Do we need dataflow programming?

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Programming vs Execution

- ✓Dataflow based execution
  - ✓Think ILP, Out of order execution
  - ✓Automatically derived by hardware/compiler/etc
- ✓Dataflow programming
  - ✓Think Workflows
  - ✓Flow of data **explicitly** specified by human

Task-based vs Dataflow-based

Is task execution the same thing?

OpenMP

StarPU

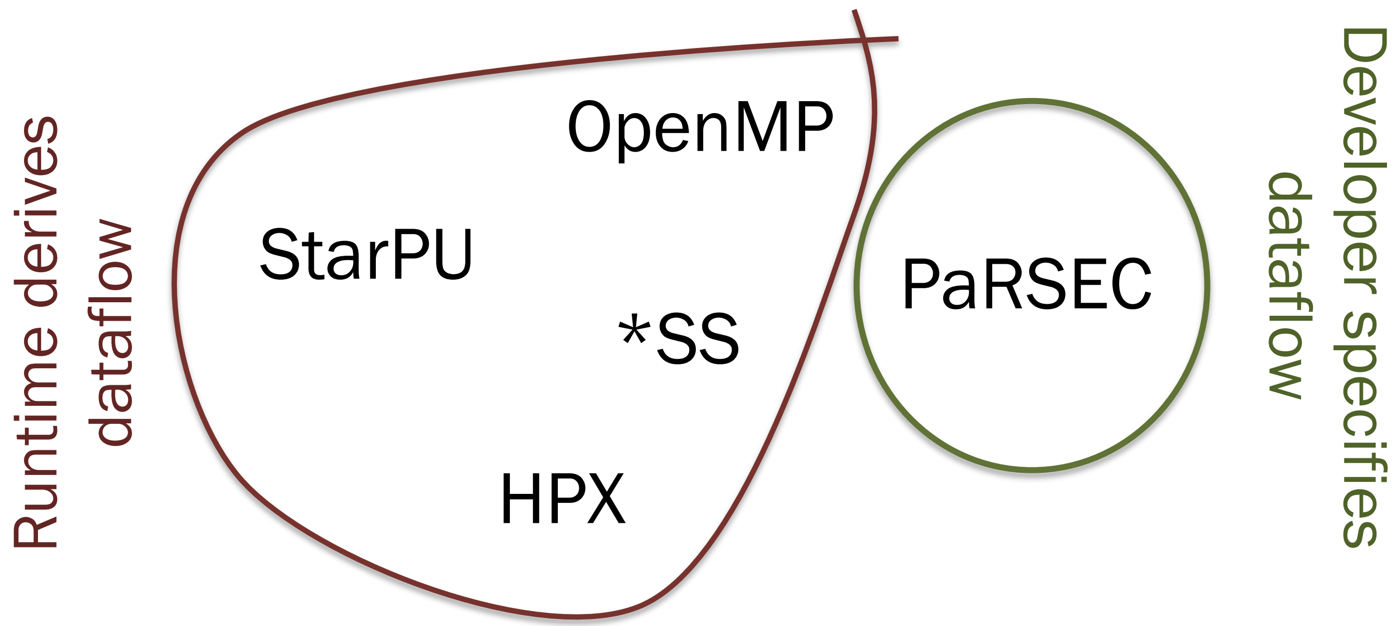
PaRSEC

*SS

HPX

Task-based vs Dataflow-based

Is task execution the same thing?



Limits of deriving the dataflow

```
P: nodes
N: number of kernel executions
Tk: kernel execution time
To: overhead of discovery

To*N << Tk*N/P =>
To*N <= 0.1*Tk*N/P =>
P <= 0.1*Tk/To

To = 100ns, Tk = 100us => P <= 100
```

Explicit Dataflow Programming

Why does Explicit Dataflow Programming (EDP) differ from everything else?

The human developer explicitly expresses the semantics of the algorithm/application in a way that the runtimes/compilers can directly take advantage of without deriving information.

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The human developer explicitly expresses the semantics of the algorithm/application in a way that the runtimes/compilers can directly take advantage of without deriving information.

Benefits:

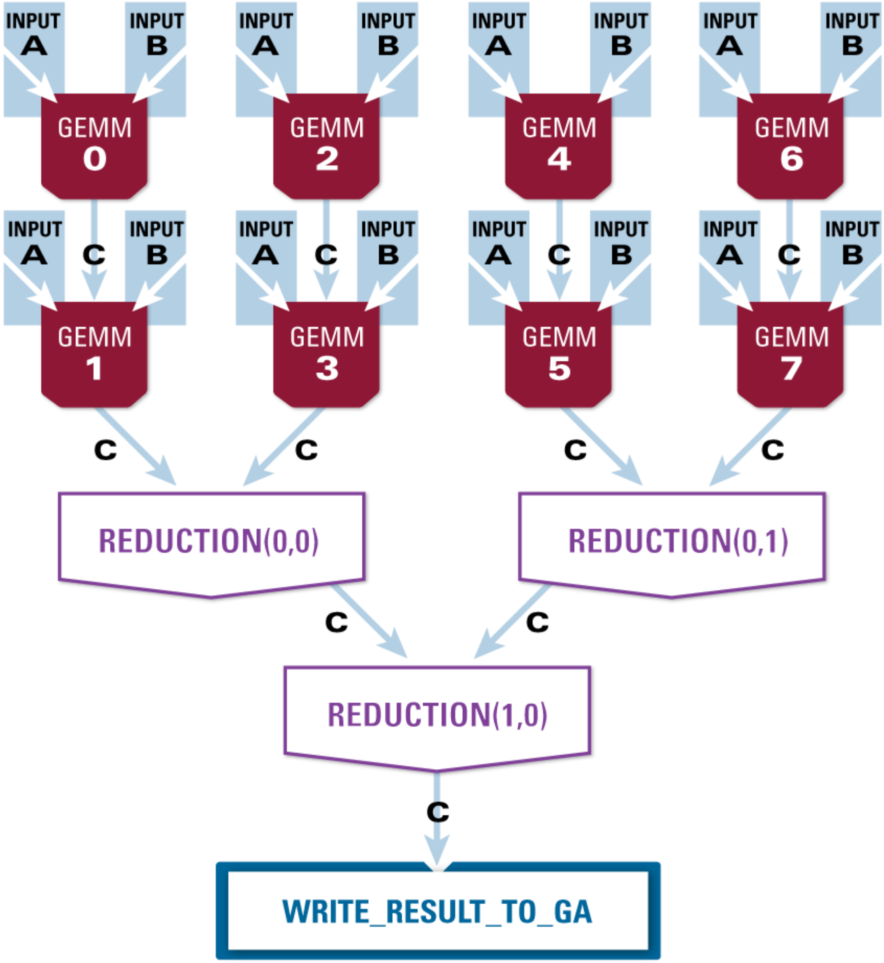
Perfect Parallelism, Automatic Comm./Comp. overlap, Collective operation detection.

