LITHE

Composing Parallel Software Efficiently

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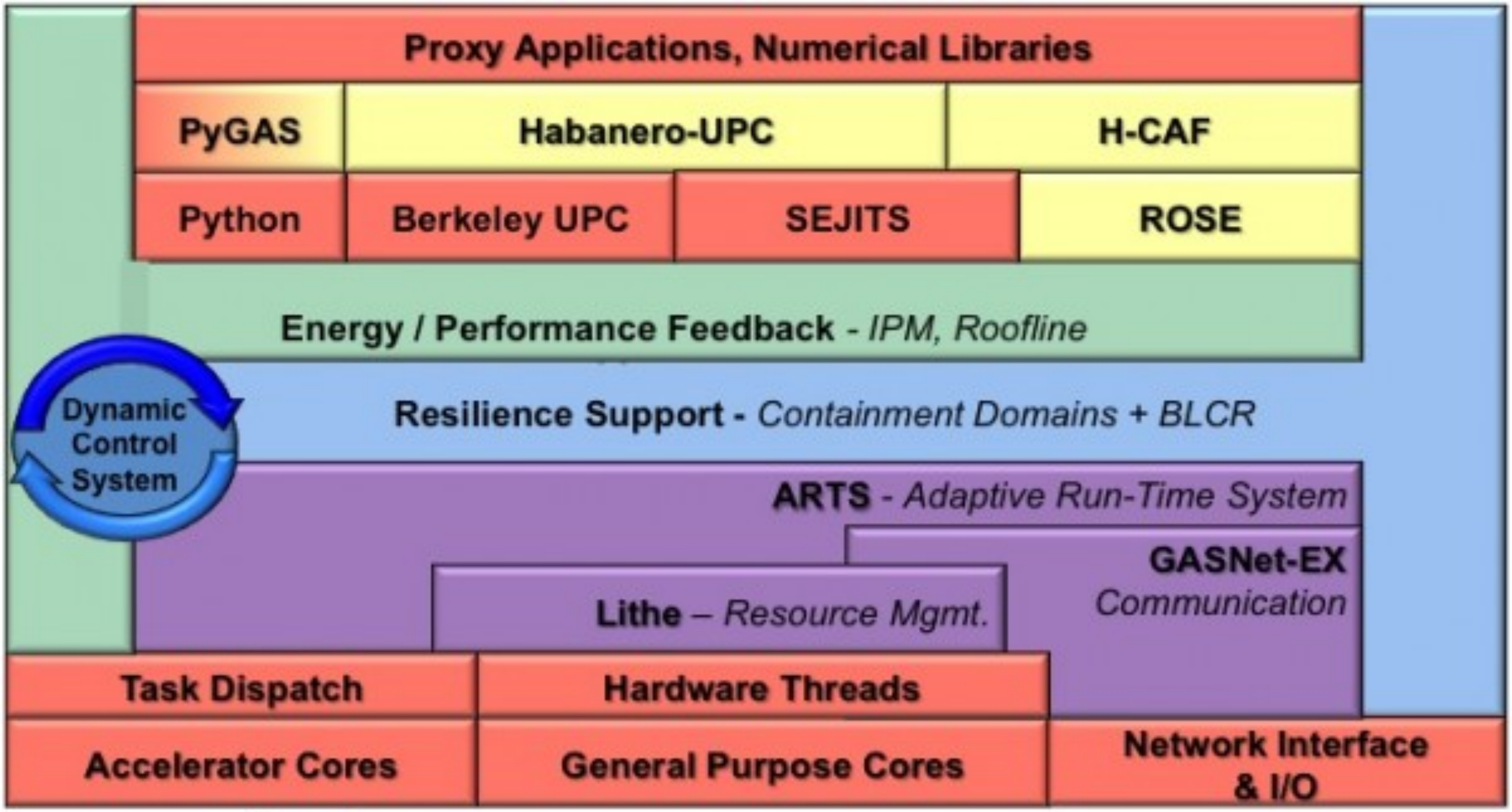
DEGAS Group Meeting
April 26th, 2013
http://lithe.eecs.berkeley.edu

Where Does Lithe Fit?



Proxy Applications, Numerical Libraries

PyGAS

Habanero-UPC

H-CAF

Python

Berkeley UPC

SEJITS

ROSE

Energy / Performance Feedback - *IPM, Roofline*

Dynamic Control System

Resilience Support - *Containment Domains + BLCR*

ARTS - *Adaptive Run-Time System*

GASNet-EX *Communication*

Lithe – *Resource Mgmt.*

Task Dispatch

Hardware Threads

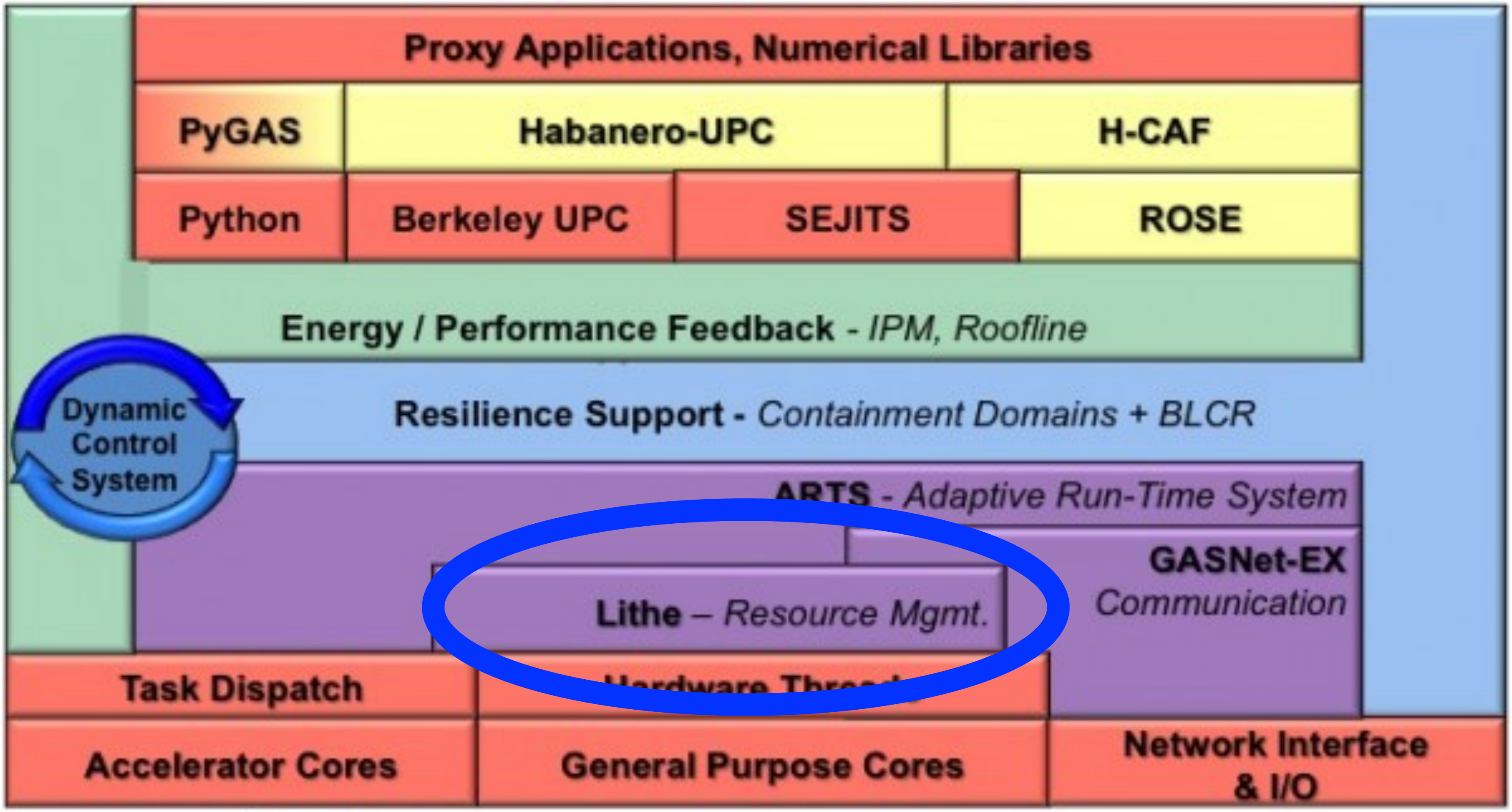
Accelerator Cores

General Purpose Cores

Network Interface & I/O

🟥 Activities funded outside of DEGAS

Where Does Lithe Fit?



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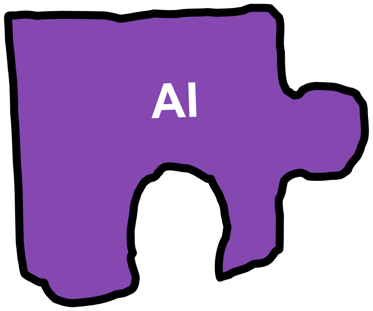
Composition is King

```
game()  {
   forall frames:
     AI.compute() ;





}
```



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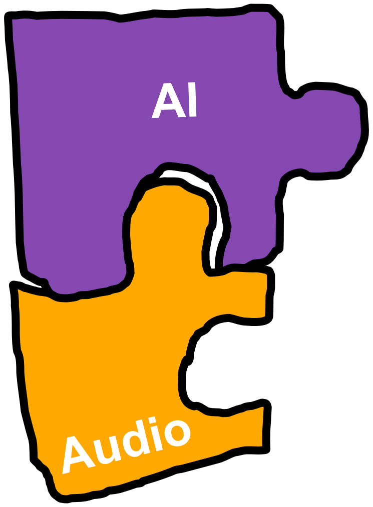

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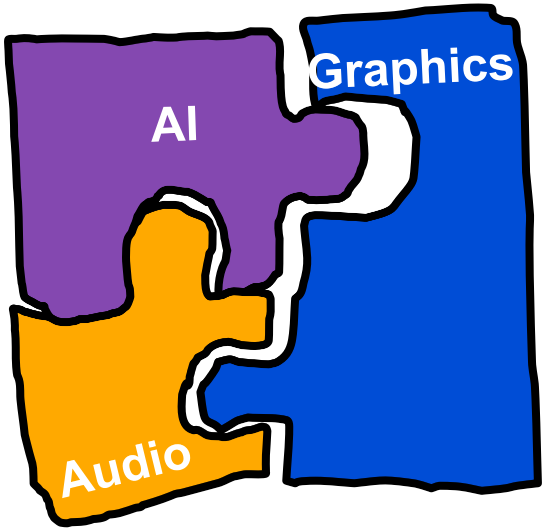

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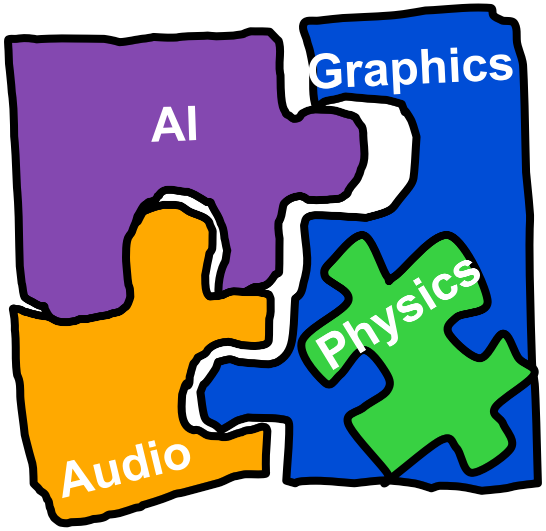

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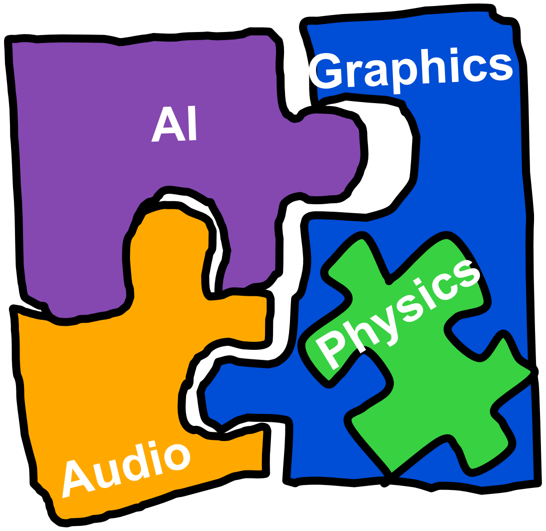

- **Productivity:** Don’t want to implement & understand everything.

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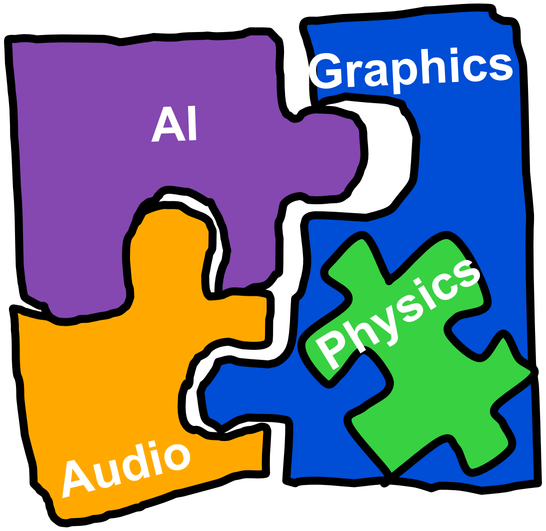

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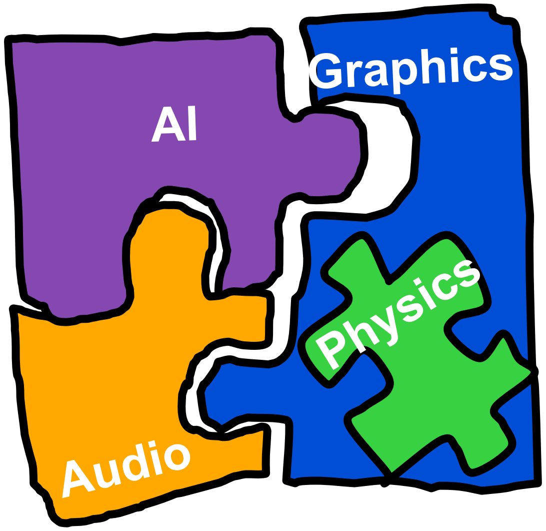

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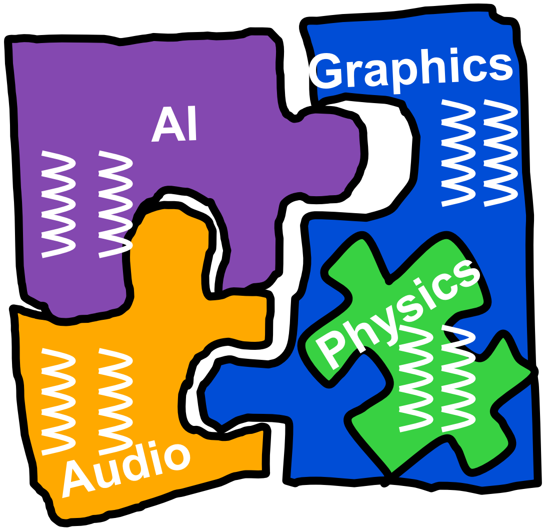

