Programação Paralela com OpenMP

ELC139 - Programação Paralela

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Outline

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Task parallelism

Task parallelism

- **Task parallelism** or functional parallelism or control parallelism.
- Decomposes the computation rather than the manipulated data.
  - Programming model for tasks that perform different computations.
- Ex.: Cilk, Intel TBB, OpenMP.

Task dependency

- Tasks with dependencies can unfold a directed acyclic graph (DAG).
  - Expressed by synchronization such as `sync` keyword.
- If data dependencies are considered, the algorithm unfolds a data flow graph (DFG).
- Ex.: Jade, Athapascan, OpenMP (new), KAAPI/XKaapi, StarPU, OmpSs, Intel Offload.

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OpenMP tasks

Task construct

```
#pragma omp task
```

Barrier taskwait

```
#pragma omp taskwait
```

- Independent units of work.
- Recursive tasks.
- Unfold parallelism at runtime.
- The OpenMP implementation decides when/where to execute:
  - Immediately (in depth, depth-first or work-first)
  - Latter (in breadth, breadth-first or help-first)

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Linked list

```
node* p = head;
while(p) {
  process(p);
  p = p->next;
}
```

OpenMP tasks

Linked list - parallel version

```
#pragma omp parallel
{
#pragma omp single
  {
    node* p = head;
    while(p) {
#pragma omp task firstprivate(p)
      process(p);
      p = p->next;
    }
  }
}
```

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OpenMP tasks

Cálculo de Fibonacci

```
int fib( int n ) {
  int x, y;
  if( n < 2 ) return n;
  x = fib( n - 1);
  y = fib( n - 2);
  return x + y;
}
```

Paralelismo de Tarefas

Cálculo de Fibonacci com OpenMP

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int fib( int n ) {
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  if( n < 2 ) return n;
#pragma omp task
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```

Correto?

Não pois x e y são privados fora do escopo das tarefas.

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Não pois x e y são privados fora do escopo das tarefas.

Paralelismo de Tarefas

Cálculo de Fibonacci com OpenMP

```
int fib( int n ) {
  int x, y;
  if( n < 2 ) return n;
#pragma omp task shared(x)
  x = fib( n - 1);
#pragma omp task shared(y)
  y = fib( n - 2);
#pragma omp taskwait
  return x + y;
}
```

Agora sim

Necessitamos dos dois valores no cálculo.

Outline

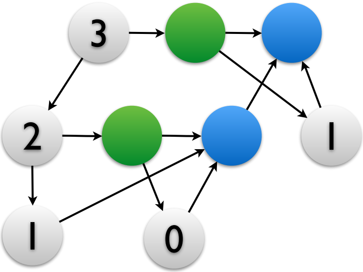
Data flow dependency

Concept

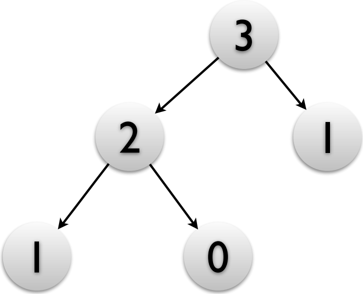
Similar to a DAG of tasks, but combines **task dependencies with data-driven execution**.

- Execution is controlled by the **Data Flow Graph (DFG)**.
- Unlike the program recursion structure of **full strict model**.

Fully strict mode (Cilk)



Data flow graph



Data flow dependency

Data access modes

- Read only (**RO or R**) - only read, no permission to modify.
- Write only (**WO or W**) - only write, no wait for data inputs.
- Read and Write (**RW**) - or exclusive mode, read and write.
- Cumulative Write (**CW**) - concurrent write and cumulative.

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Data flow dependency

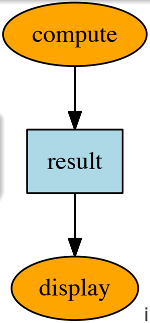
The concepts here are the same from computer architecture in which we can replace **instruction** by **task**.