Perf. Case study: NWChem CCSD

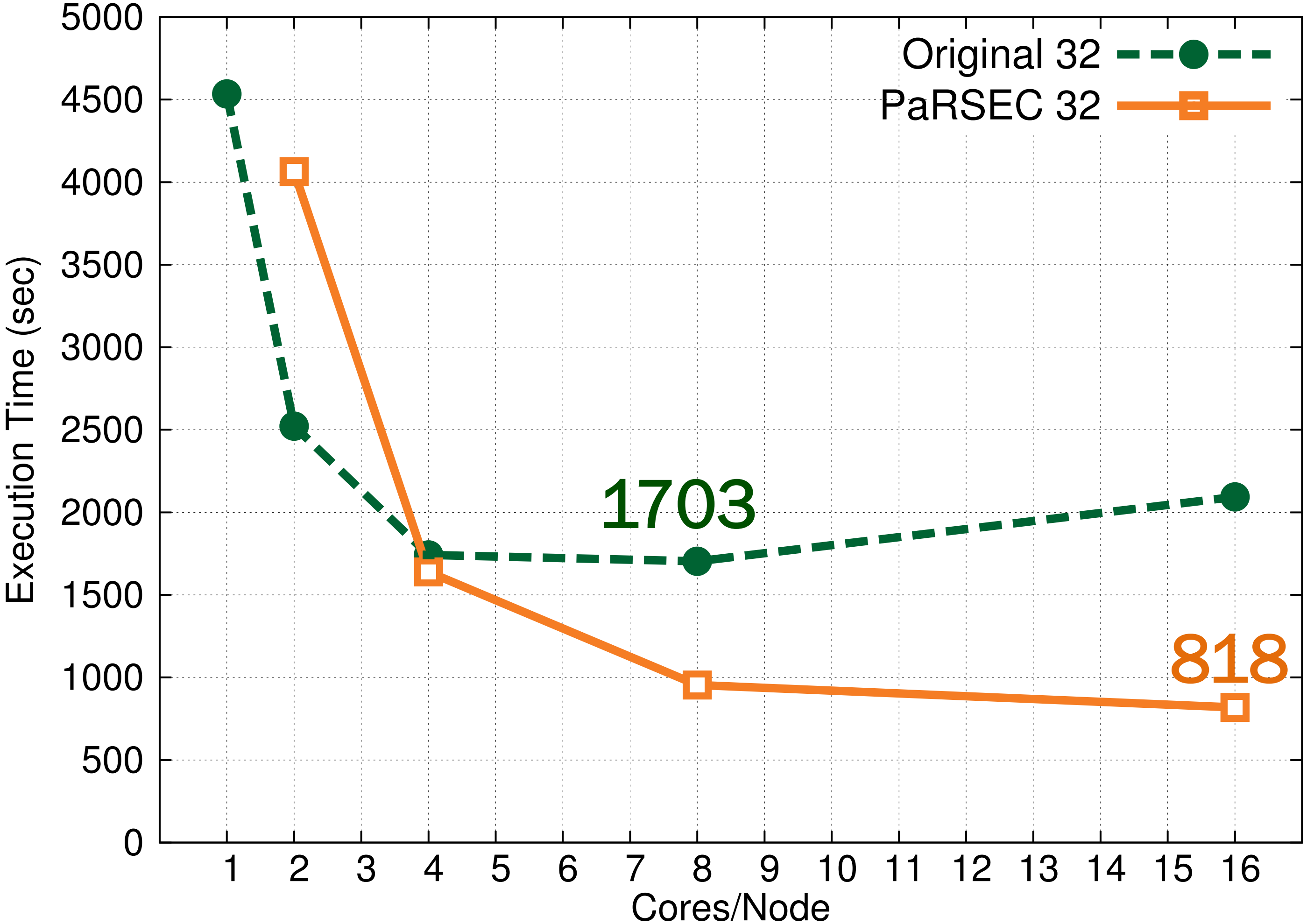
```
DO {x4}
  CALL nxt_ctx_next(ctx, icounter, next)          Global work stealing
  IF ( (int_mb(...)+...).ne.8 ) THEN
    CALL MA_PUSH_GET()                            Allocate and initialize C
    CALL DFILL()
    DO {x2}
      IF ( (int_mb(...)+... .eq. int_mb(...) ) THEN
        CALL MA_PUSH_GET(...,k_a)                 Allocate and fetch A
        CALL GET_HASH_BLOCK(d_a, dbl_mb(k_a), ...)  (same for B, not shown)

        CALL DGEMM(...)                           Actual work
      END IF
    END DO
    CALL TCE_SORT_4(dbl_mb(k_c), ...)
    CALL ADD_HASH_BLOCK(d_c, dbl_mb(k_c), ...)    Push C back
END DO
```