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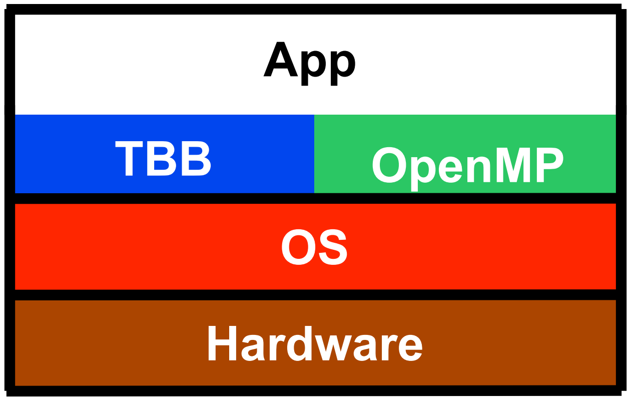
Multiple Components Oversubscribe Resources



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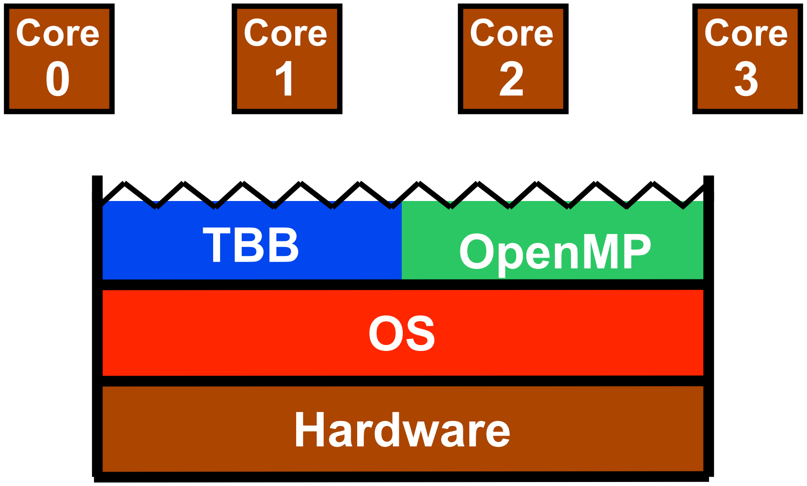

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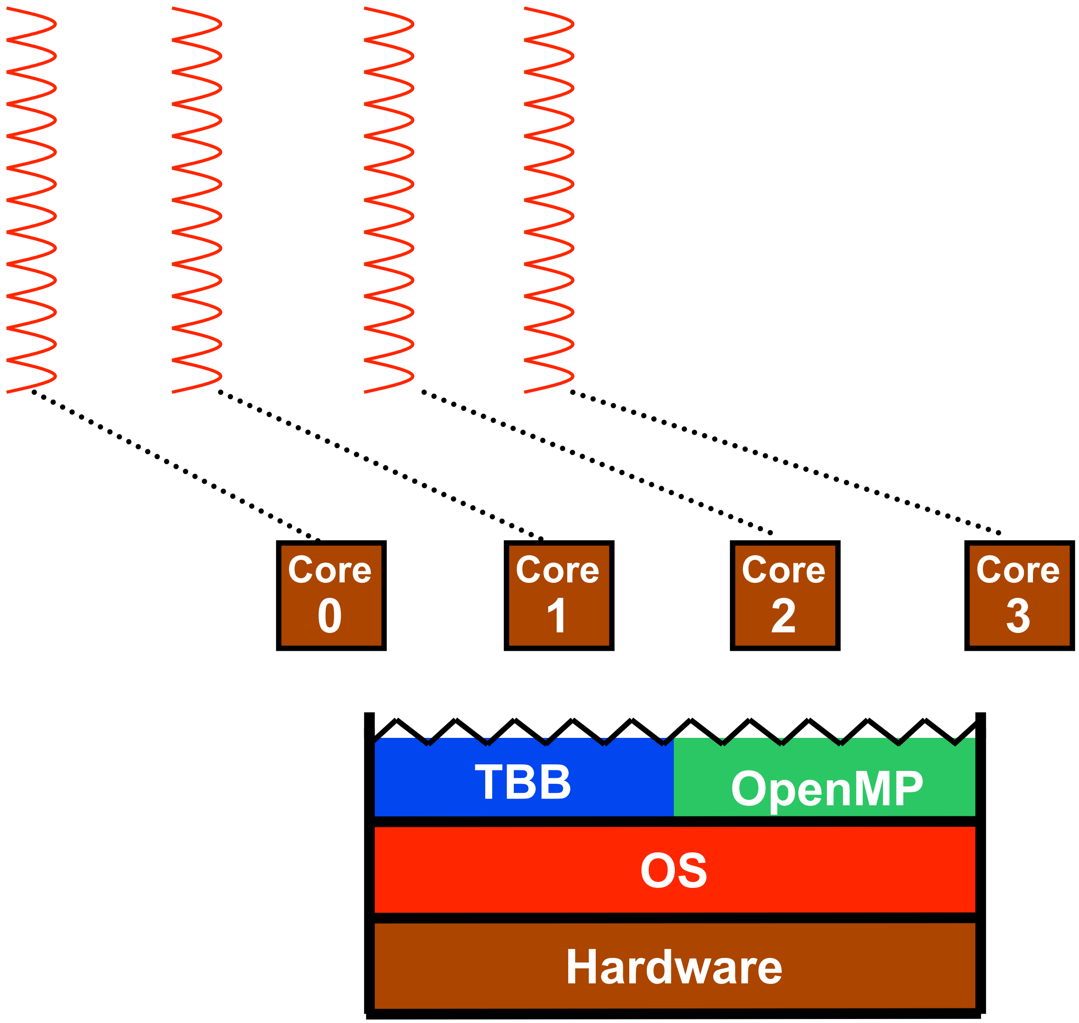
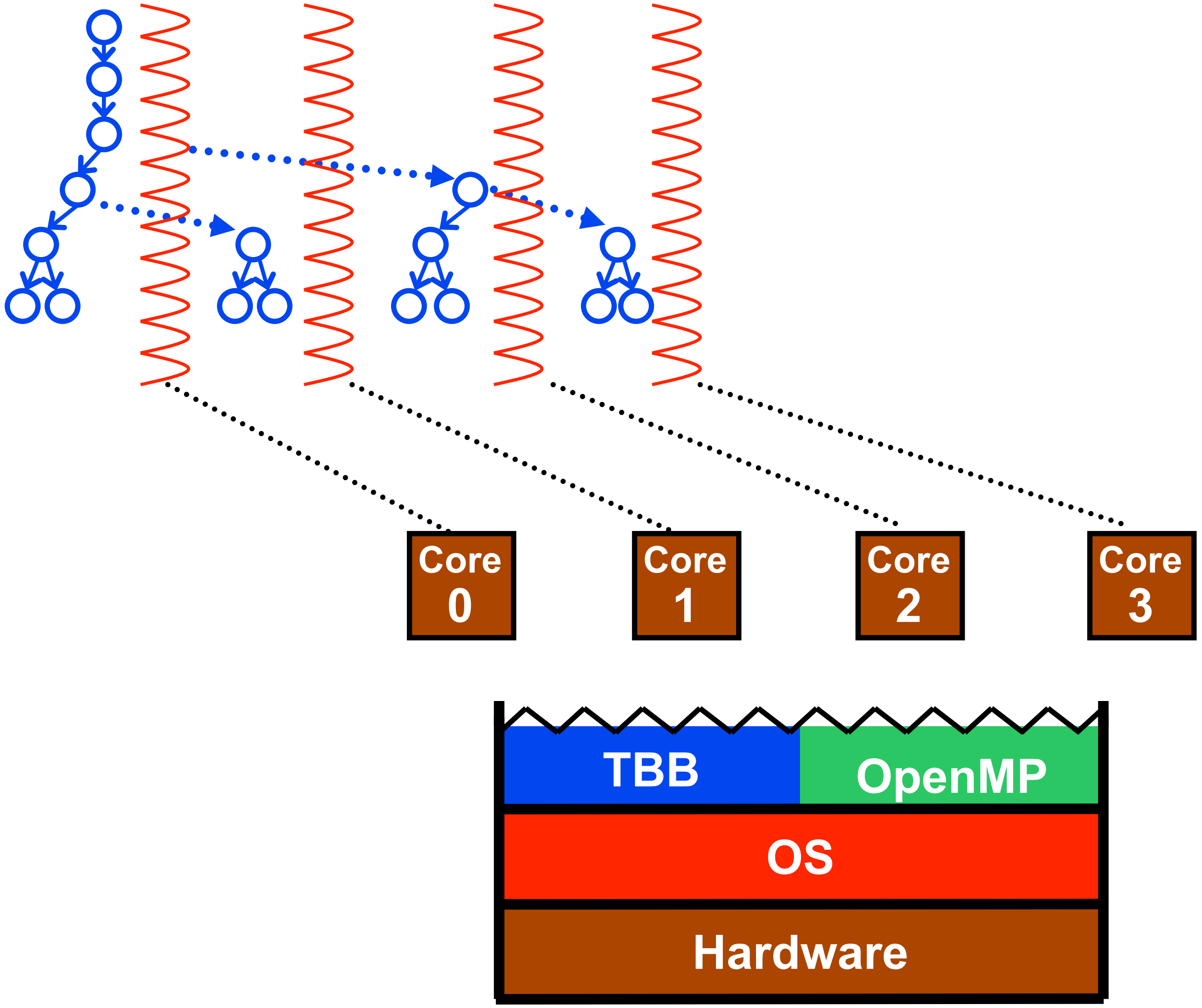


Multiple Components Oversubscribe Resources

`tbb::task()`



Core 0

Core 1

Core 2

Core 3

TBB

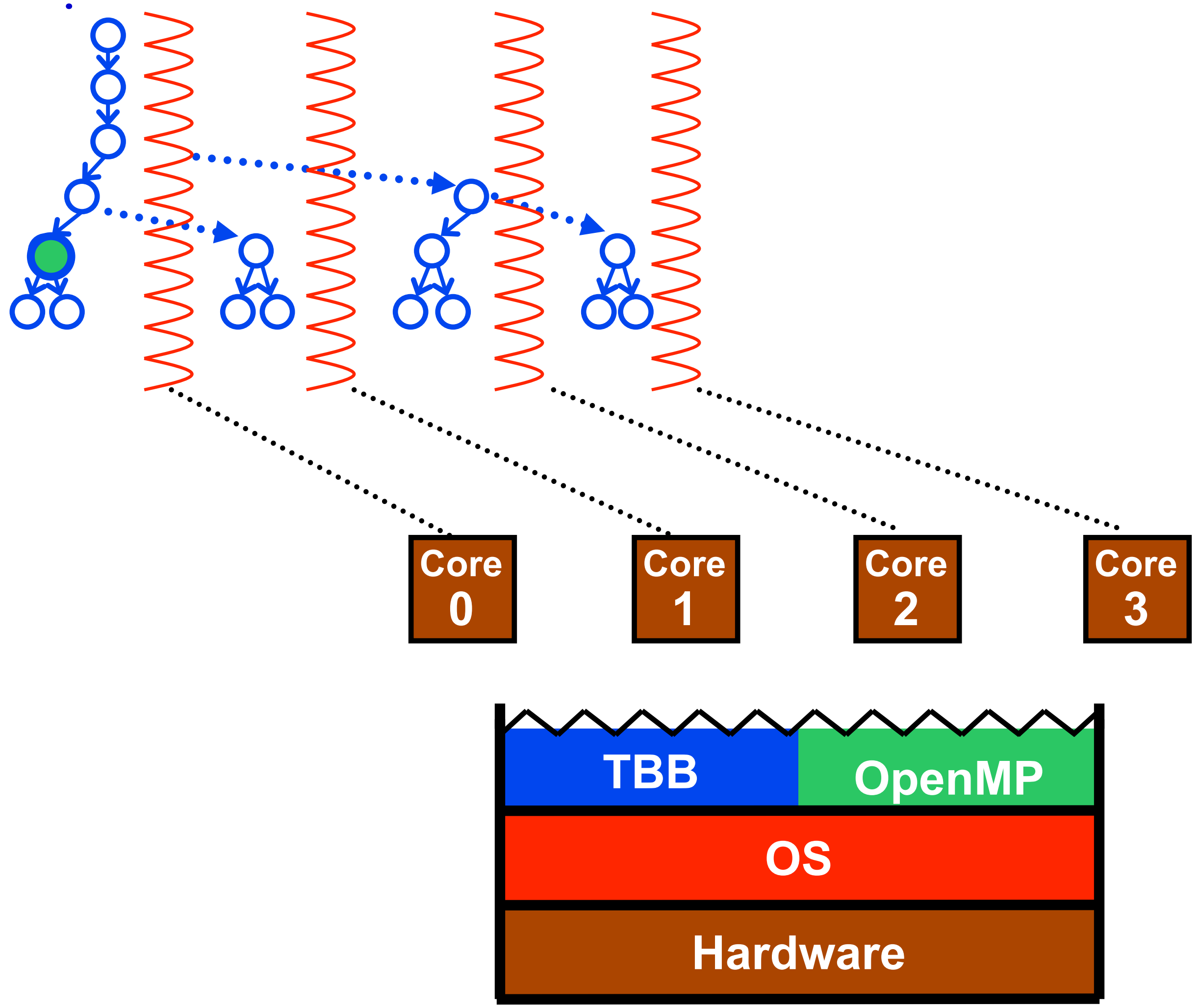
OpenMP

OS

Hardware

Multiple Components Oversubscribe Resources

```
tbb::task() {
  matmult();
  :
```



Multiple Components Oversubscribe Resources

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tbb::task() {
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```

```
matmult {
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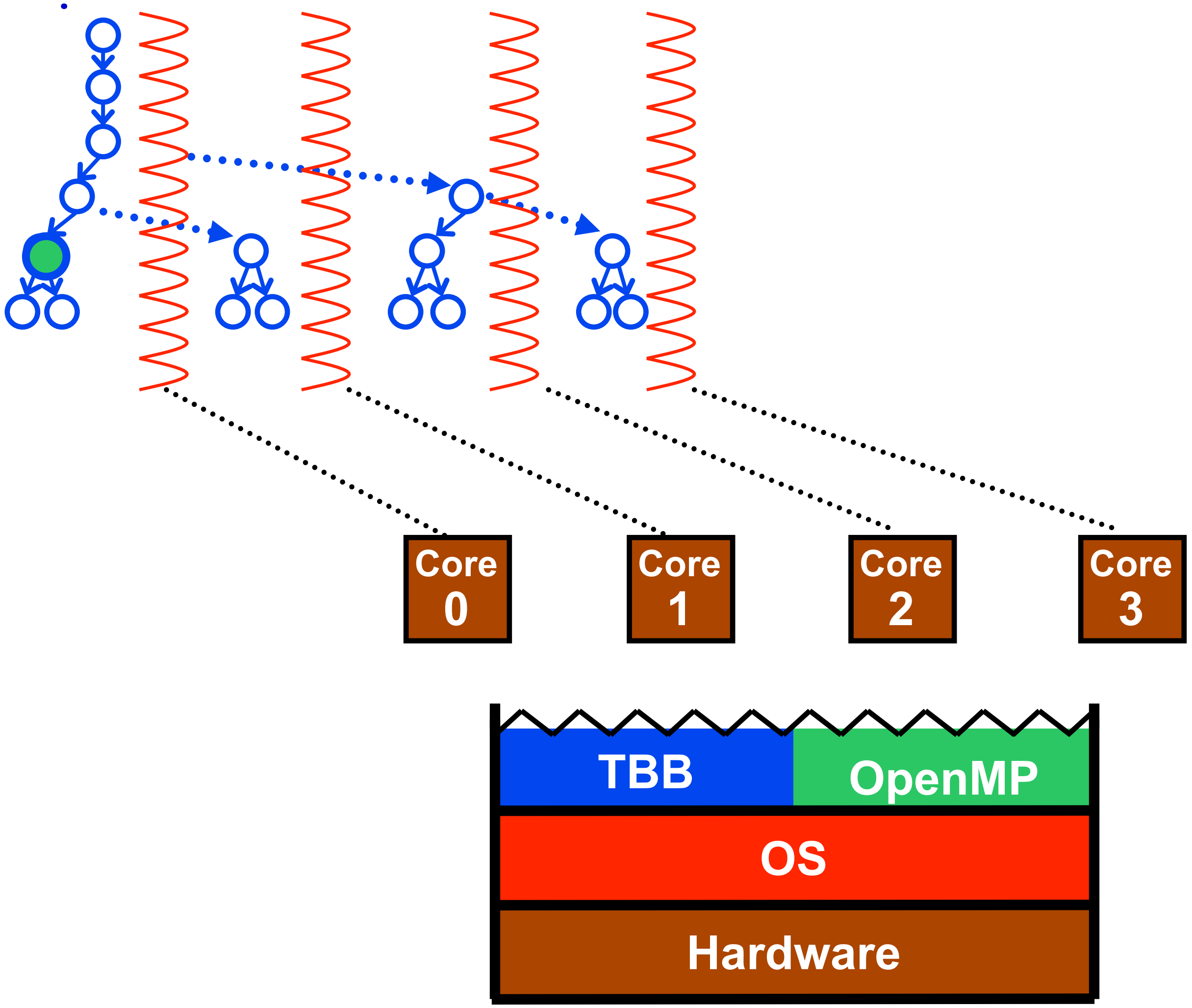
  :
```



