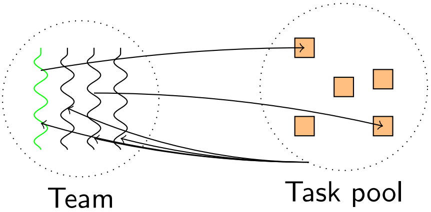
- OpenMP tasks
- Task synchronization

Outline

- OpenMP tasks
- Task synchronization

Task parallelism model

- Tasks are work units whose execution may be deferred
  - they can also be executed immediately
- Threads of the team cooperate to execute them



Creating tasks

Implicit and explicit tasks

- `Parallel` regions create tasks
  - One implicit task is created and assigned to each thread
- Each thread that encounters a `task` construct
  - Packages the code and data
  - Creates a new explicit task

Creating (explicit) tasks

The task construct

```
#pragma omp task [clauses]
        structured block
```

Where some possible clauses are:

- shared
- private
- firstprivate
  - Values are captured at creation time
- `if(`*expression*`)`
- `final(`*expression*`)`
- `mergeable`

Example: list traversal

```
void traverse_list ( List l )
{
  Element e;
  for ( e = l->first; e ; e = e->next )
     #pragma omp task
       process(e);
}
```

Example: list traversal

Completing the picture

We need threads to execute the tasks ...

```
List l

#pragma omp parallel
traverse_list(l);
...

void traverse_list ( List l )
{
  Element e;
  for ( e = l->first; e ; e = e->next )
     #pragma omp task    // e is firstprivate by default
       process(e);
}
```

... but not that many! This will generate multiple traversals

Example: list traversal

Using **single** ...

```
List l

#pragma omp parallel
#pragma single
traverse_list(l);
...

void traverse_list ( List l )
{
  Element e;
  for ( e = l->first; e ; e = e->next )
     #pragma omp task
       process(e);
}
```

One thread creates the tasks of the traversal. The rest (and this one once task generation is finished) cooperate to execute them

Default task data-sharing attributes

When no data clauses are specified, some rules apply:

- Global variables are shared
- Variables declared in the scope of a task are private
- The rest are `firstprivate` except when a `shared` attribute can be lexically inherited

Task default data-sharing attributes

In practice...

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a = // shared
            b = // firstprivate
            c = // shared
            d = // firstprivate
            e = // private
}}}
```

The `if` clause: immediate task execution

- If the expression of an `if` clause evaluates to false
  - The encountering task is suspended
  - The new task is executed immediately
    - with its own data environment
    - different task with respect to synchronization
  - The parent task resumes when the task finishes
  - Allows implementations to optimize task creation

The `final` clause: immediate task execution (nested)

- If the expression of a `final` clause evaluates to `true`
  - The generated task and all of its child tasks will be final
  - The execution of a final task is sequentially **included** in the generating task (executed immediately)
- When a `mergeable` clause is present on a task construct, and the generated task is an **included** task, the implementation may generate a merged task instead (i.e. no task and context creation for it).

Final and mergeable tasks (data race!)

```
int fib(int n) {
  int i, j;

  if (n<2)
    return n;
  #pragma omp task shared(i) final(n <= THOLD) mergeable
  i=fib(n-1);
  #pragma omp task shared(j) final(n <= THOLD) mergeable
  j=fib(n-2);

  ....

  return i+j;
}
```

Outline

- OpenMP tasks
- Task synchronization

Task synchronization

There are two types of task barriers:

- `taskwait`
  - Suspends the current task waiting on the completion of **child tasks** of the current task. The taskwait construct is a stand-alone directive
- `taskgroup`
  - Suspends the current task at the end of structured block waiting on completion of **child tasks** of the current task **and their descendent** tasks.

Taskwait

```
#pragma omp taskwait
```

```
#pragma omp task {}        // T1
#pragma omp task           // T2
{
    #pragma omp task {}    // T3
}
#pragma omp task {}        // T4

#pragma omp taskwait
                      ←  Only T1, T2 and T4 are guaranteed to have finished here
}
```

Taskwait for correct Fibonacci parallelization

```
int fib(int n) {
  int i, j;

  if (n<2)
    return n;
  #pragma omp task shared(i) final(n <= THOLD) mergeable
  i=fib(n-1);
  #pragma omp task shared(j) final(n <= THOLD) mergeable
  j=fib(n-2);

  #pragma omp taskwait
  return i+j;
}
```

Taskgroup

```
#pragma omp taskgroup
        structured block
```

```
#pragma omp task {}          // T1
#pragma omp taskgoup
{
    #pragma omp task         // T2
    {
        #pragma omp task {}  // T3
    }
    #pragma omp task {}      // T4
}
```

Only T2, T3 and T4 are guaranteed to have finished here

Data sharing inside tasks

In addition one can use `critical` and `atomic` to synchronize the access to shared data inside the task

```
void process (Element e)
{
   ...
  #pragma omp atomic
     solutions_found++;
   ...
}
...
```

Task dependences

Definition of dependences between sibling tasks (i.e. from the same father)

```
#pragma omp task [depend (in : var_list)]
                 [depend (out : var_list)]
                 [depend (inout : var_list)]
```

Task dependences are derived from the dependence type (`in`, `out` or `inout`) and its items in `var_list`. This list may include array sections

Task dependences

- The `in` dependence-type: the generated task will be a dependent task of all previously generated sibling tasks that reference at least one of the list items in an `out` or `inout` dependence-type list
- The `out` and `inout` dependence-types: the generated task will be a dependent task of all previously generated sibling tasks that reference at least one of the list items in an `in`, `out`, or `inout` dependence-type list.

Task dependences

Example: wave-front execution

```
#pragma omp parallel private(i, j)
#pragma omp single
{
   for (i=1; i<n i++) {
         for (j=1; j<n;j++) {
            #pragma omp task
                        depend(in : block[i-1][j], block[i][j-1])
                        depend(out: block[i][j])
            foo(i,j);
         }
     }
}
```

Parallelism (PAR)

Short tutorial on OpenMP

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