Data dependencies

- Task t_i produces a result that may be used by a task t_j.
- Task t_j is data dependent on task t_k, and t_k is data dependent on t_i ($t_i \rightarrow t_k \rightarrow t_j$).

```
compute( input, &result );

display( &result );
```



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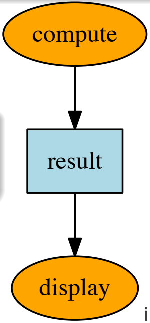


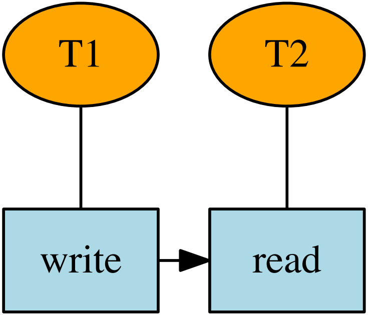
Data hazards

Data hazards

There is a **dependence** between task and the we must preserve the execution order.

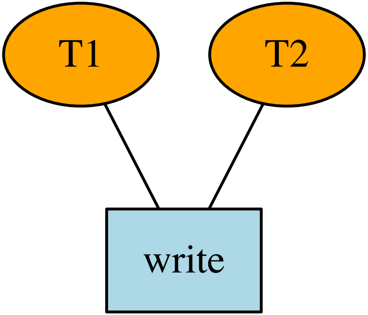
- **RAW** (*Read after Write*).
- **WAW** (*Write after Write*).
- **WAR** (*Write after Read*).

Data flow dependency



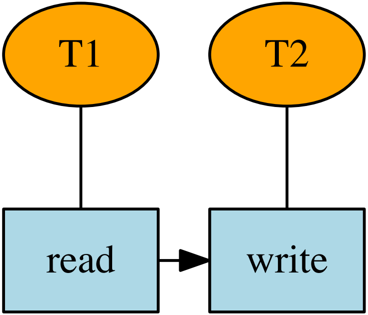
- **RAW** (*Read after Write*) - or true dependency, data dependency.
- A task depends on the result produced by a previous task.

Data flow dependency



- **WAW** (*Write after Write*) - or output dependency.
- The execution order will affect the final output.

Data flow dependency



- **WAR** (*Write after Read*) - or anti-dependency.
- A task writes a value before it is read.

Data flow example

In our next examples, we will use the following keywords:

- **in** - read access.
- **out** - write access.
- **inout** - read and write access.

```
void reading(in int a) {}
void modifying(inout int b) {}
main(void)
{
  int a;
  reading( a );
  reading( a );
  reading( a );
  modifying( a );
  modifying( a );
}
```

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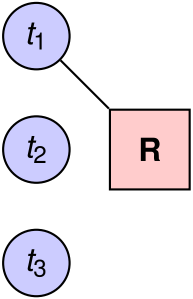

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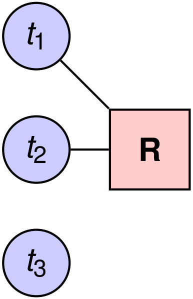

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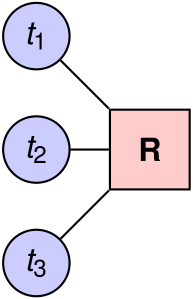

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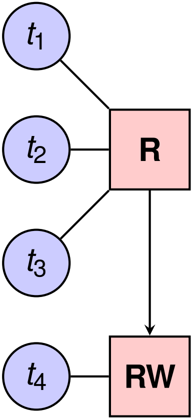

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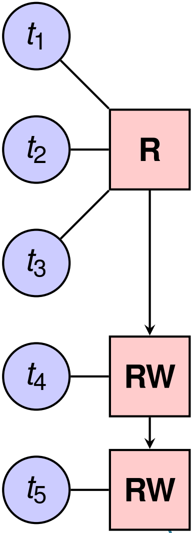

Fibonacci example

```
void fibo( int n, int* res )
{
  int x, y;
  if( n < 2 ){
    *res = n;
  } else {
    fibo( n-1, &x );
    fibo( n-2, &y );
    *res = x+y;
  }
}

int main(void) {
  int n = 3, res;
  fibo( n, &res );
  print( res );
  return 0;
}
```

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Fibonacci example

Notice

This recursive Fibonacci is not the best implementation, but it serves our purposes.

Dependency example (again)

In our next example, we will use the following keywords:

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- **cout** - cumulative write with global reduction.

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```

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Fibonacci example

Previous Fibonacci example

```
} else {
  fibo( n-1, &x );
  fibo( n-2, &y );
  *res = x+y;
}
```

Synchronization problem

If our tasks execute in parallel, we would like **to wait** for the results from the previous two `fibo` tasks.