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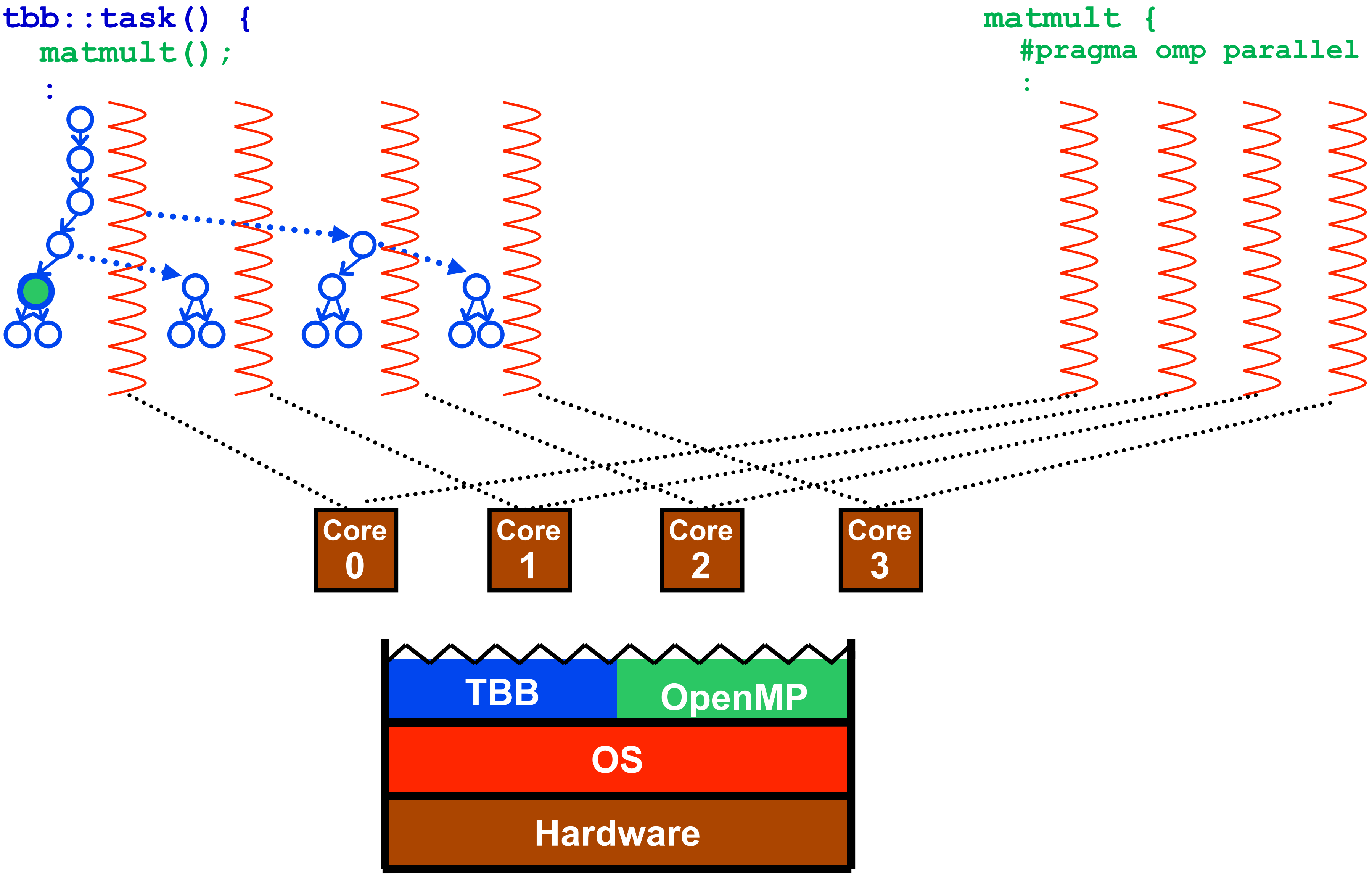

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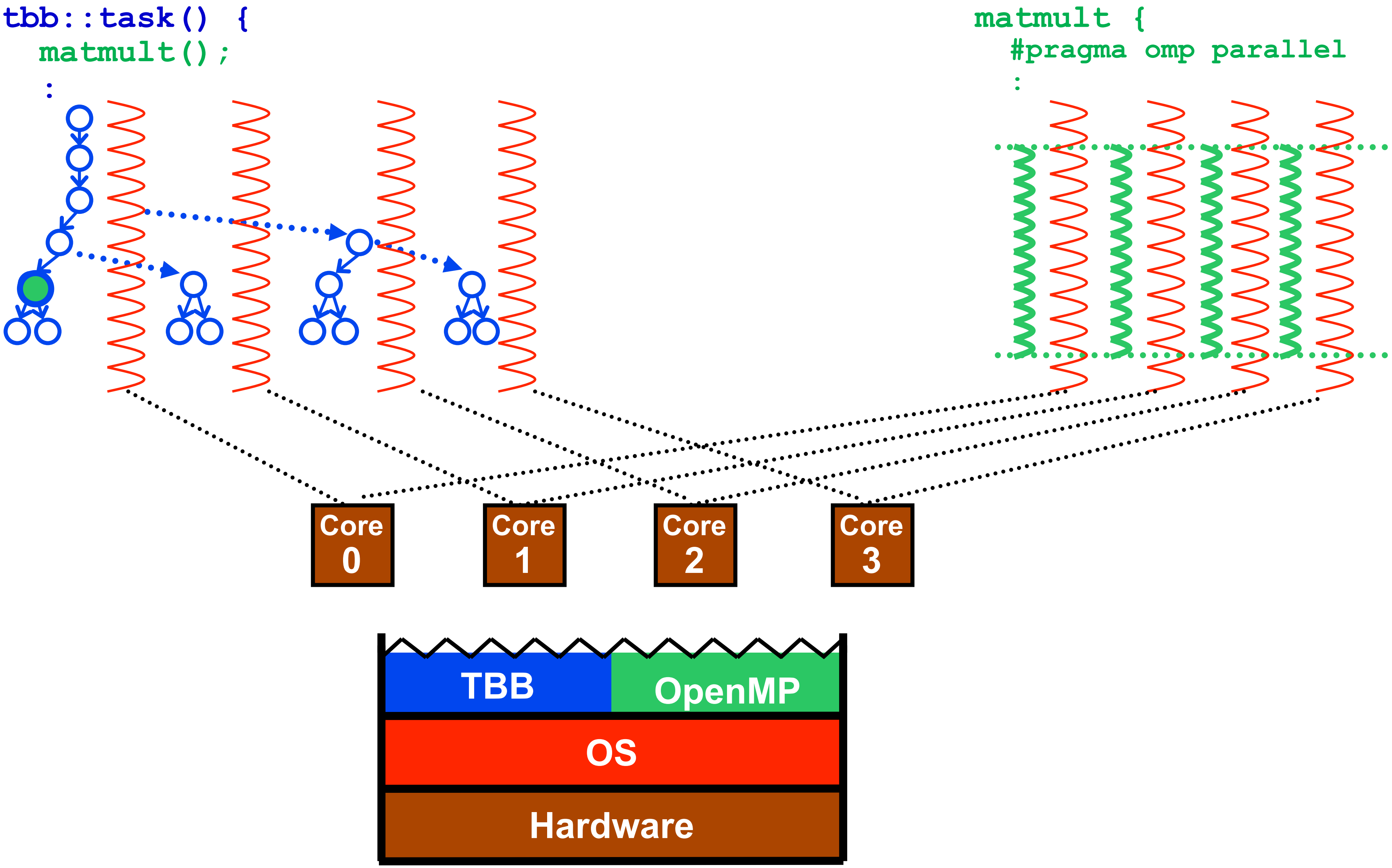

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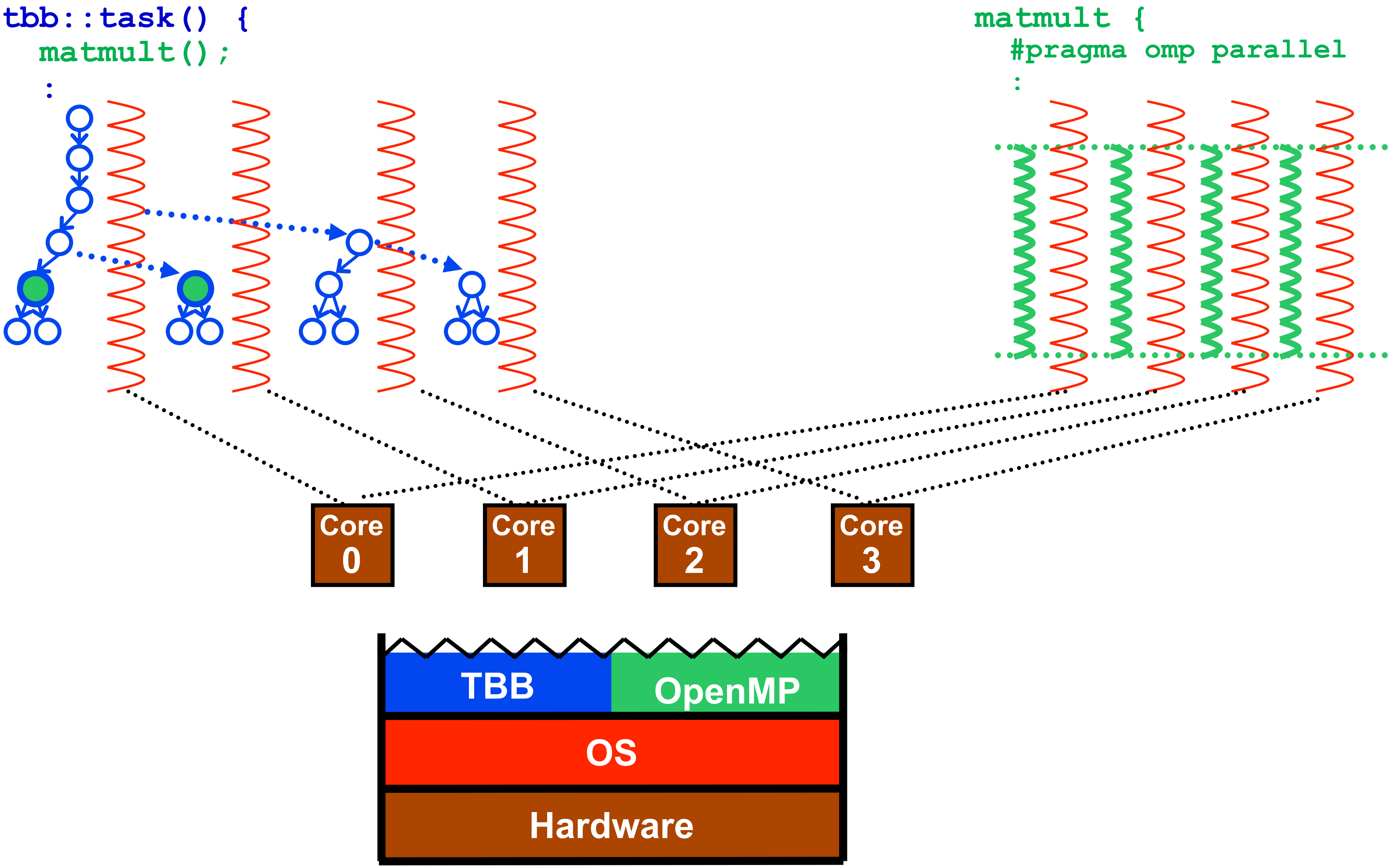