Structure of PTG computation



CCSD Execution Time on 32 nodes

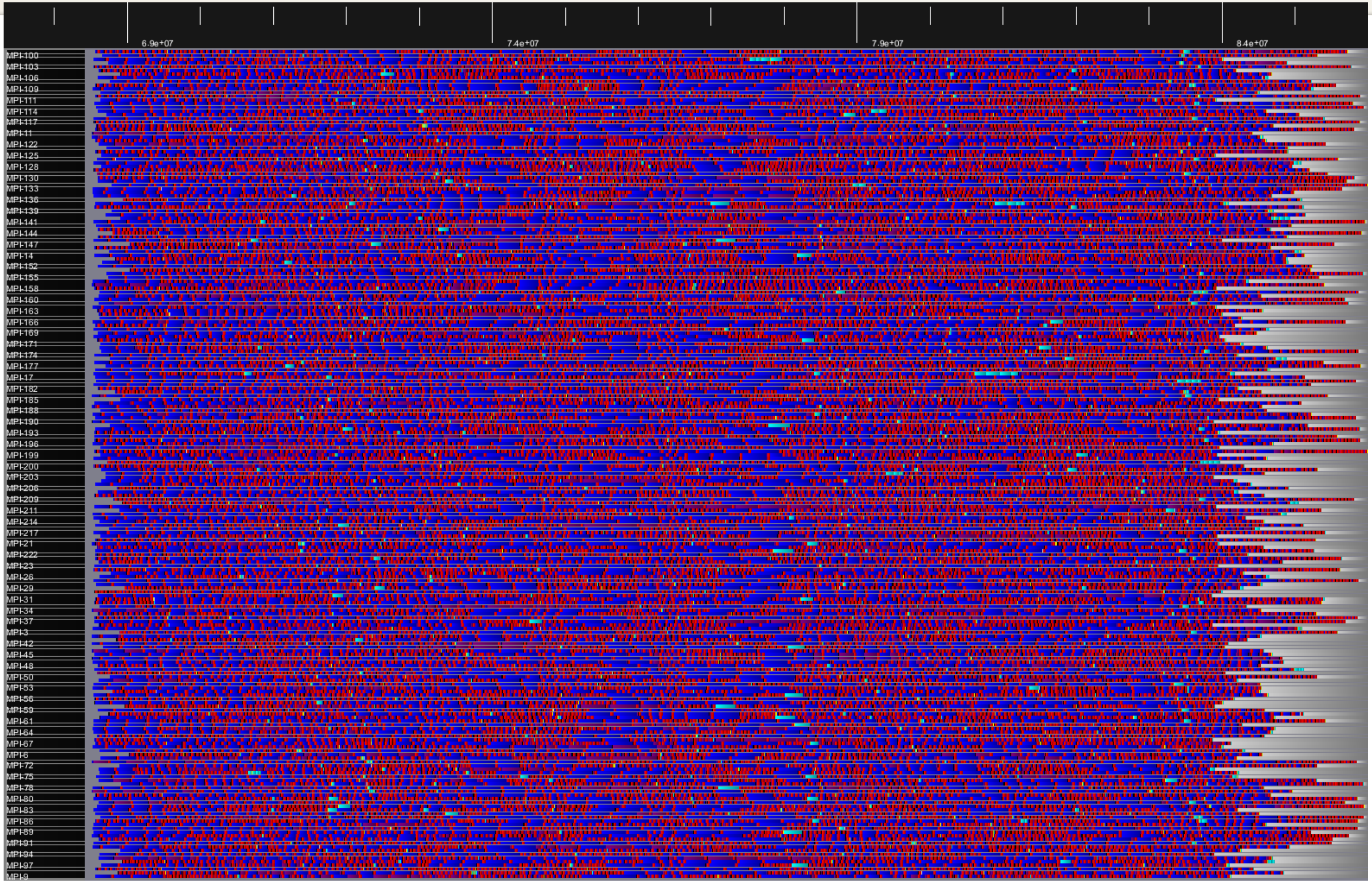


Performance bottlenecks

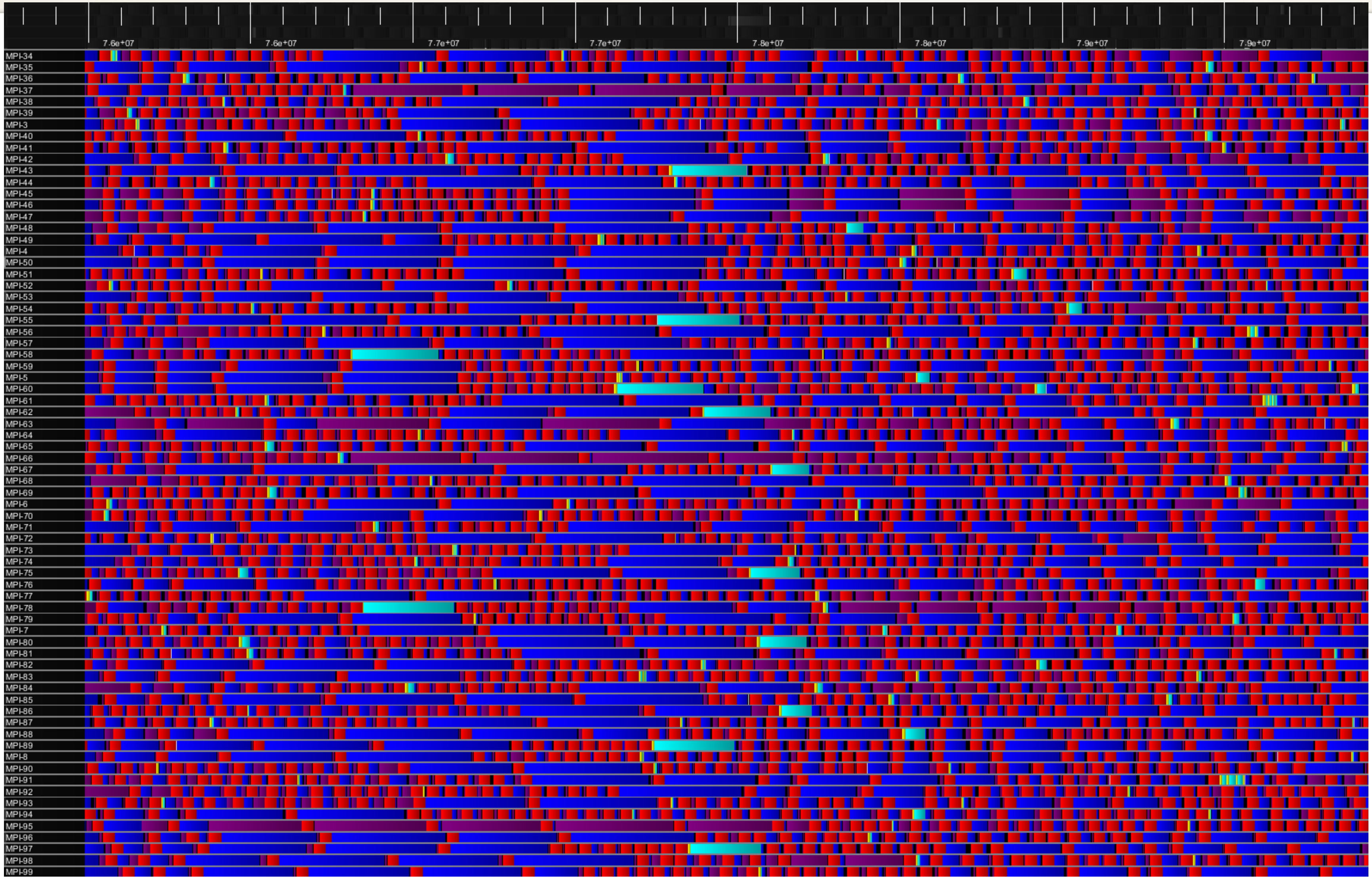
```
DO {x4}
 CALL nxt_ctx_next(ctx, icounter, next)
 IF ( (int_mb(...)+...).ne.8 ) THEN
  CALL MA_PUSH_GET()
  CALL DFILL()
  DO {x2}
    IF ( (int_mb(...)+... .eq. int_mb(...) ) THEN
      CALL MA_PUSH_GET(...,k_a)
      CALL GET_HASH_BLOCK(d_a, dbl_mb(k_a), ...)
      CALL DGEMM(...)
    END IF
  END DO
  CALL TCE_SORT_4(dbl_mb(k_c), ...)
  CALL ADD_HASH_BLOCK(d_c, dbl_mb(k_c), ...)
END DO
```