Solution

1. An explicit synchronization (Cilk's style).
2. A task that depends on the results from the two `fibo` tasks.

Fibonacci example

Previous Fibonacci example

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Fibonacci example

```
void sum( out int* res, in int x, in int y )
{
  *a = x + y;
}

void fibo( in int n, out int* res )
{
  int x, y;
  if( n < 2 ){
    *res = n;
  } else {
    fibo( n-1, &x );
    fibo( n-2, &y );
    sum( res, x, y );
  }
}
```

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Fibonacci example

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```

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Fibonacci example (cumulative)

```
void fibo( in int n, cout int* res )
{
  int x, y;
  if( n < 2 ){
    *res += n;
  } else {
    fibo( n-1, &x );
    fibo( n-2, &y );
  }
}
```

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```
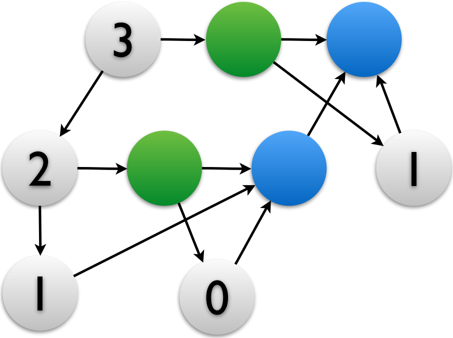
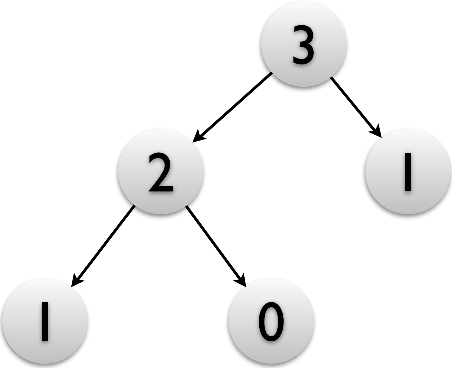

Data flow graph

- Data flow graph (DFG) combines task dependencies with data driven execution.

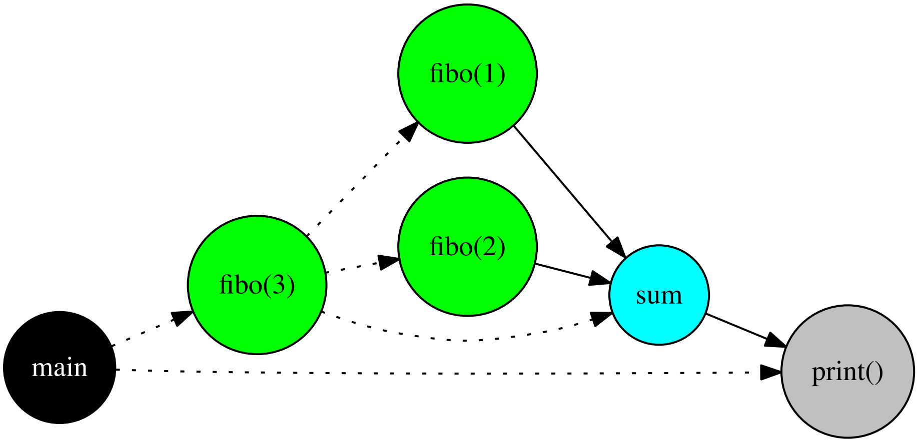
Fully strict mode (Cilk)



Data flow graph



DAG of Fibonacci $n = 3$



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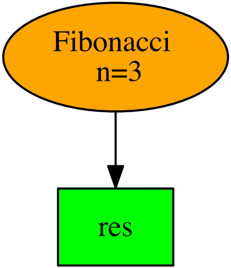
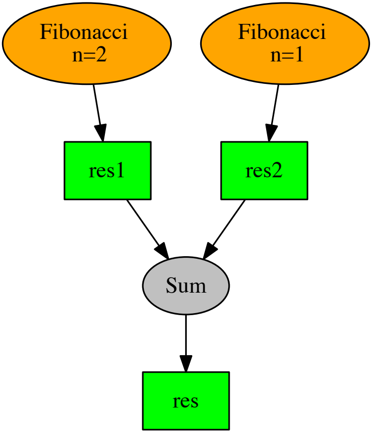