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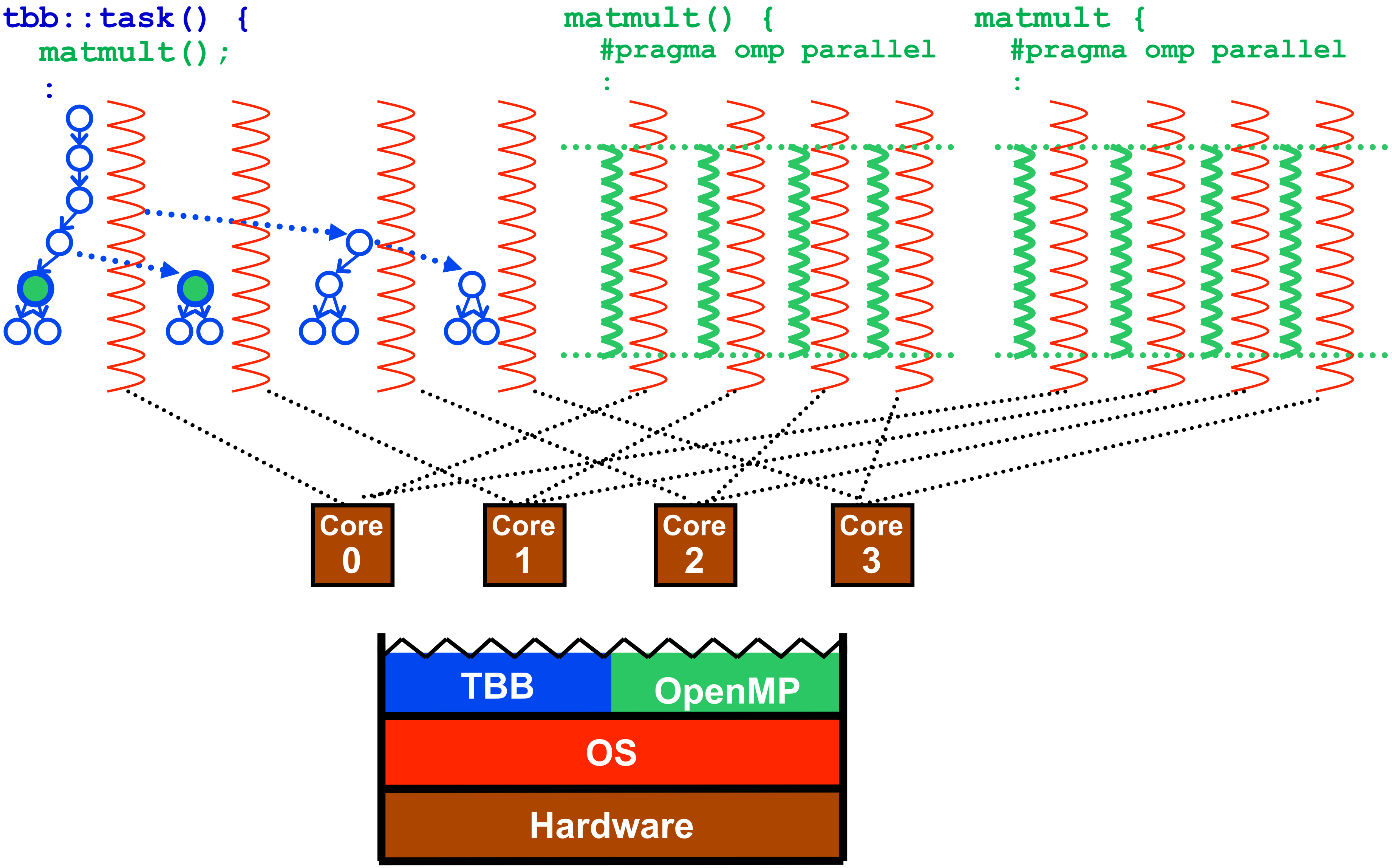
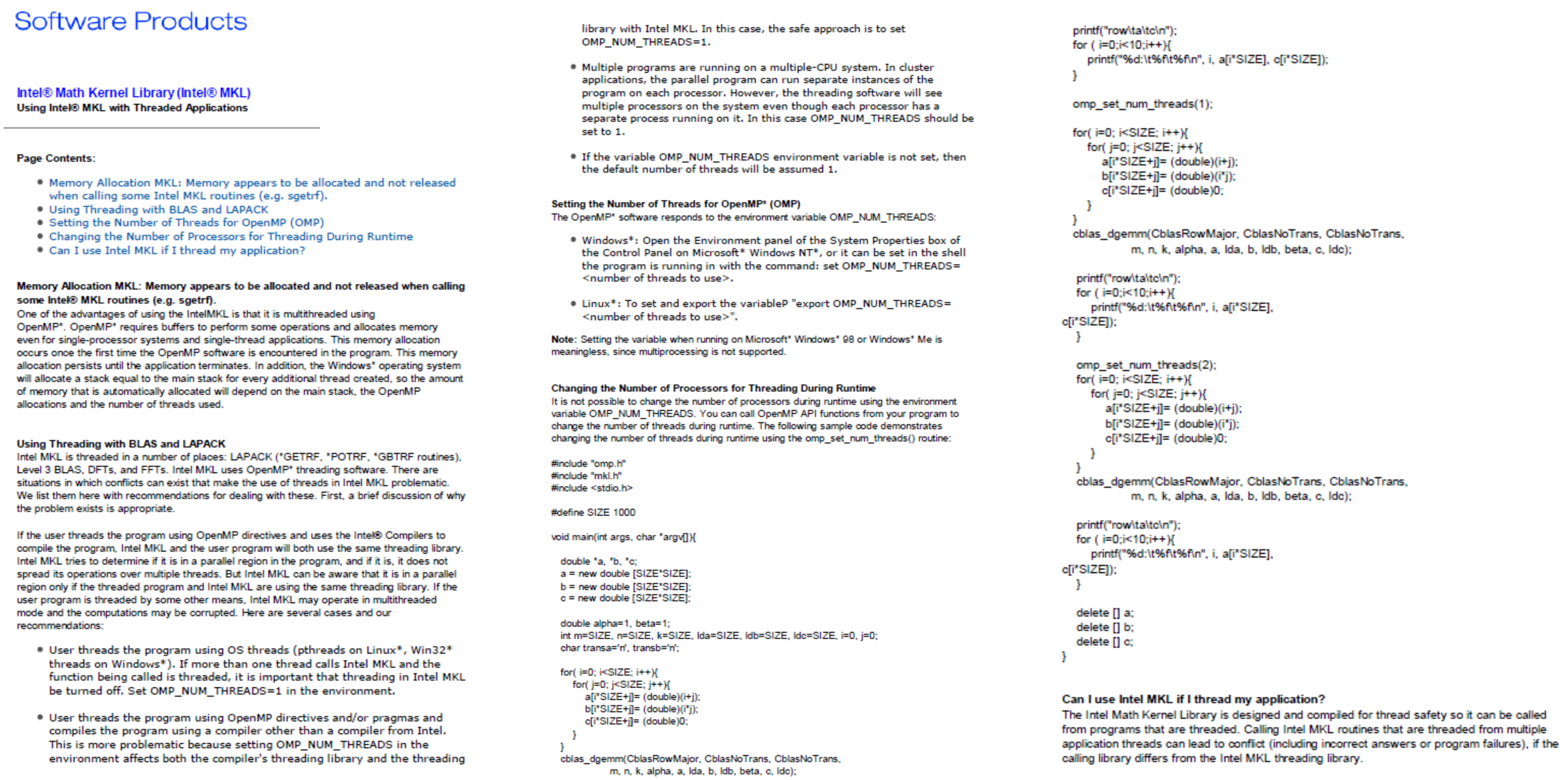


MKL Quick Fix

Using Intel MKL with Threaded Applications

```
http://www.intel.com/support/performancetools/libraries/mkl/sb/CS-017177.htm
```



Software Products

Intel® Math Kernel Library (Intel® MKL)
Using Intel® MKL with Threaded Applications

Page Contents:

Memory Allocation MKL: Memory appears to be allocated and not released when calling some Intel® MKL routines (e.g. sgetrf).
One of the advantages of using the IntelMKL is that it is multithreaded using OpenMP*. OpenMP* requires buffers to perform some operations and allocates memory even for single-processor systems and single-thread applications. This memory allocation occurs once the first time the OpenMP software is encountered in the program. This memory allocation persists until the application terminates. In addition, the Windows* operating system will allocate a stack equal to the main stack for every additional thread created, so the amount of memory that is automatically allocated will depend on the main stack, the OpenMP allocations and the number of threads used.

Using Threading with BLAS and LAPACK
Intel MKL is threaded in a number of places: LAPACK (*GETRF, *POTRF, *GBTRF routines), Level 3 BLAS, DFTs, and FFTs. Intel MKL uses OpenMP* threading software. There are situations in which conflicts can exist that make the use of threads in Intel MKL problematic. We list them here with recommendations for dealing with these. First, a brief discussion of why the problem exists is appropriate.

If the user threads the program using OpenMP directives and uses the Intel® Compilers to compile the program, Intel MKL and the user program will both use the same threading library. Intel MKL tries to determine if it is in a parallel region in the program, and if it is, it does not spread its operations over multiple threads. But Intel MKL can be aware that it is in a parallel region only if the threaded program and Intel MKL are using the same threading library. If the user program is threaded by some other means, Intel MKL may operate in multithreaded mode and the computations may be corrupted. Here are several cases and our recommendations:

- User threads the program using OS threads (pthreads on Linux*, Win32* threads on Windows*). If more than one thread calls Intel MKL and the function being called is threaded, it is important that threading in Intel MKL be turned off. Set OMP_NUM_THREADS=1 in the environment.

- User threads the program using OpenMP directives and/or pragmas and compiles the program using a compiler other than a compiler from Intel. This is more problematic because setting OMP_NUM_THREADS in the environment affects both the compiler's threading library and the threading library with Intel MKL. In this case, the safe approach is to set OMP_NUM_THREADS=1.

- Multiple programs are running on a multiple-CPU system. In cluster applications, the parallel program can run separate instances of the program on each processor. However, the threading software will see multiple processors on the system even though each processor has a separate process running on it. In this case OMP_NUM_THREADS should be set to 1.

- If the variable OMP_NUM_THREADS environment variable is not set, then the default number of threads will be assumed 1.

Setting the Number of Threads for OpenMP* (OMP)
The OpenMP* software responds to the environment variable OMP_NUM_THREADS:

- Windows*: Open the Environment panel of the System Properties box of the Control Panel on Microsoft* Windows NT*, or it can be set in the shell the program is running in with the command: set OMP_NUM_THREADS=<number of threads to use>.

- Linux*: To set and export the variableP "export OMP_NUM_THREADS=<number of threads to use>".

Note: Setting the variable when running on Microsoft* Windows* 98 or Windows* Me is meaningless, since multiprocessing is not supported.

Changing the Number of Processors for Threading During Runtime
It is not possible to change the number of processors during runtime using the environment variable OMP_NUM_THREADS. You can call OpenMP API functions from your program to change the number of threads during runtime. The following sample code demonstrates changing the number of threads during runtime using the omp_set_num_threads() routine:

```
#include "omp.h"
#include "mkl.h"
#include <stdio.h>

#define SIZE 1000

void main(int args, char *argv[]){

  double *a, *b, *c;
  a = new double [SIZE*SIZE];
  b = new double [SIZE*SIZE];
  c = new double [SIZE*SIZE];

  double alpha=1, beta=1;
  int m=SIZE, n=SIZE, k=SIZE, lda=SIZE, ldb=SIZE, ldc=SIZE, i=0, j=0;
  char transa='n', transb='n';

  for( i=0; i<SIZE; i++){
     for( j=0; j<SIZE; j++){
        a[i*SIZE+j]= (double)(i+j);
        b[i*SIZE+j]= (double)(i*j);
        c[i*SIZE+j]= (double)0;
     }
  }
  cblas_dgemm(CblasRowMajor, CblasNoTrans, CblasNoTrans,
              m, n, k, alpha, a, lda, b, ldb, beta, c, ldc);
  printf("row\ta\tc\n");
  for ( i=0;i<10;i++){
     printf("%d:\t%f\t%f\n", i, a[i*SIZE], c[i*SIZE]);
  }

  omp_set_num_threads(1);

  for( i=0; i<SIZE; i++){
     for( j=0; j<SIZE; j++){
        a[i*SIZE+j]= (double)(i+j);
        b[i*SIZE+j]= (double)(i*j);
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     }
  }
  cblas_dgemm(CblasRowMajor, CblasNoTrans, CblasNoTrans,
              m, n, k, alpha, a, lda, b, ldb, beta, c, ldc);

   printf("row\ta\tc\n");
   for ( i=0;i<10;i++){
      printf("%d:\t%f\t%f\n", i, a[i*SIZE],
c[i*SIZE]);
   }

   omp_set_num_threads(2);
   for( i=0; i<SIZE; i++){
      for( j=0; j<SIZE; j++){
         a[i*SIZE+j]= (double)(i+j);
         b[i*SIZE+j]= (double)(i*j);
         c[i*SIZE+j]= (double)0;
      }
   }
   cblas_dgemm(CblasRowMajor, CblasNoTrans, CblasNoTrans,
              m, n, k, alpha, a, lda, b, ldb, beta, c, ldc);

   printf("row\ta\tc\n");
   for ( i=0;i<10;i++){
      printf("%d:\t%f\t%f\n", i, a[i*SIZE],
c[i*SIZE]);
   }

   delete [] a;
   delete [] b;
   delete [] c;
}
```

Can I use Intel MKL if I thread my application?
The Intel Math Kernel Library is designed and compiled for thread safety so it can be called from programs that are threaded. Calling Intel MKL routines that are threaded from multiple application threads can lead to conflict (including incorrect answers or program failures), if the calling library differs from the Intel MKL threading library.

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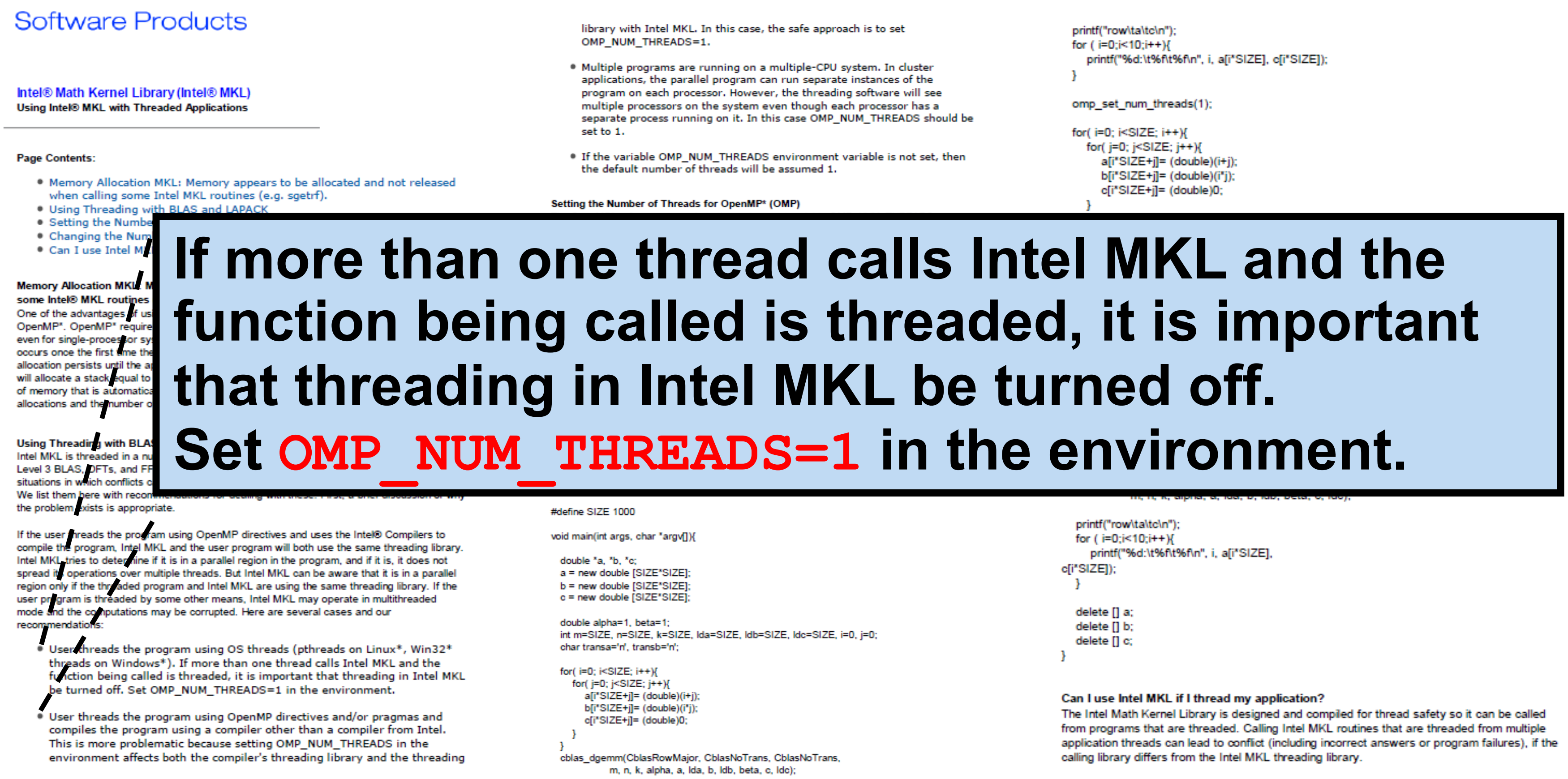

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- Setting the Numbe
- Changing the Num
- Can I use Intel M

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omp_set_num_threads(1);