1. Global atomic
2. Coarse grain parallelism
3. No opportunity for comm/comp overlap

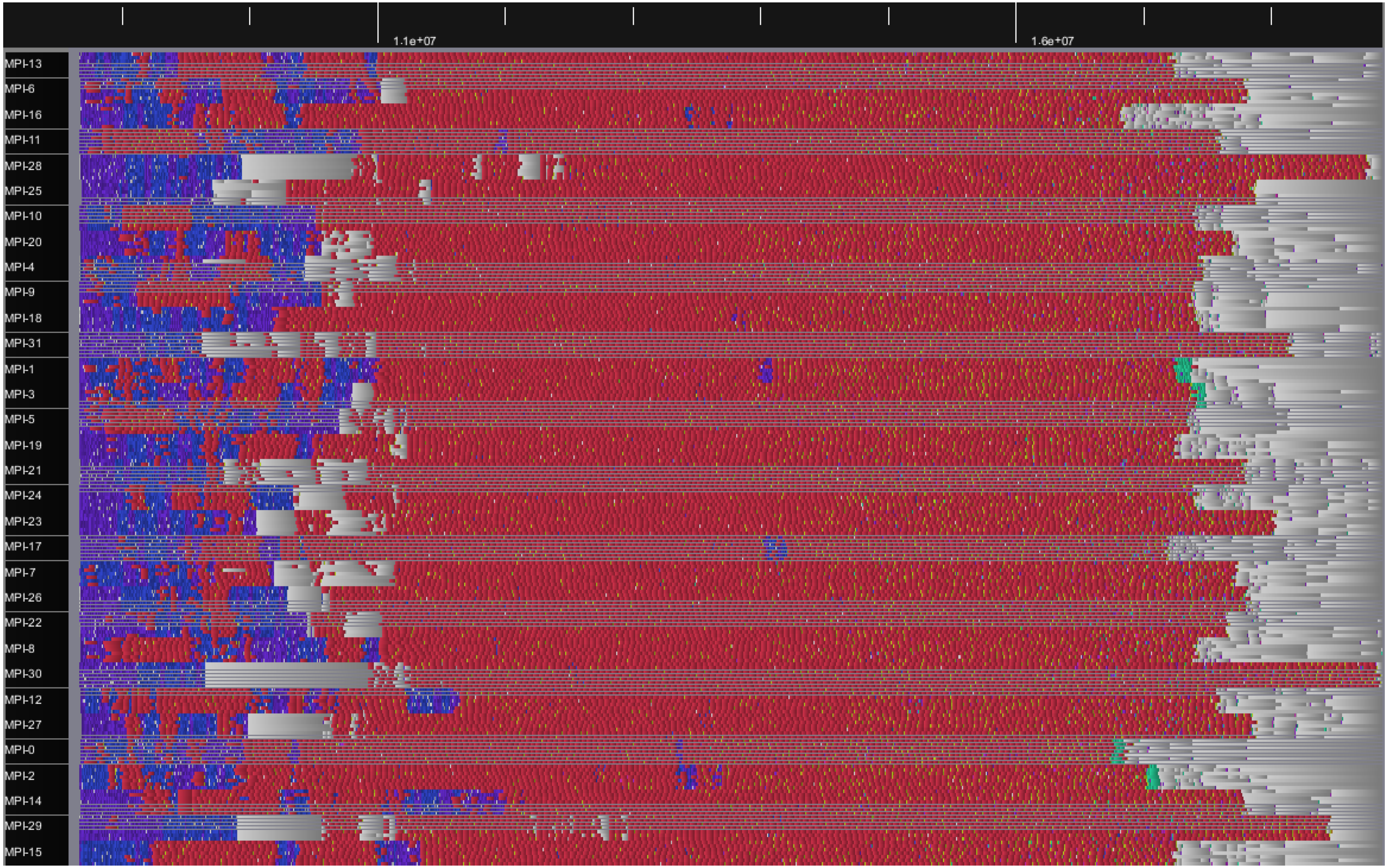
Trace of Original code



Trace of Original code (zoom)



Trace of PaRSEC implementation



Whose fault is the bad performance?

Audience participation. Choose who to blame:

- MPI
- Developers
- Programming paradigm (Coarse Grain Parallelism)
- Vetter (for not telling his users about dataflow)

Whose fault is it?

Audience participation. Choose who to blame:

- MPI
- Developers
- Programming paradigm (Coarse Grain Parallelism)
- Vetter (for not telling his users about dataflow)

MPI has a simple and an advanced API and many developers use only the simple one.
- Rusty

Message so far

- Using CGP does <u>not</u> scale
- Using Dataflow execution <u>does</u>
- BUT, developers have to understand their code

Sure, but can we make EDP easy?

Can we make dataflow <u>execution</u> harness all the benefits without explicit dataflow <u>programming</u>?

Sure, but can we make EDP easy?

Can we make dataflow <u>execution</u> harness all the benefits without explicit dataflow <u>programming</u>?

Yes, we can. In some cases. Maybe?