DFG of Fibonacci $n = 3$



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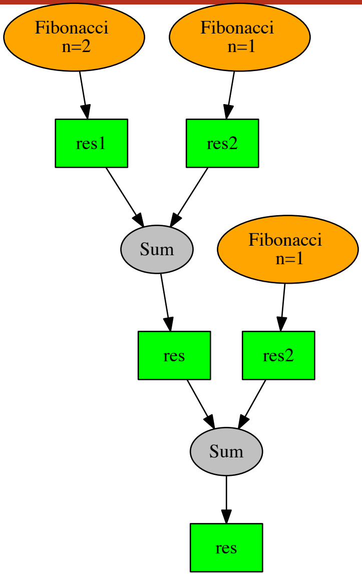

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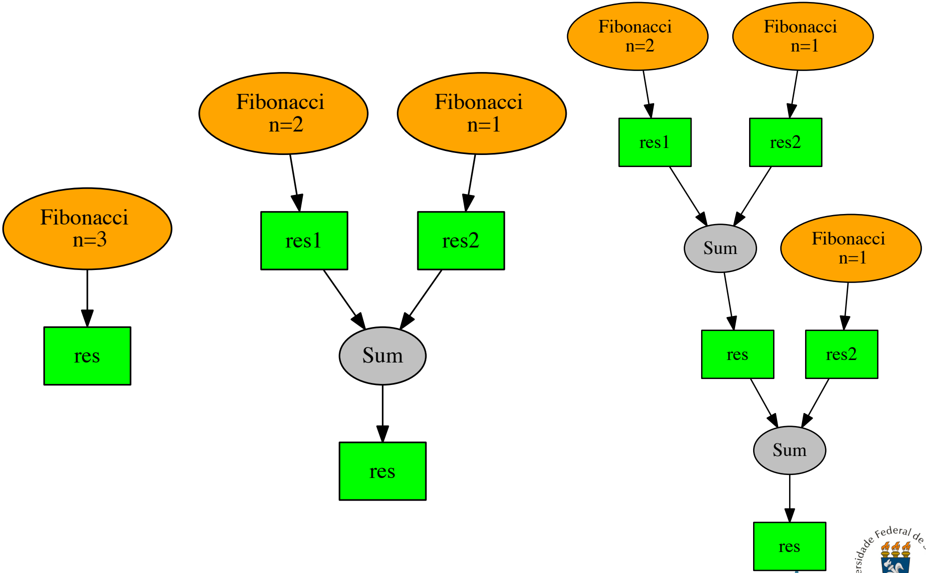