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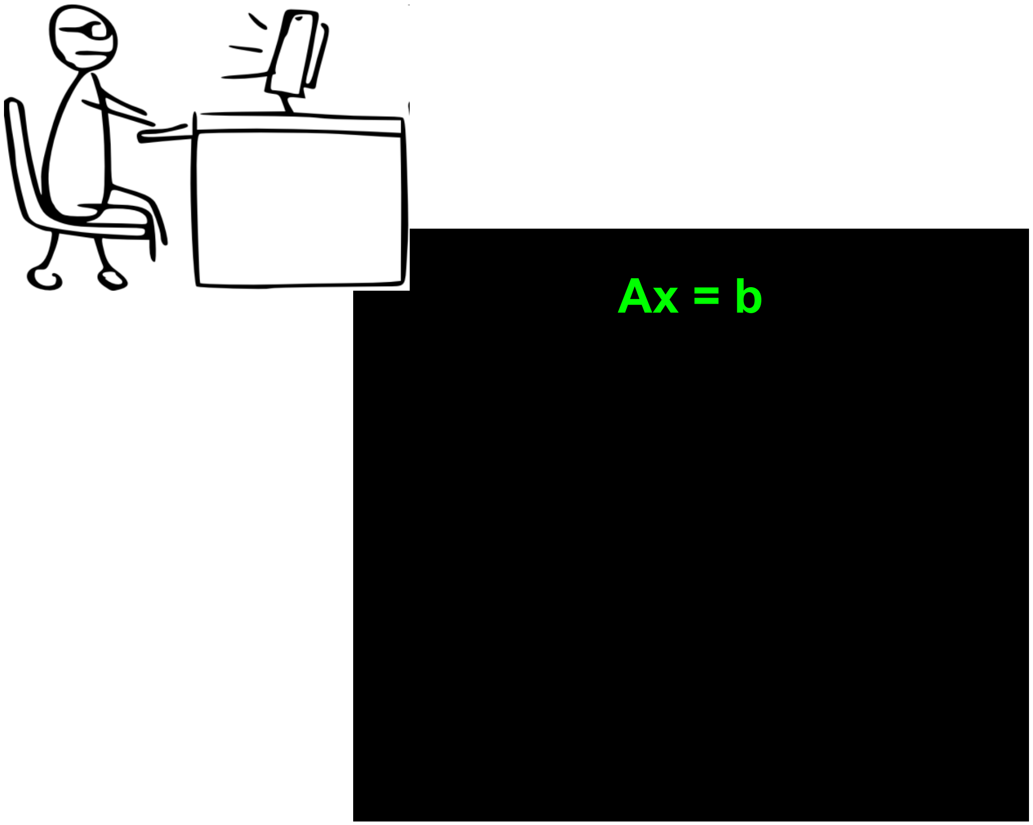
Breaks Black Box Abstraction

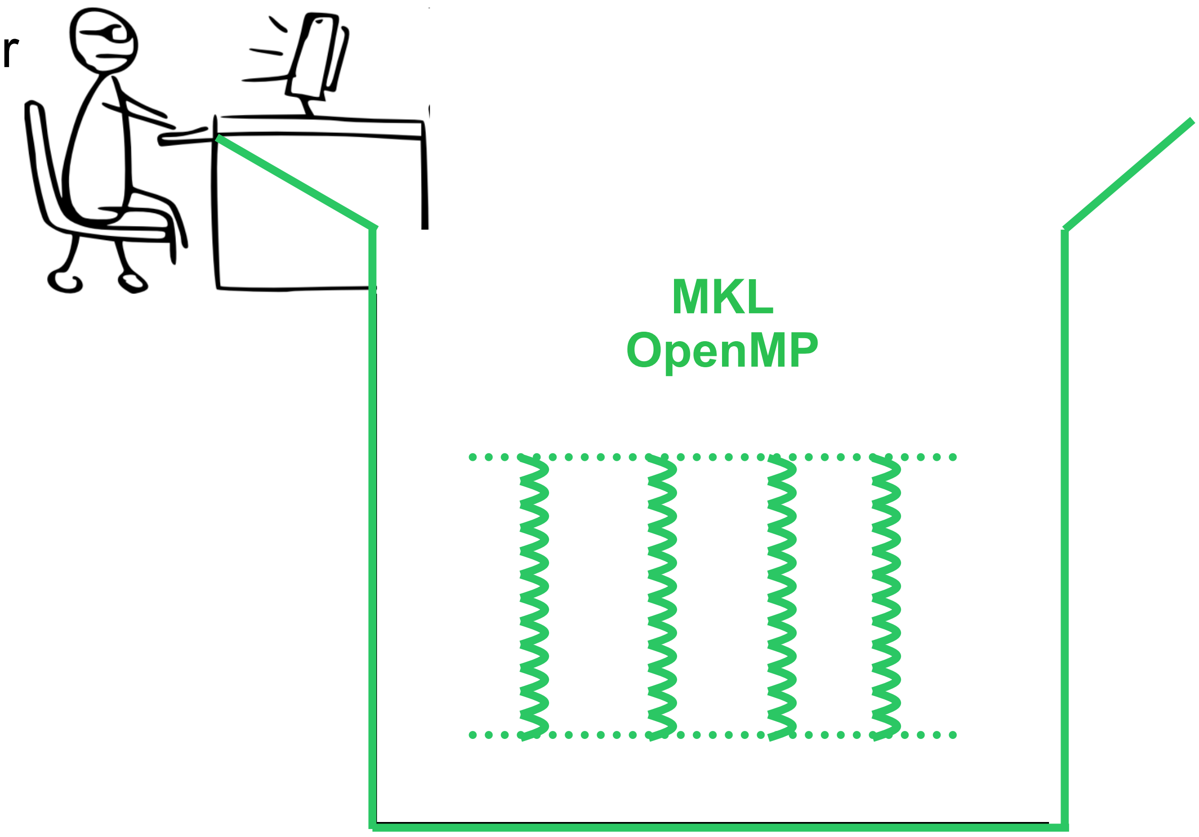


Programmer

Ax = b

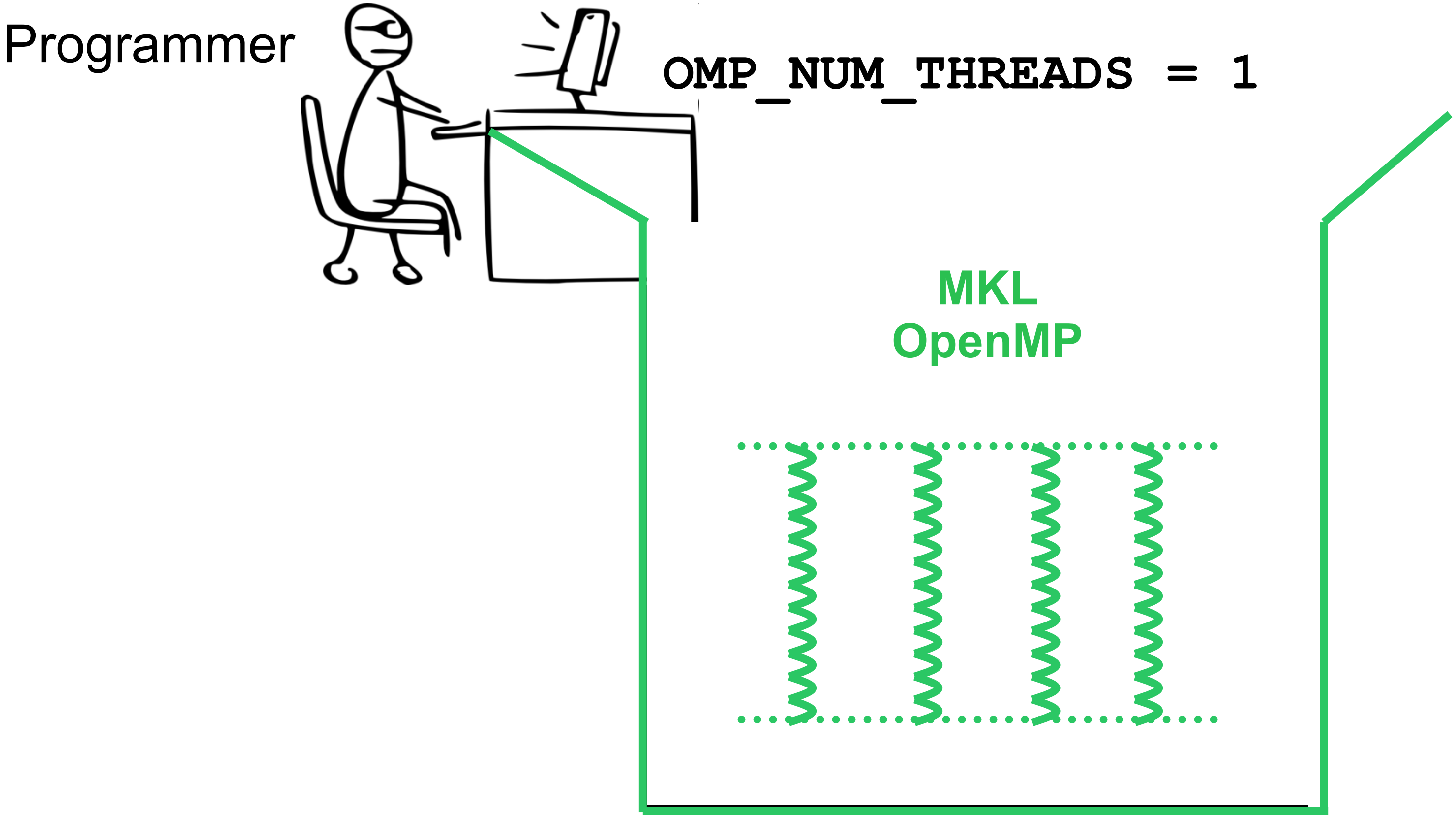
Breaks Black Box Abstraction

Programmer



MKL
OpenMP

Breaks Black Box Abstraction

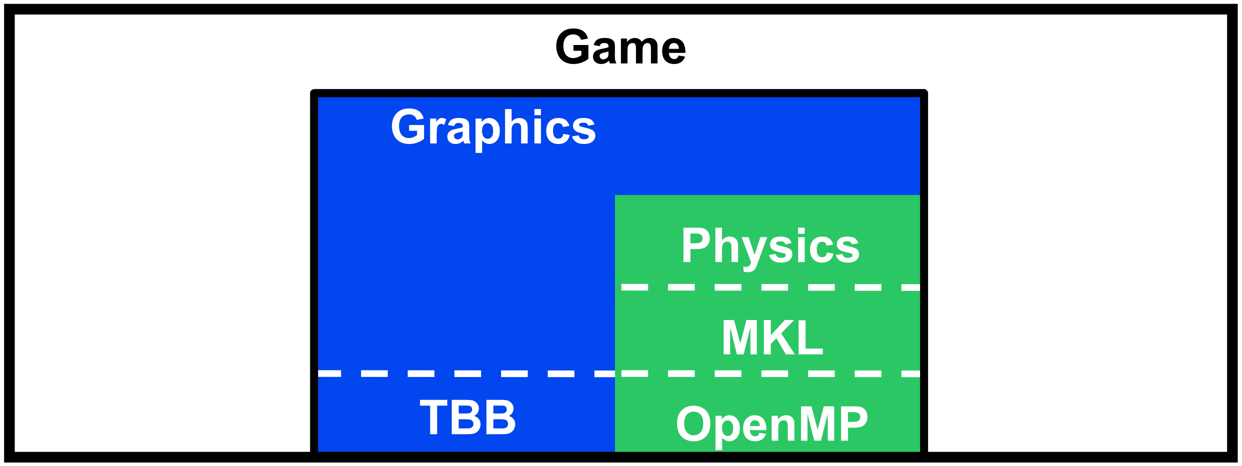


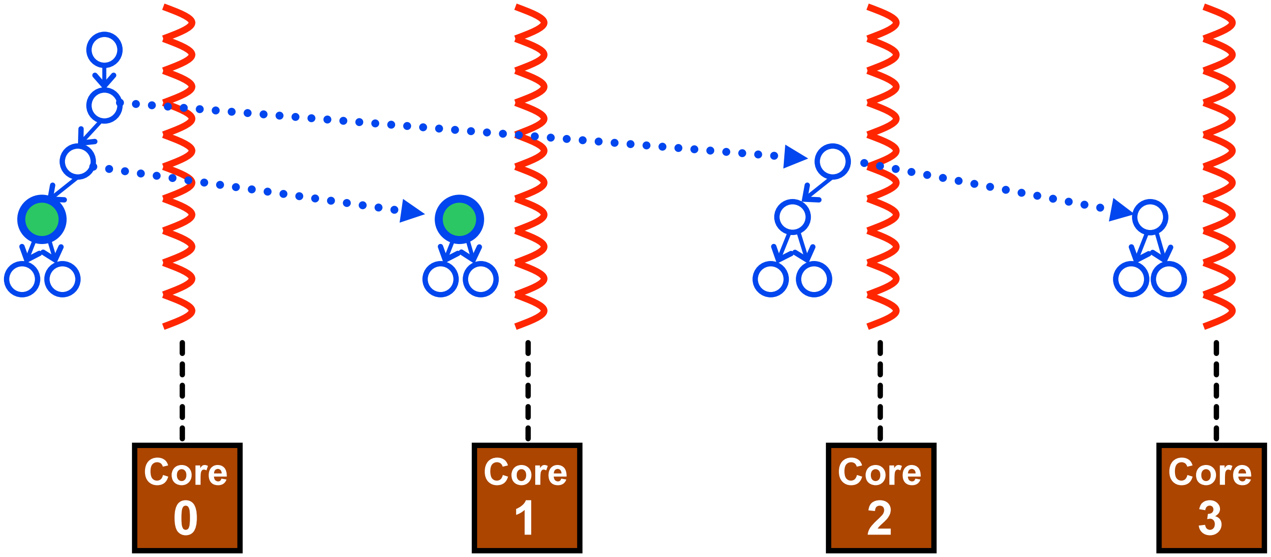
Programmer

OMP_NUM_THREADS = 1

MKL
OpenMP

Exports Problem to User





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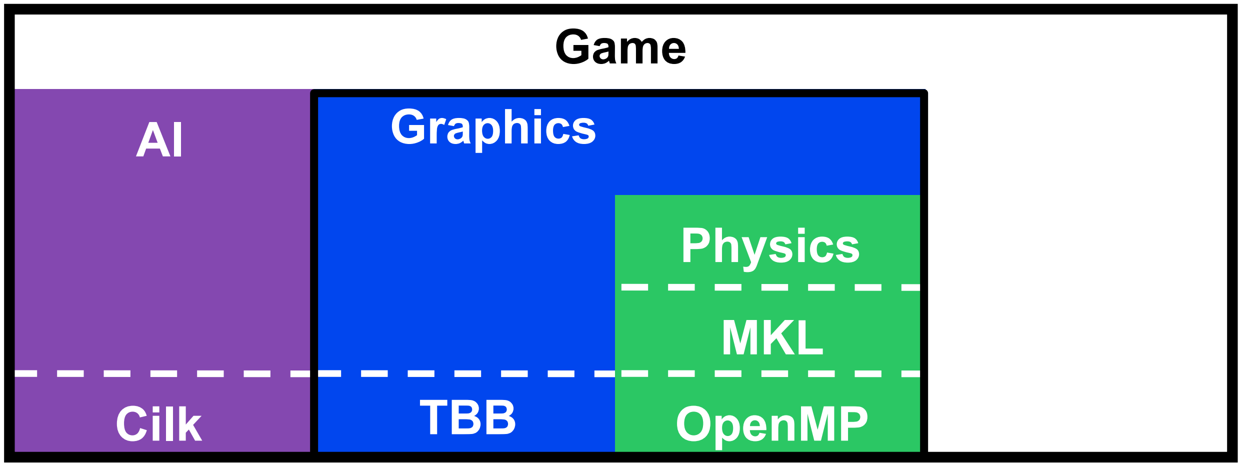