Bridging Explicit & Implicit dataflow

✓Reduce the cost of discovery

- Code specialization
  - Developer expertise
  - Results of compiler analysis

✓Harness benefits of parametric representation

- Compress the Graph on the fly
  - Detect patterns in series that translate to expressions, or functions
  - Use compiler inserted hints

Reduce the unnecessary discovery

```
DO {x4}
  CALL nxt_ctx_next(ctx, icounter, next)
  IF ( (int_mb(...)+...).ne.8 ) THEN
    CALL MA_PUSH_GET()
    CALL DFILL()
    DO {x2}
      IF ( (int_mb(...)+... .eq. int_mb(...) ) THEN
        CALL MA_PUSH_GET(...,k_a)
        CALL GET_HASH_BLOCK(d_a, dbl_mb(k_a), ...)
        CALL DGEMM(...)
      END IF
    END DO
    CALL TCE_SORT_4(dbl_mb(k_c), ...)
    CALL ADD_HASH_BLOCK(d_c, dbl_mb(k_c), ...)
END DO
```

Insert_Task

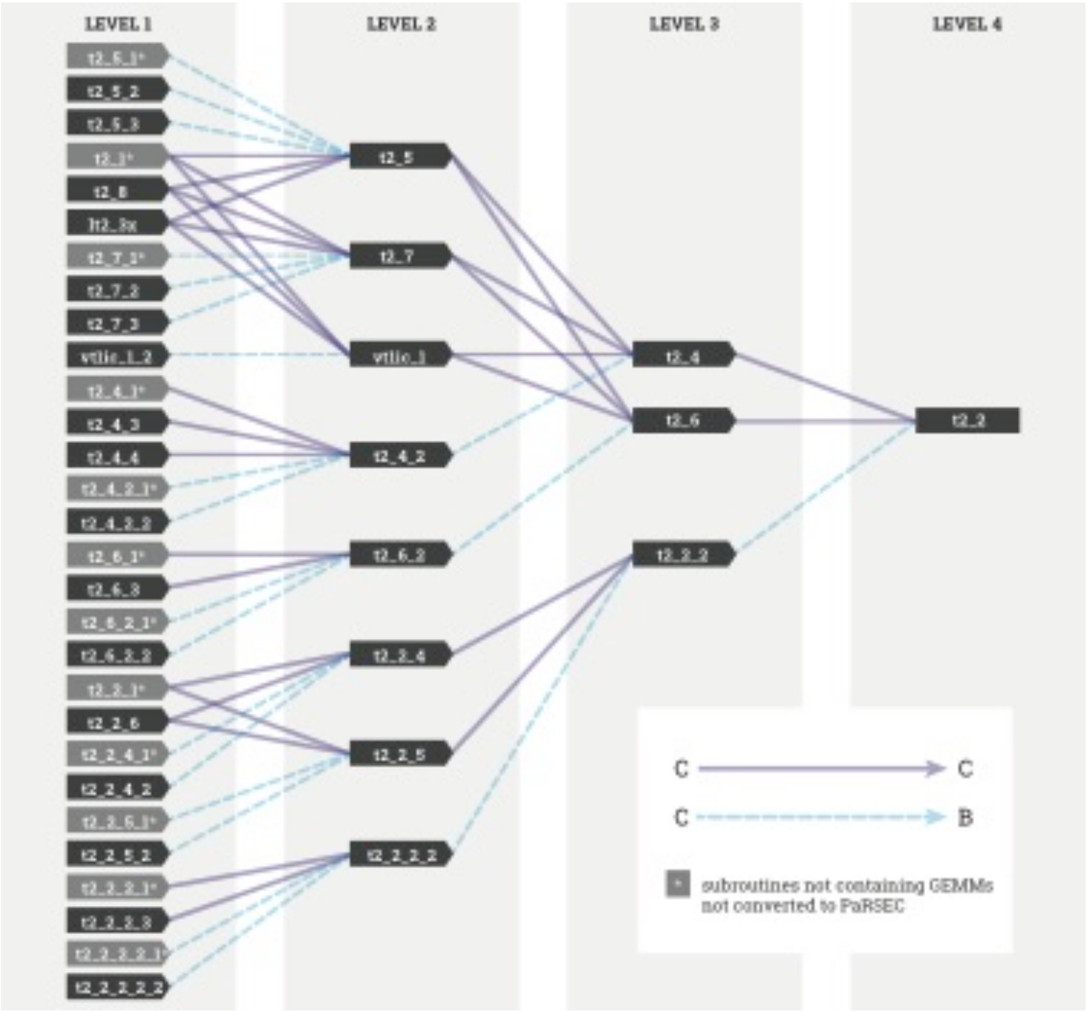
Reduce the unnecessary discovery

```
DO {x4}
  CALL nxt_ctx_next(ctx, icounter, next)
  IF ( (int_mb(...)+...).ne.8 ) THEN
    CALL MA_PUSH_GET()                          <- Handle Generation
    CALL DFILL()
    DO {x2}
      IF ( (int_mb(...)+... .eq. int_mb(...) ) THEN
        CALL MA_PUSH_GET(...,k_a)               <- Handle Generation
        CALL GET_HASH_BLOCK(d_a, dbl_mb(k_a), ...)  <- Data Fetching
        CALL DGEMM(...)                         <- Insert_Task
      END IF
    END DO
    CALL TCE_SORT_4(dbl_mb(k_c), ...)
    CALL ADD_HASH_BLOCK(d_c, dbl_mb(k_c), ...)  <- Data Flushing
END DO
```