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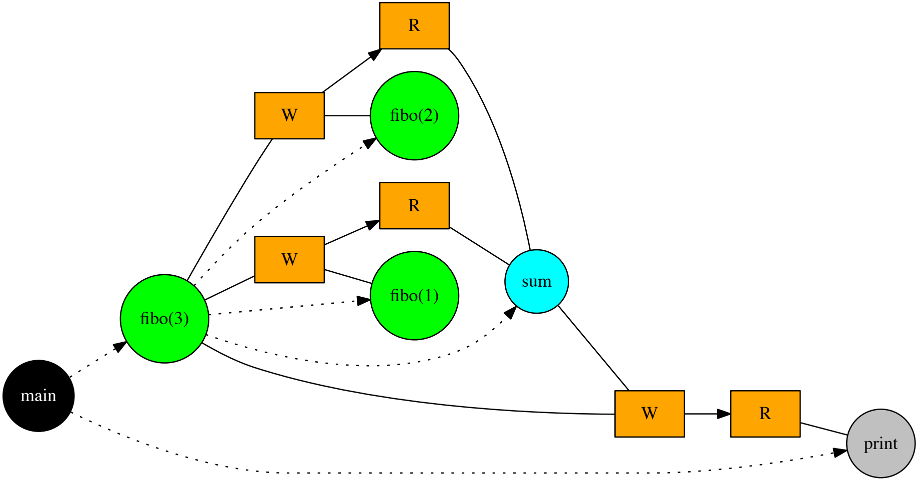
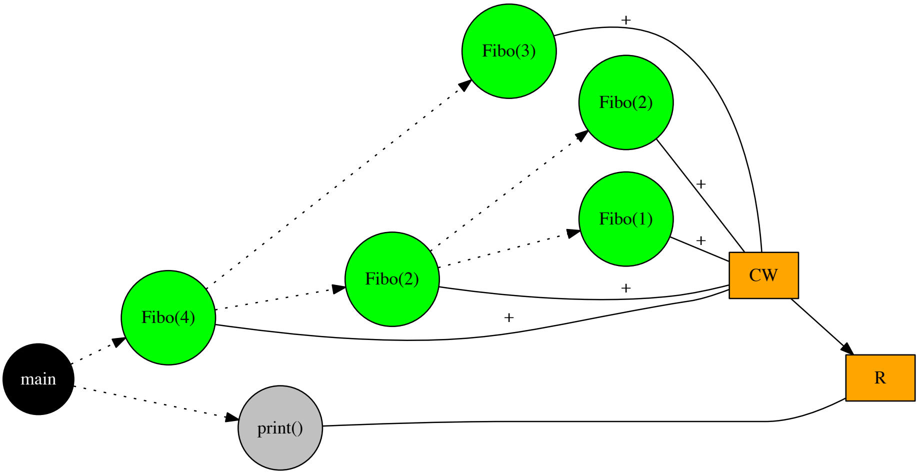
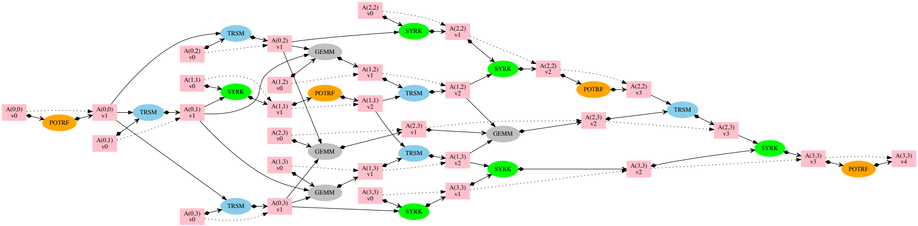


DFG of Fibonacci $n = 3$ (cumulative)



DFG of Cholesky factorization



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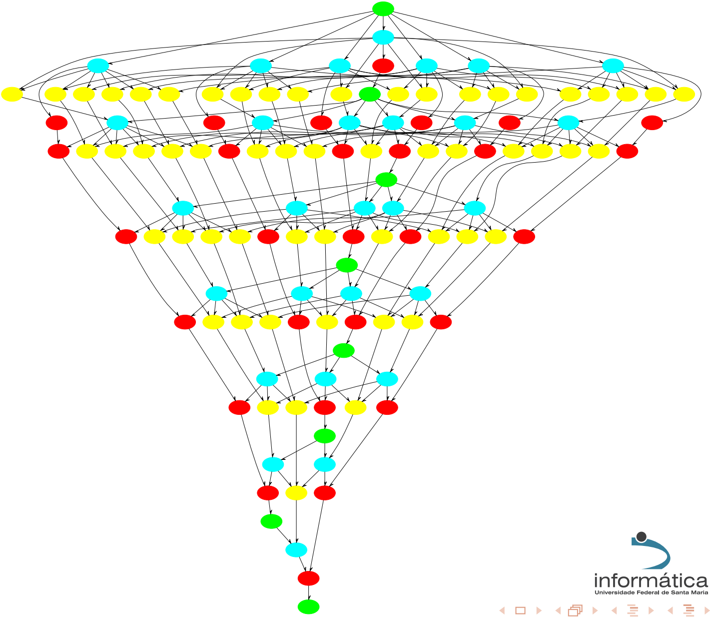
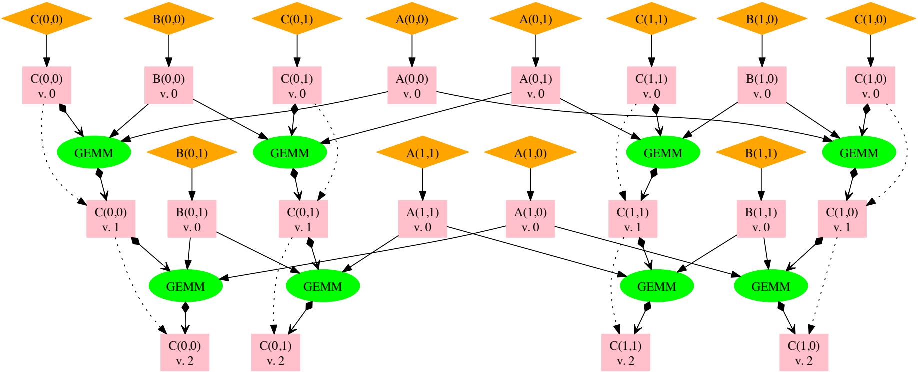