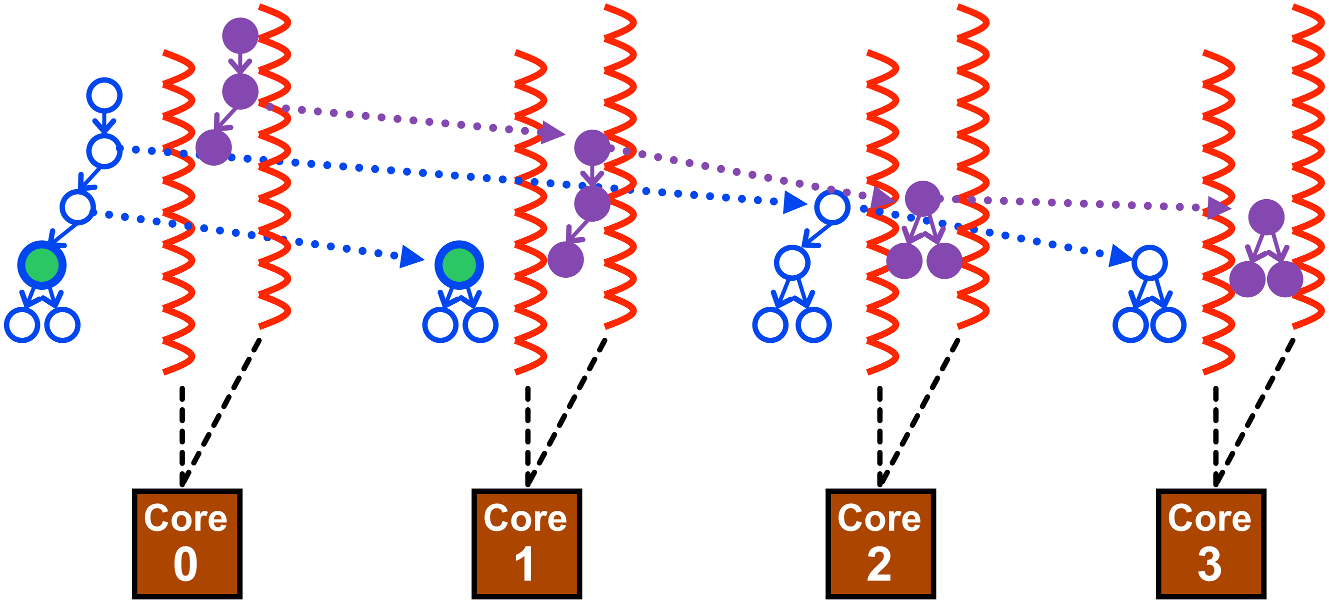

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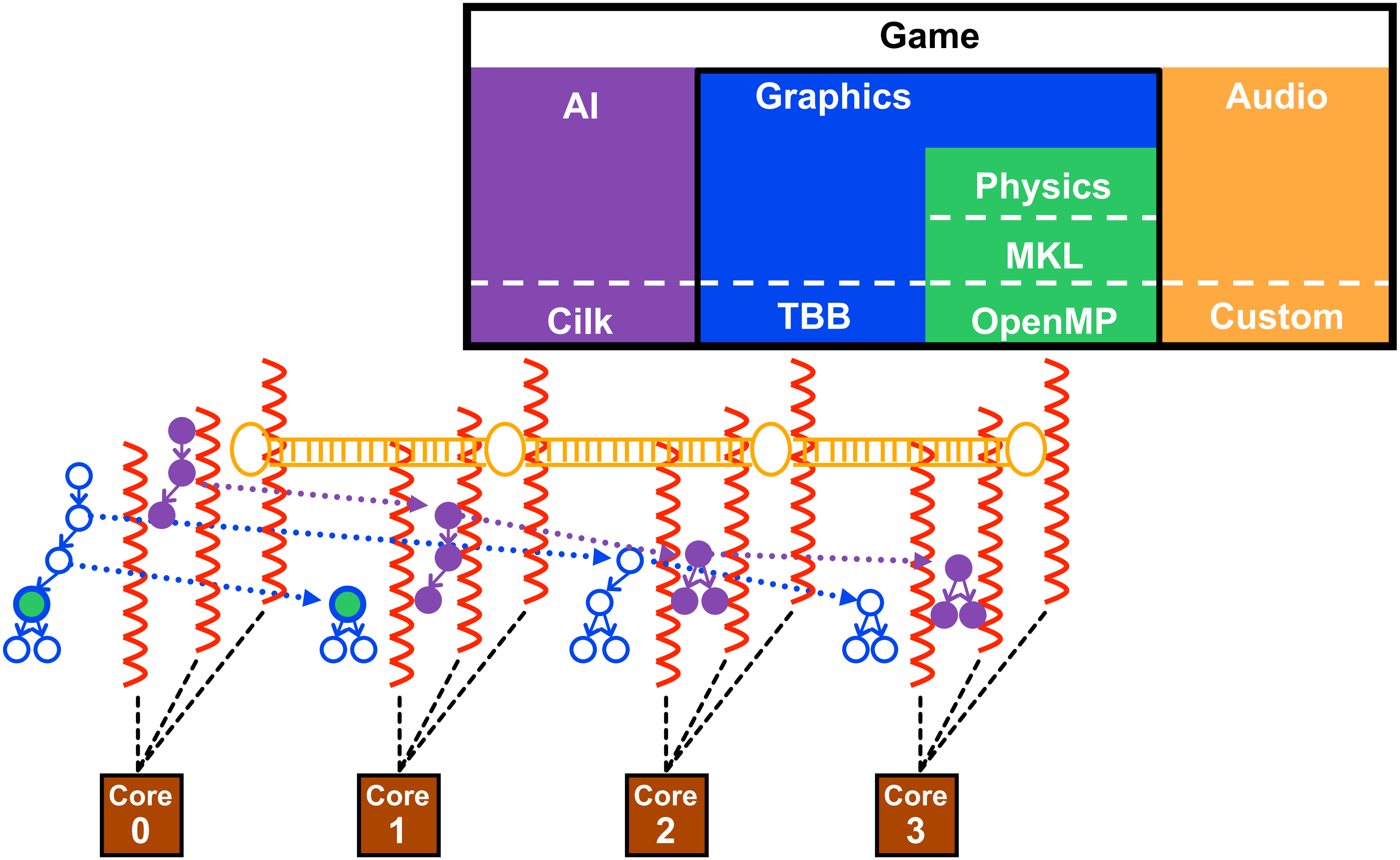