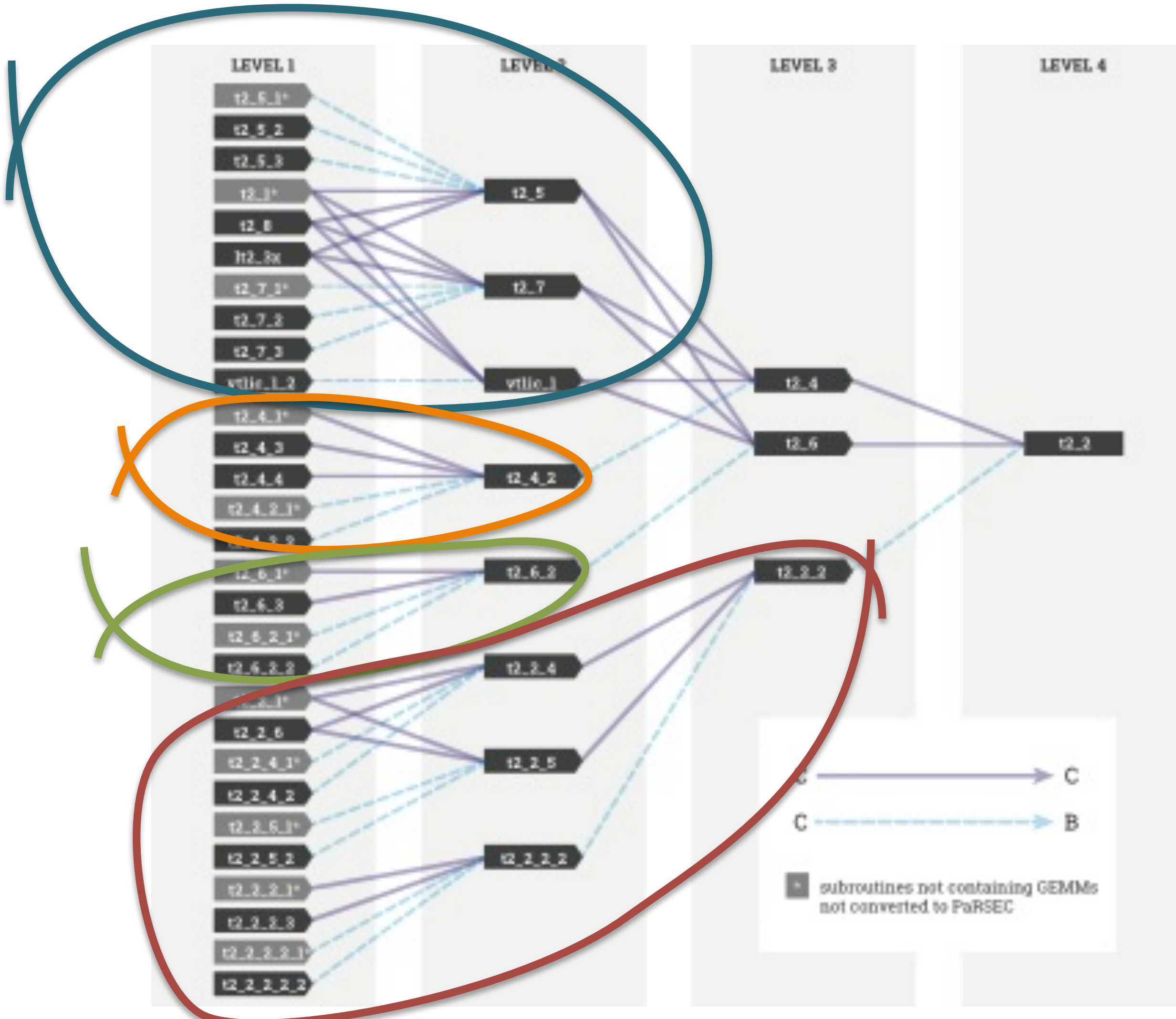
Reduce the unnecessary discovery

```
DO {x4}                                            Pleasantly Parallel
  CALL nxt_ctx_next(ctx, icounter, next)
  IF ( (int_mb(...)+...).ne.8 ) THEN
    CALL MA_PUSH_GET()                             Handle Generation
    CALL DFILL()
    DO {x2}
      IF ( (int_mb(...)+... .eq. int_mb(...) ) THEN
        CALL MA_PUSH_GET(...,k_a)                  Handle Generation
        CALL GET_HASH_BLOCK(d_a, dbl_mb(k_a), ...) Data Fetching
        CALL DGEMM(...)                            Insert_Task
      END IF
    END DO
    CALL TCE_SORT_4(dbl_mb(k_c), ...)
    CALL ADD_HASH_BLOCK(d_c, dbl_mb(k_c), ...)     Data Flushing
END DO
```