DFG of Blocked matrix multiplication



Dependências de Dados

- OpenMP 4.0 inclui dependências de dados entre tarefas (`task`)
- Diretiva `depend`
  - `in` – dados de entrada
  - `out` – dados de saída
  - `inout` – dados de entrada e saída
  - `depobj` – dependencias manuais (`omp_depend_t`)
- Sincronização recursiva pela construção `taskgroup`
  - Sincroniza um bloco de código
  - `taskwait` sincroniza tarefas criadas no mesmo nível

```
#pragma omp taskgroup
{
  #pragma omp task depend(in:dados) depend(out:saida)
  foo(dados, saida);
}
```

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  - `depobj` – dependencias manuais (`omp_depend_t`)
- Sincronização recursiva pela construção `taskgroup`
  - Sincroniza um bloco de código
  - `taskwait` sincroniza tarefas criadas no mesmo nível

```
#pragma omp taskgroup
{
  #pragma omp task depend(in:dados) depend(out:saida)
  foo(dados, saida);
}
```

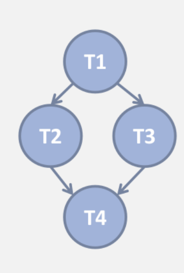
Dependências de Dados

```
int x = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x) // T1
  { .... }

  #pragma omp task depend(in: x) // T2
  { .... }

  #pragma omp task depend(in: x) // T3
  { .... }

  #pragma omp task depend(inout: x)  // T4
  { .... }
}
```



Dependências de Dados

Fibonacci com OpenMP `depend`

```
int fib( int n ) {
  int x, y;
  if( n < 2 ) return n;
  #pragma omp taskgroup
  {
    #pragma omp task shared(x) depend(in:n) depend(out:x)
    x = fib( n - 1);
    #pragma omp task shared(y) depend(in:n) depend(out:y)
    y = fib( n - 2);
  }
  return x + y;
}
```

Dependências de Dados

Espera por dados com `taskwait`

```
int x = 0, y = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x)
  x++;

  #pragma omp task depend(in: y)
  std::cout << y << std::endl;

  #pragma omp taskwait depend(in: x)
  std::cout << x << std::endl;
}
```

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Dependências de Dados

- Dependências manuais com `depobj`
- Permite dependências complexas.
- Novo tipo opaco `omp_depend_t`

```
int x = 0, y = 0;
#pragma omp parallel
#pragma omp single
{
  omp_depend_t obj;
  #pragma omp depobj(obj) depend(inout: x)

  #pragma omp task depend(depobj: obj) // T1
  x++;

  #pragma omp depobj(obj) update(in)

  #pragma omp task depend(depobj: obj) // T2
  std::cout << y << std::endl;

  #pragma omp depobj(obj) destroy
}
```

Multiplicação de matrizes $C = AxB + C$

```c
void gemm_omp(double *A, double *B, double *C, int n)
{
  #pragma omp parallel
  {
    int i, j, k;
    #pragma omp for
    for (i = 0; i < n; i++) {
        for (j = 0; j < n; j++) {
            for (k = 0; k < n; k++) {
                C[i*n+j ] += A[i*n+k]*B[k*n+j];
            }
        }
    }
  }
}
```

Dependências de Dados

Multiplicação de matrizes $C = AxB + C$

```
void matmul(int NB, float A[NB][NB], float B[NB][NB], float
 ↪  C[NB][NB])
{
#pragma omp parallel
#pragma omp single
{
  for(int i = 0; i < NB; i++)
    for(int j = 0; j < NB; j++)
      for(int k = 0; k < NB; k++)
#pragma omp task depend(in:A[i][k],B[k][j])
 ↪  depend(inout:C[i][j])
        matmul_tile( A[i][k], B[k][j], C[i][j] );
  }
}
```

https://joao-ufsm.github.io/par2023a/