Game

AI

Graphics

Audio

Physics

MKL

Cilk

TBB

OpenMP

Custom

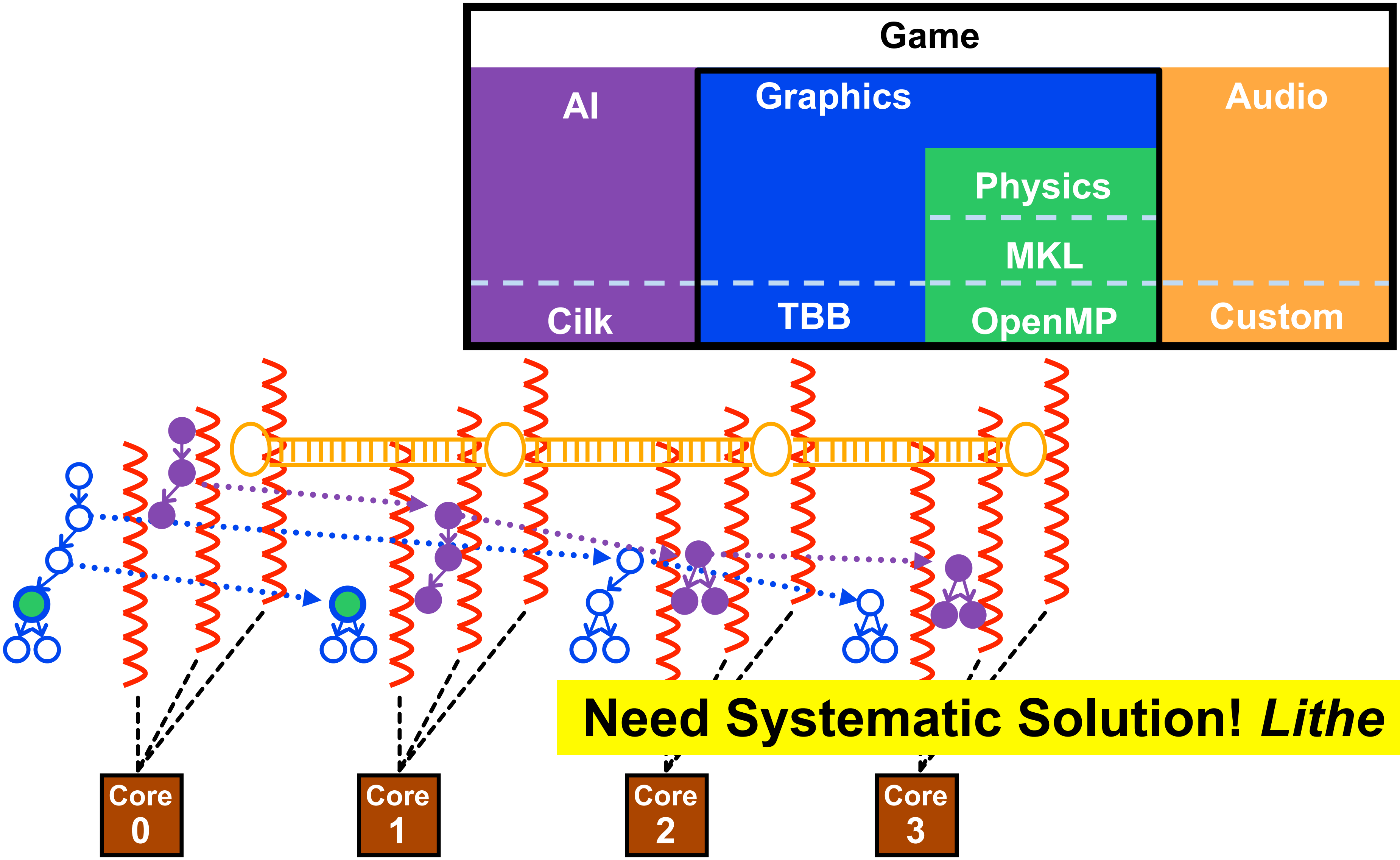
Core 0

Core 1

Core 2

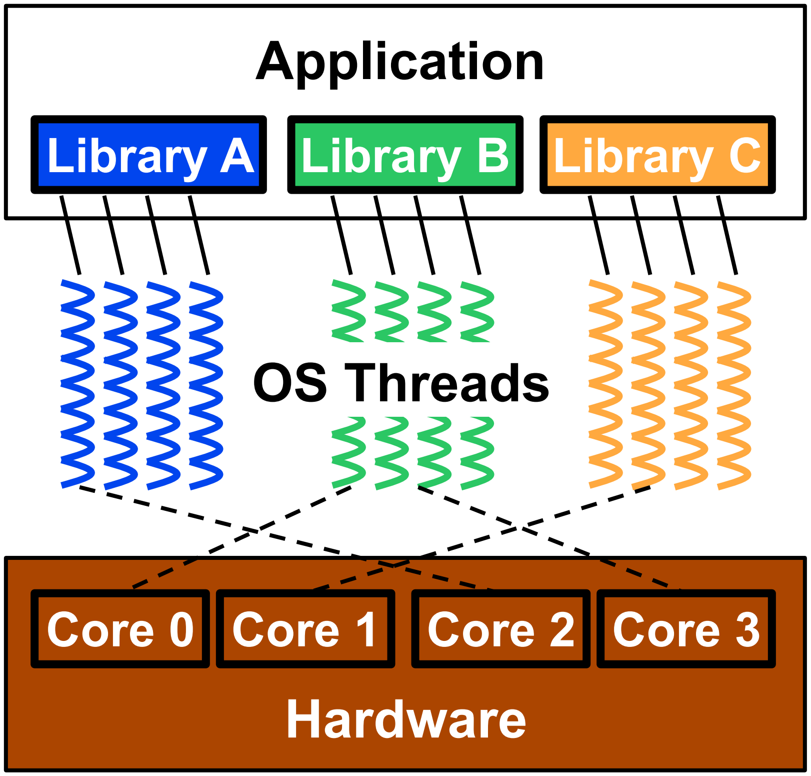
Core 3

Exports Problem to User

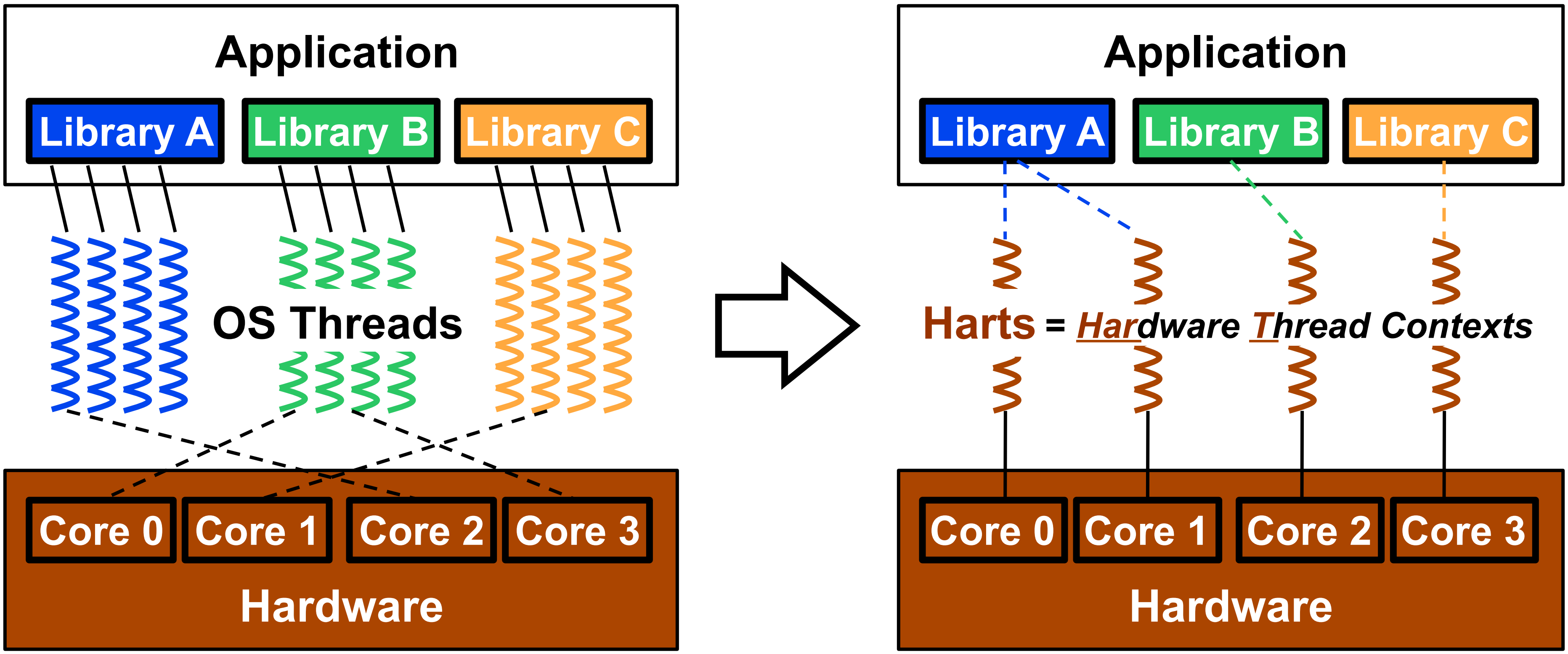


Need Systematic Solution! *Lithe*

Better Resource Abstraction: HARTS



Better Resource Abstraction: HARTS



Application

Library A

Library B

Library C

OS Threads

Core 0

Core 1

Core 2

Core 3

Hardware

Application

Library A

Library B

Library C

Harts = *Hardware Thread Contexts*

Core 0

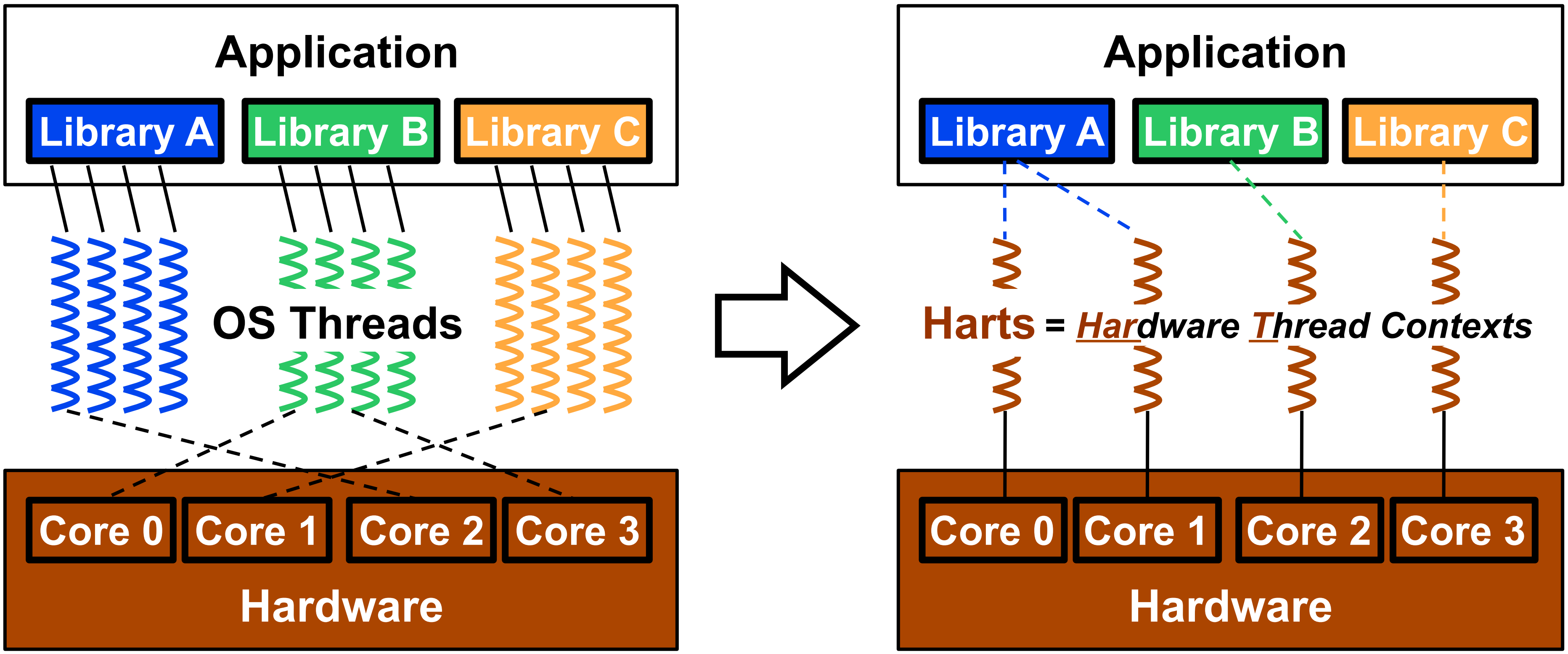
Core 1

Core 2

Core 3

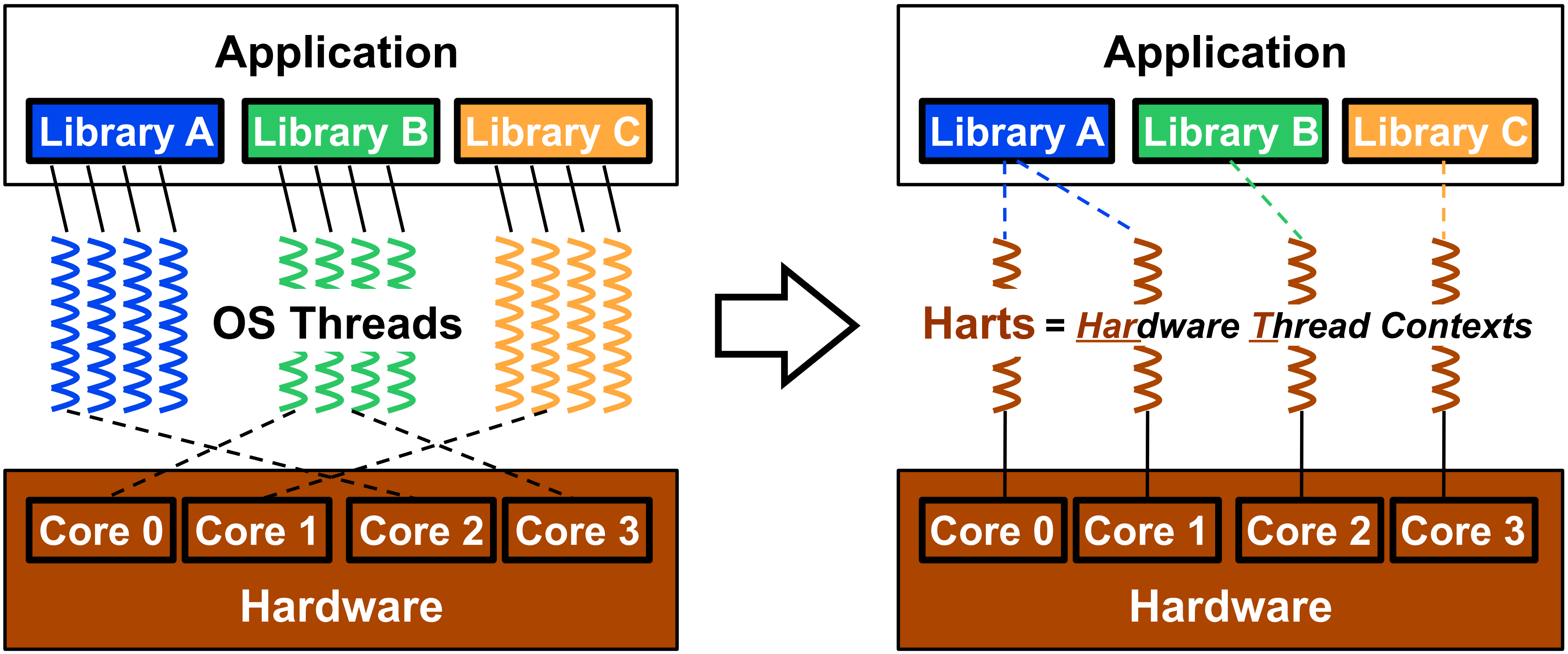
Hardware

Better Resource Abstraction: HARTS



- Create as many threads as wanted.
- Allocated a finite amount of harts.

Better Resource Abstraction: HARTS



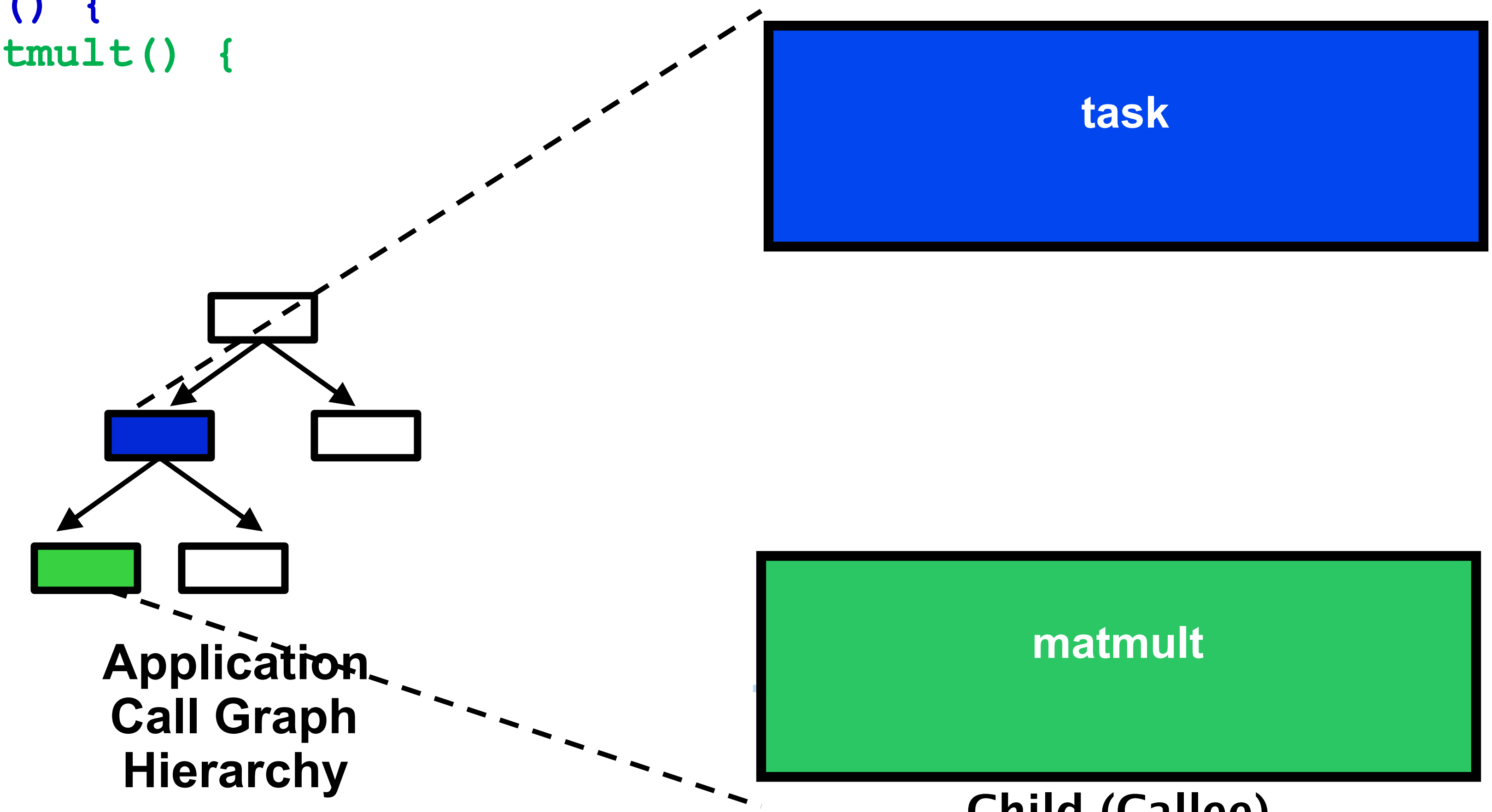
- ❖ Create as many threads as wanted.
- ❖ Threads = Resource + Programming Abstraction

- ❖ Allocated a finite amount of harts.
- ❖ Harts = Resource Abstraction

Cooperative Hierarchical Resource Scheduling

```
task() {
  matmult() {

     :
   }
   :
}
```



Parent (Caller)

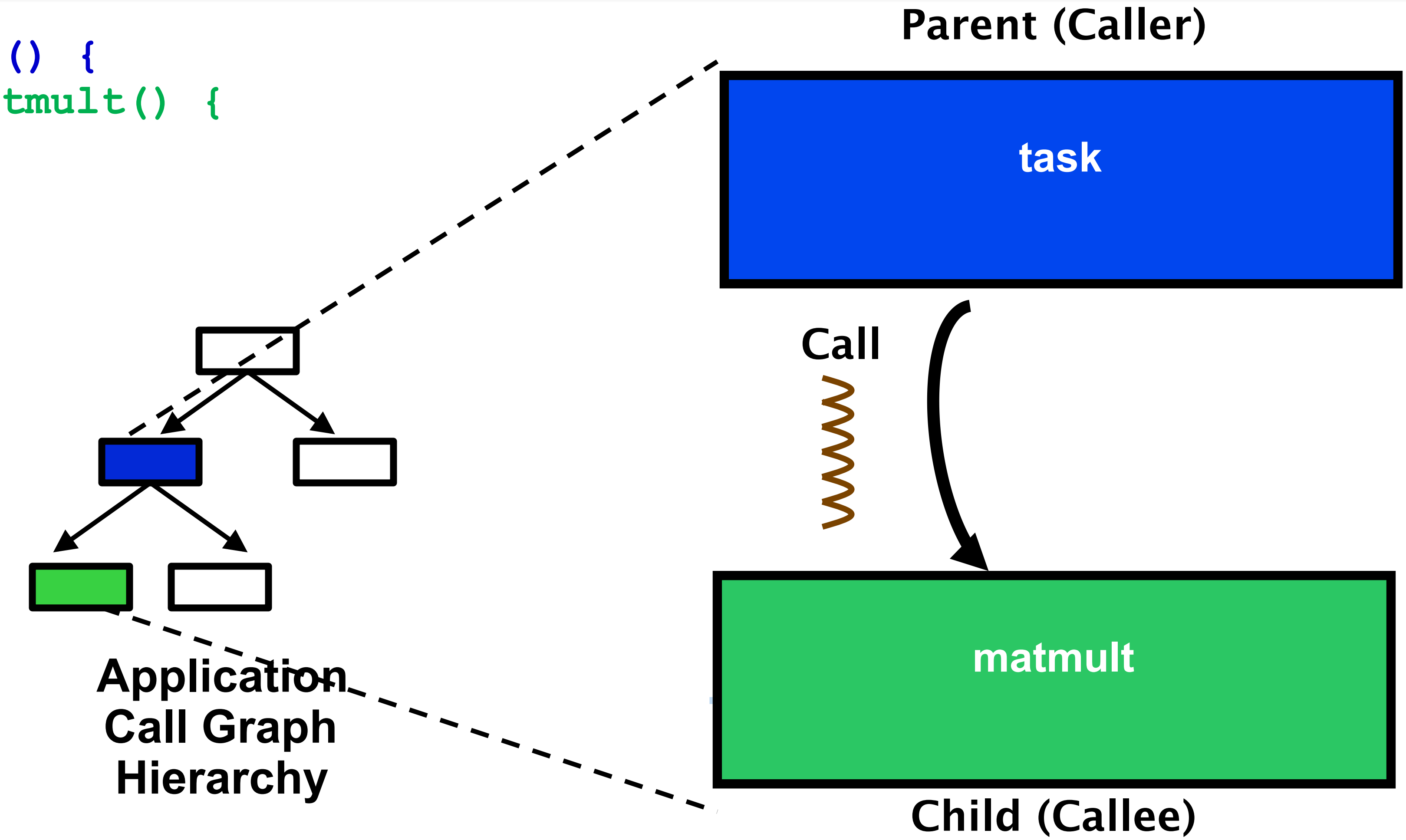
Application Call Graph Hierarchy

Child (Callee)

Cooperative Hierarchical Resource Scheduling

```
task() {
  matmult() {

     :
   }
   :
}
```