Dataflow between subroutines



Code grouping based on dataflow



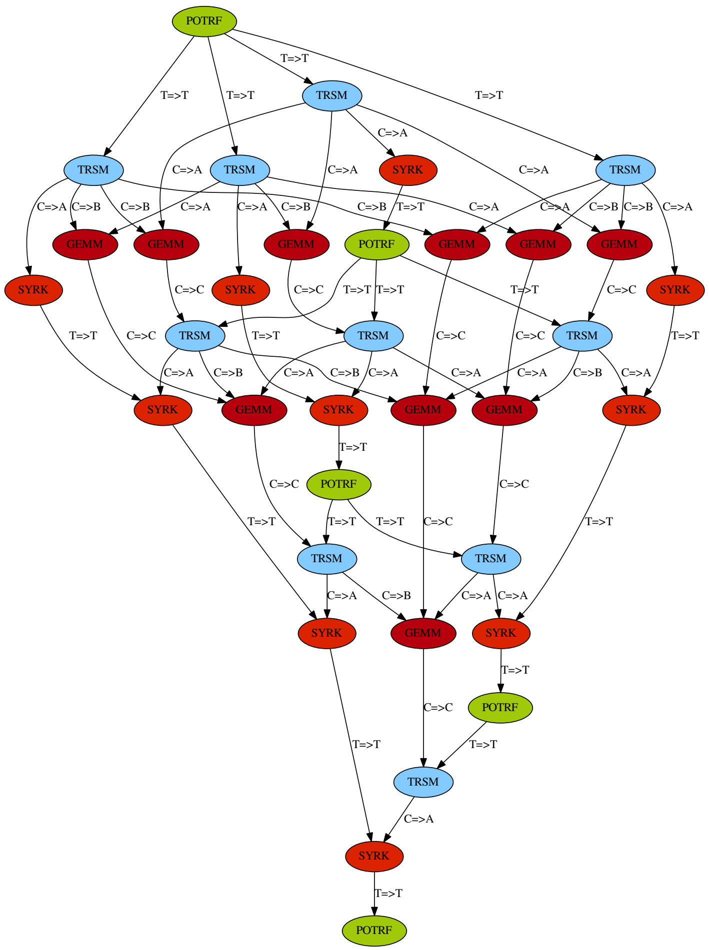
Message so far

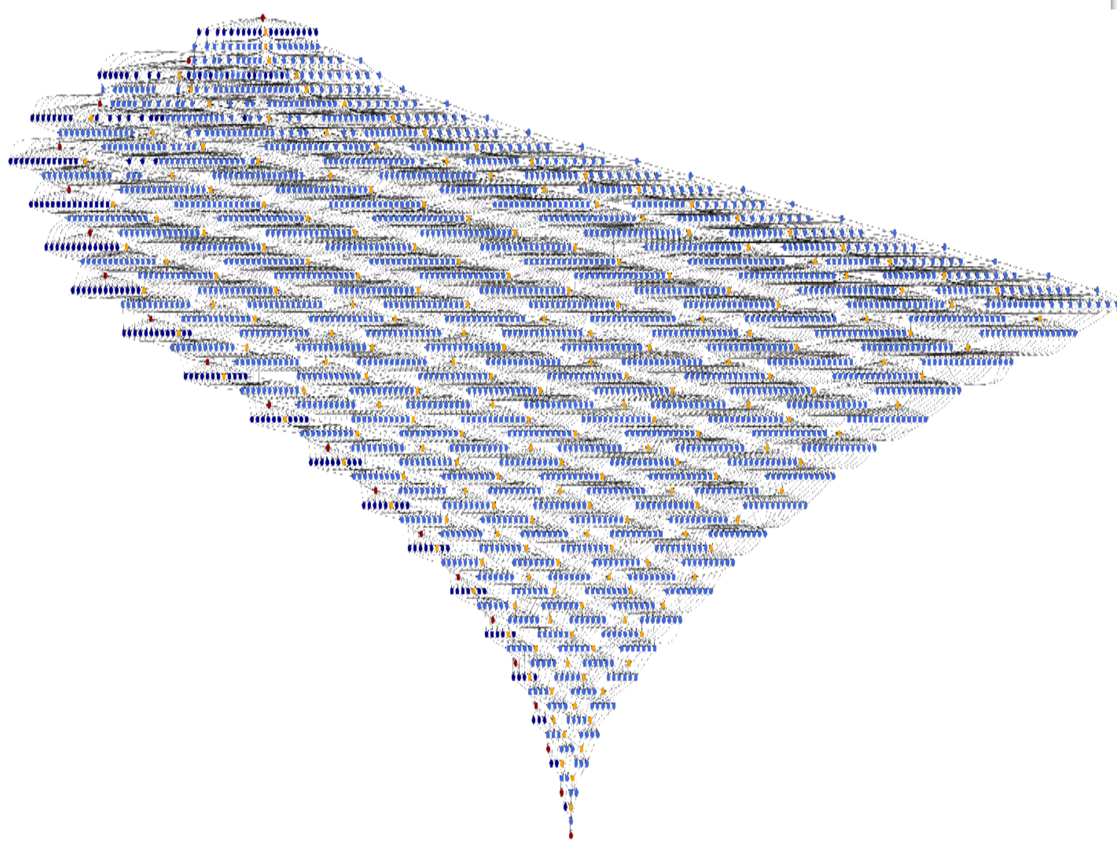
- Discovering the whole DAG does <u>not</u> scale
- Pruning the DAG requires human expertise
- Compiler analysis can assist with pruning
- BUT, developers have to understand their code

Compressing the DAG to a PTG?

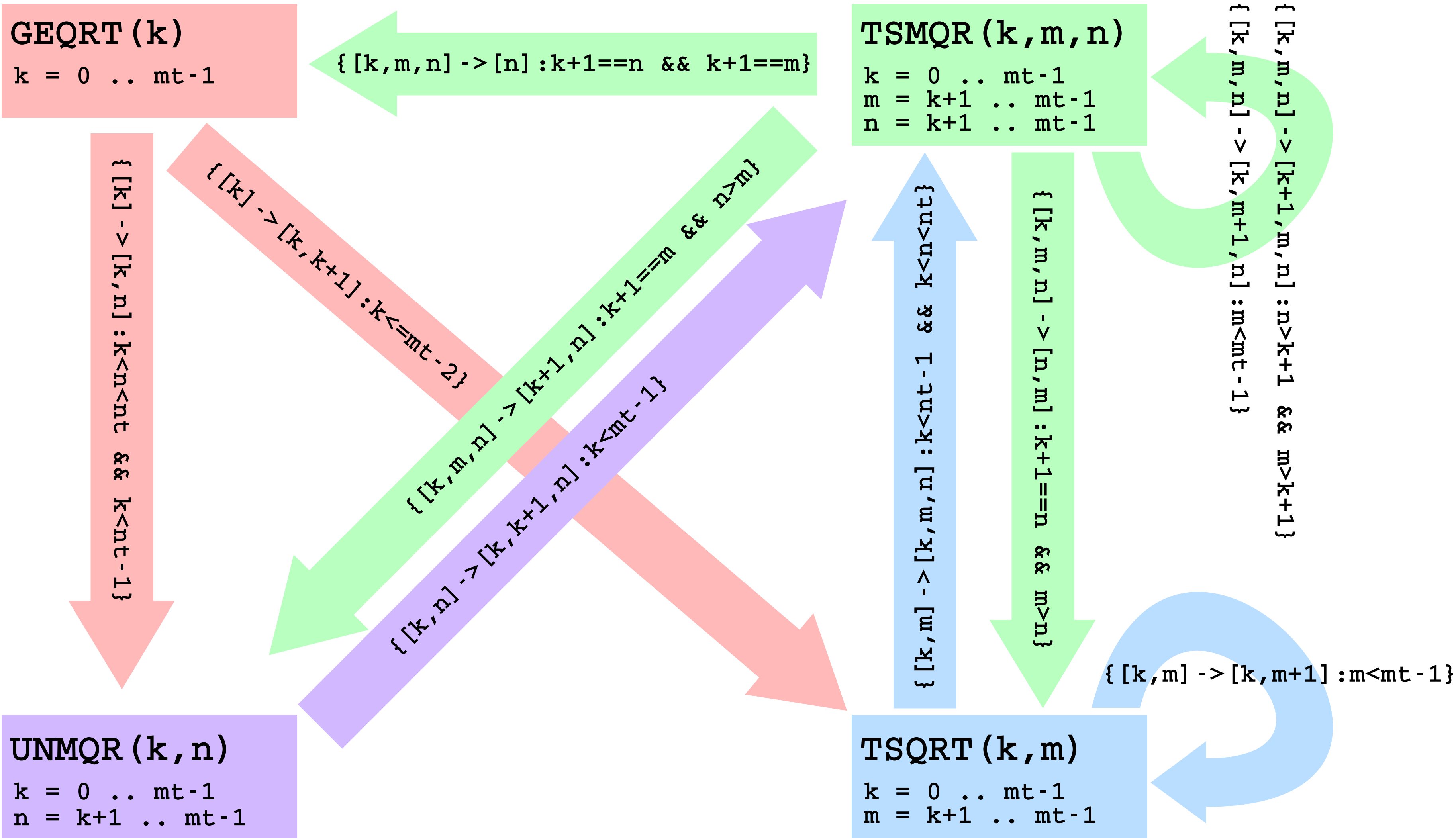
```
for (k = 0; k < MT; k++) {
    Insert_Task( zgeqrt,  A[k][k], INOUT,  T[k][k], OUTPUT);
    for (m = k+1; m < MT; m++) {
        Insert_Task( ztsqrt,  A[k][k], INOUT | REGION_D|REGION_U,
                              A[m][k], INOUT | LOCALITY,
                              T[m][k], OUTPUT);
    }
    for (n = k+1; n < NT; n++) {
        Insert_Task( zunmqr,  A[k][k], INPUT | REGION_L,
                              T[k][k], INPUT,
                              A[k][n], INOUT);
        for (m = k+1; m < MT; m++) {
            Insert_Task( ztsmqr, A[k][n], INOUT,
                                 A[m][n], INOUT | LOCALITY,
                                 A[m][k], INPUT,
                                 T[m][k], INPUT);
```

What does a DAG look like?





Fully compressed DAG (PTG)



Compressing the DAG to a PTG?

```
for (k = 0; k < MT; k++) {
    Insert_Task( zgeqrt,  A[k][k],                     );
    for (m = k+1; m < MT; m++) {
        Insert_Task( ztsqrt,  A[k][                    GION_U,
                              A[m][
                              T[m][
    }
    for (n = k+1; n < NT; n++) {
        Insert_Task( zunmqr,  A[k][
                              T[k][
                              A[k][n], INOUT);
        for (m = k+1; m < MT; m++) {
            Insert_Task( ztsmqr, A[k][n], INOUT,
                                 A[m][n], INOUT | LOCALITY,
                                 A[m][k], INPUT,
                                 T[m][k], INPUT);
```

Task_A
Task_B
Task_B
Task_B
Task_C
Task_D
Task_D
Task_D
...

Compressing the DAG to a PTG?

```
for (k = 0; k < MT; k++) {
    Insert_Task( zgeqrt,  A[k][k], 
    for (m = k+1; m < MT; m++) {
        Insert_Task( ztsqrt,  A[k][                             GION_U,
                              A[m][
                              T[m][
    }
    for (n = k+1; n < NT; n++) {
        Insert_Task( zunmqr,  A[k][
                              T[k][
                              A[k][n], INOUT);
        for (m = k+1; m < MT; m++) {
            Insert_Task( ztsmqr, A[k][n], INOUT,
                                 A[m][n], INOUT | LOCALITY,
                                 A[m][k], INPUT,
                                 T[m][k], INPUT);
```

Task_A
Task_B
Task_B
Task_B
Task_C
Task_D
Task_D
Task_D
...

Compressing the DAG to a PTG?

```
for (k = 0; k < MT; k++) {
    Insert_Task( zgeqrt,  A[k][k], 
    for (m = k+1; m < MT; m++) {
        Insert_Task( ztsqrt,  A[k][
                              A[m][
                              T[m][
    }
    for (n = k+1; n < NT; n++) {
        Insert_Task( zunmqr,  A[k][k], INPUT | REGION_L,
                              T[k][k], INPUT,
                              A[k][n], INOUT);
        for (m = k+1; m < MT; m++) {
            Insert_Task( ztsmqr, A[k][n], INOUT,
                                 A[m][n], INOUT | LOCALITY,
                                 A[m][k], INPUT,
                                 T[m][k], INPUT);
```

GION_U,

);

Task_A
Task_B
Task_B
Task_B
Task_C
Task_D(1-3)
...

Compressing the DAG to a PTG?

```
for (k = 0; k < MT; k++) {
    Insert_Task( zgeqrt,  A[k][k], INOUT,  T[k][k], OUTPUT);
    for (m = k+1; m < MT; m++) {
        Insert_Task( ztsqrt,  A[k][k], INOUT | REGION_D|REGION_U,
                              A[m][k], INOUT | LOCALITY,
                              T[m][k], OUTPUT);
    }
    for (n = k+1; n < NT; n++) {
        Insert_Task( zunmqr,  A[k][k], INPUT | REGION_L,
                              T[k][k], INPUT,
                              A[k][n], INOUT);
        for (m = k+1; m < MT; m++) {
            Insert_Task( ztsmqr, A[k][n], INOUT,
                                 A[m][n], INOUT | LOCALITY,
                                 A[m][k], INPUT,
                                 T[m][k], INPUT);
```

Iteration_vector(k,n,m)
Indices(A[k][n],k,n)

Compressing the DAG to a PTG?

```
for (k = 0; k < MT; k++) {
    Insert_Task( zgeqrt,  A[k][k],                               );
    for (m = k+1; m < MT; m++) {
        Insert_Task( ztsqrt,  A[k][                   GION_U,
                              A[m][
                              T[m][
    }
    for (n = k+1; n < NT; n++) {
        Insert_Task( zunmqr,  A[k][
                              T[k][
                              A[k][
        for (m = k+1; m < MT; m++)
            Insert_Task( ztsmqr, A[
                                 A[                   ,
                                 A[
                                 T[
```

Task_A
Task_B
Task_B
Task_B
Task_C
Task_D
Task_D
Task_D
Task_C
Task_D
Task_D
Task_D
Task_A
...

Compressing the DAG to a PTG?

```
for (k = 0; k < MT; k++) {
    Insert_Task( zgeqrt,  A[k][k],                            );
    for (m = k+1; m < MT; m++) {
        Insert_Task( ztsqrt,  A[k][                    GION_U,
                              A[m][
                              T[m][
    }
    for (n = k+1; n < NT; n++) {
        Insert_Task( zunmqr,  A[k][k], INPUT | REGION_L,
                              T[k][k], INPUT,
                              A[k][n], INOUT);
        for (m = k+1; m < MT; m++) {
            Insert_Task( ztsmqr, A[k][n], INOUT,
                                 A[m][n], INOUT | LOCALITY,
                                 A[m][k], INPUT,
                                 T[m][k], INPUT);
```

Task_A
Task_B
Task_B
Task_B
Task_C(k,n) k<m<MT
Task_D(k,n,m)
...

Conclusion

- ☺ Dataflow execution is more scalable than CGP
- ☺ Dataflow programming can maximize benefits
- ☹ Compilers cannot do it by themselves
  - ☹ Not even Torsten's compiler!
- ☹ Runtimes can, but at a cost

➢ Dataflow for the masses means sharing the load between developer, compiler and runtime.

Quotes

Developers know about their program much more than a compiler can ever figure out.

- Doug Miles

Let the human do what humans do best.

- Jeff Hollingsworth