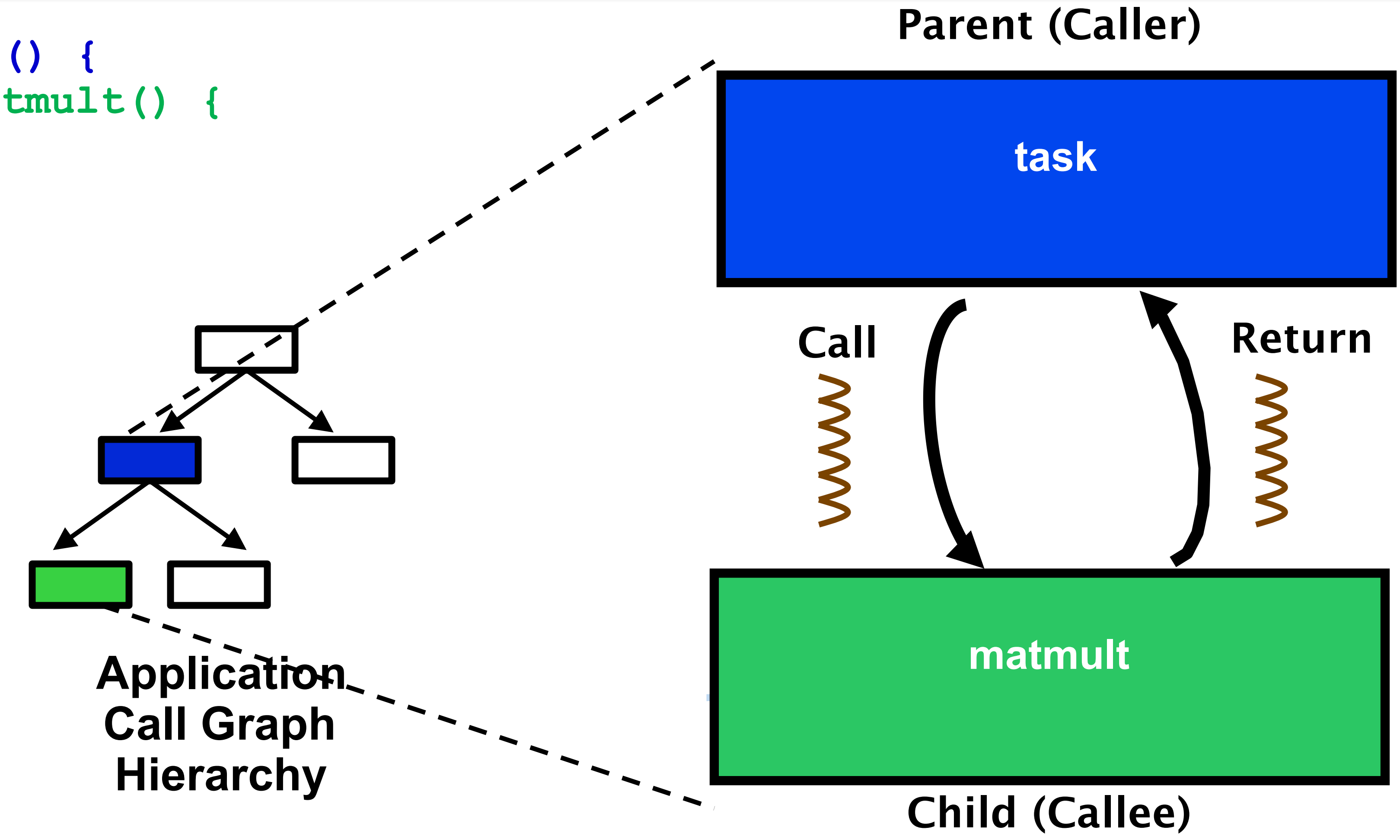


Transfer of control coupled with transfer of resources.

Cooperative Hierarchical Resource Scheduling

```
task() {
  matmult() {

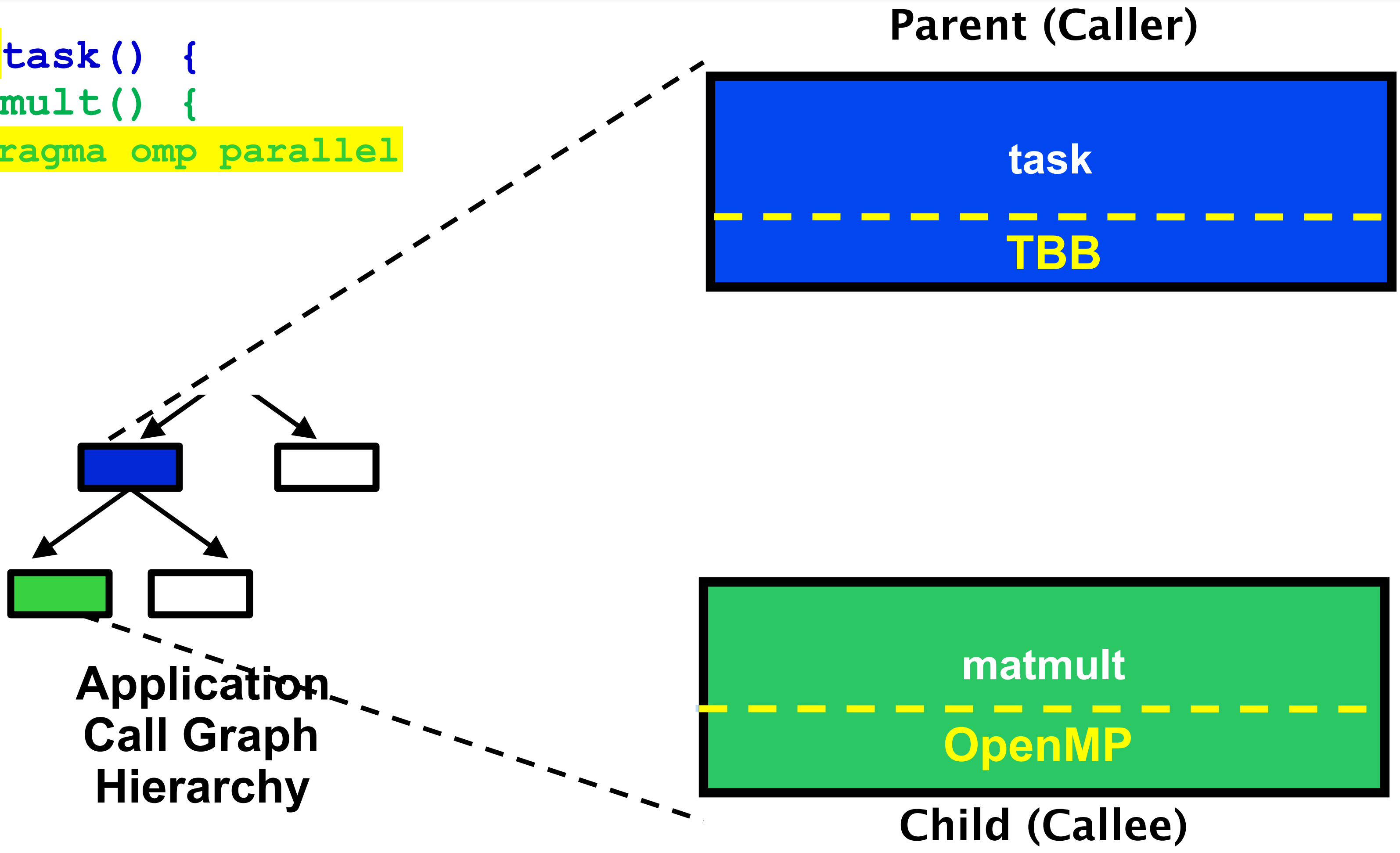
     :
   }
   :
}
```



Transfer of control coupled with transfer of resources.

Cooperative Hierarchical Resource Scheduling

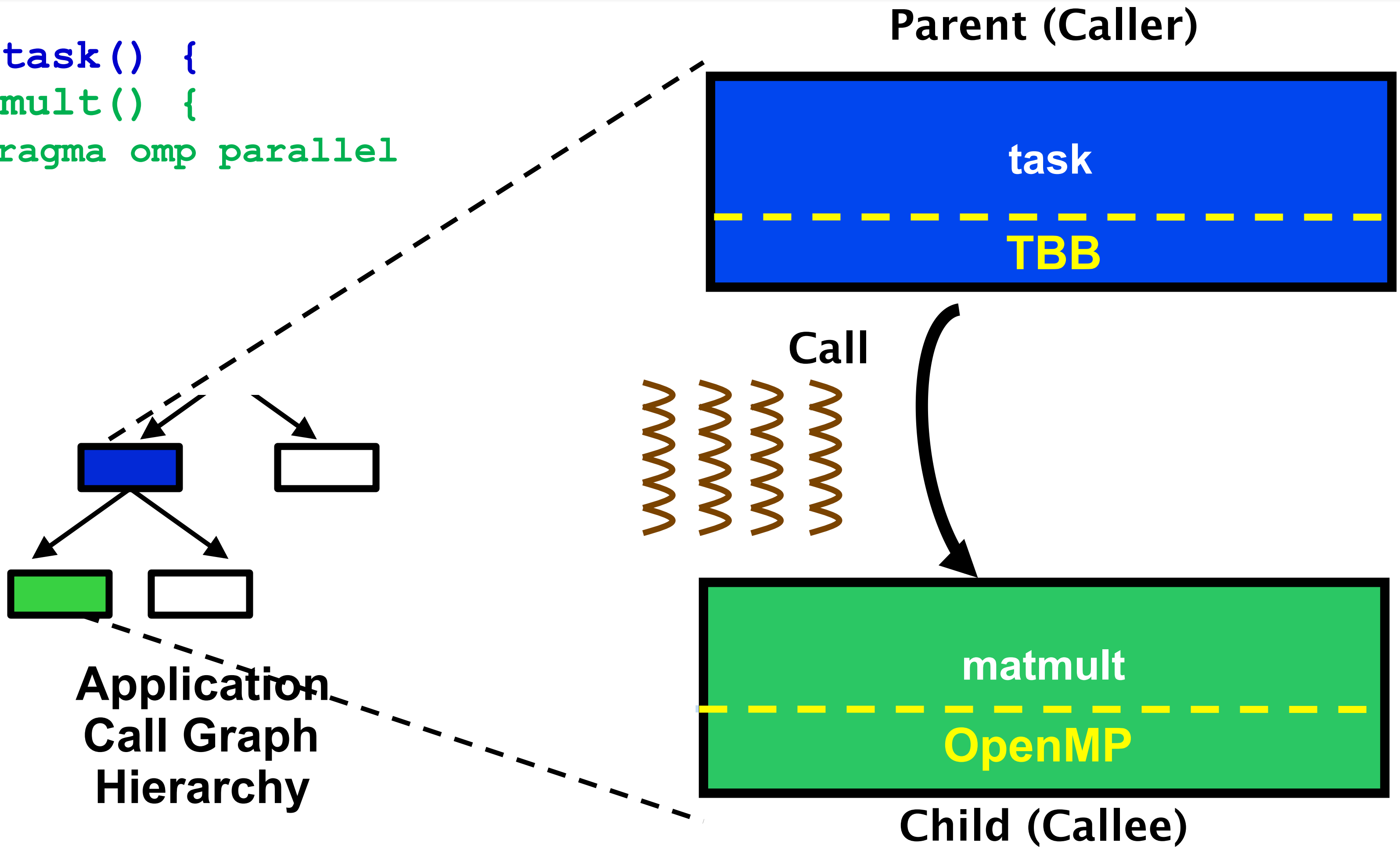
```
tbb::task() {
  matmult() {
   #pragma omp parallel
    :
  }
  :
}
```



Transfer of control coupled with transfer of resources.

Cooperative Hierarchical Resource Scheduling

```
tbb::task() {
  matmult() {
   #pragma omp parallel
    :
  }
  :
}
```



Parent (Caller)

task

TBB

Call

matmult

OpenMP

Child (Callee)

Application Call Graph Hierarchy

Transfer of control coupled with transfer of resources.

Cooperative Hierarchical Resource Scheduling

```
tbb::task() {
  matmult() {
   #pragma omp parallel
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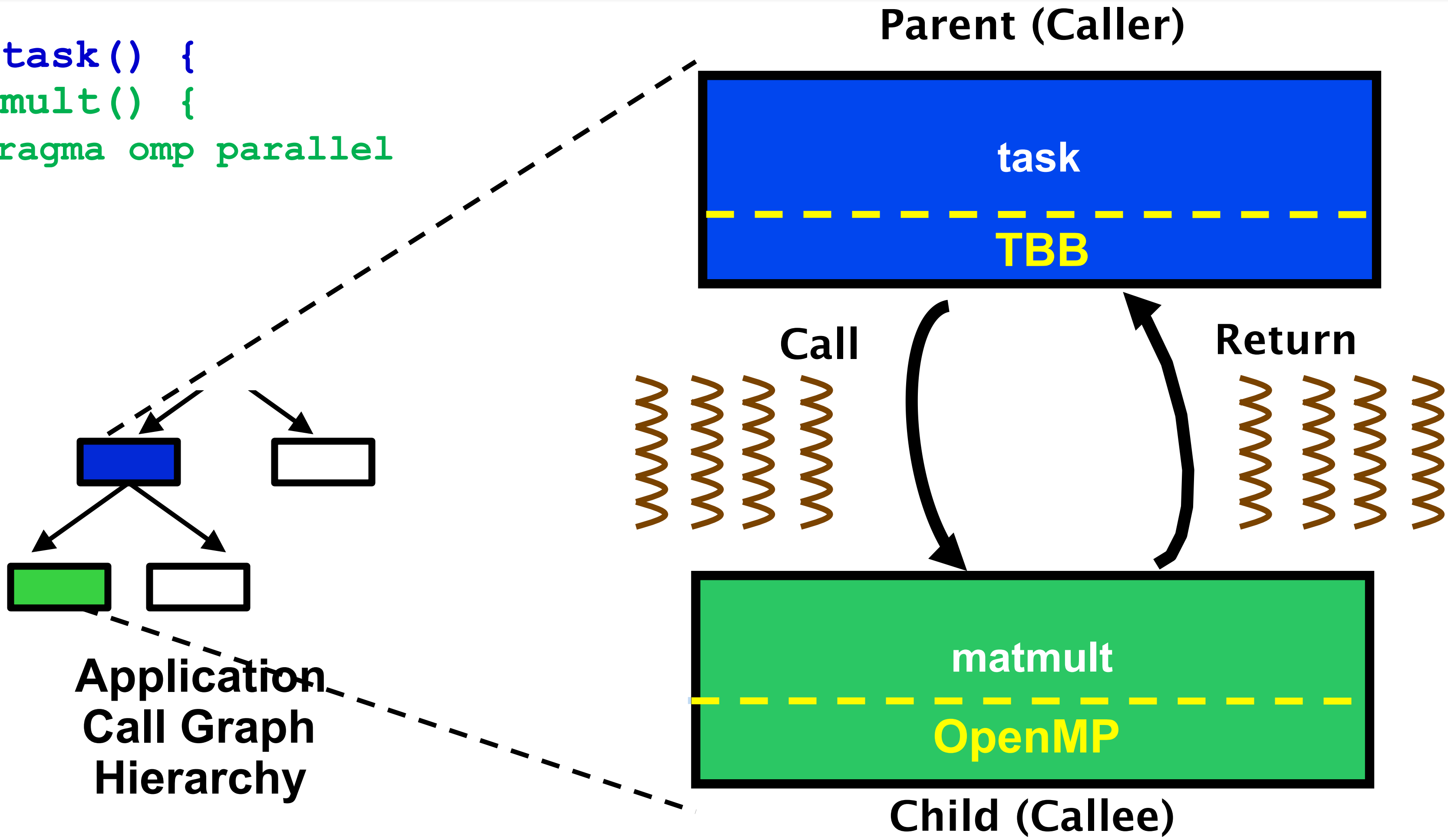
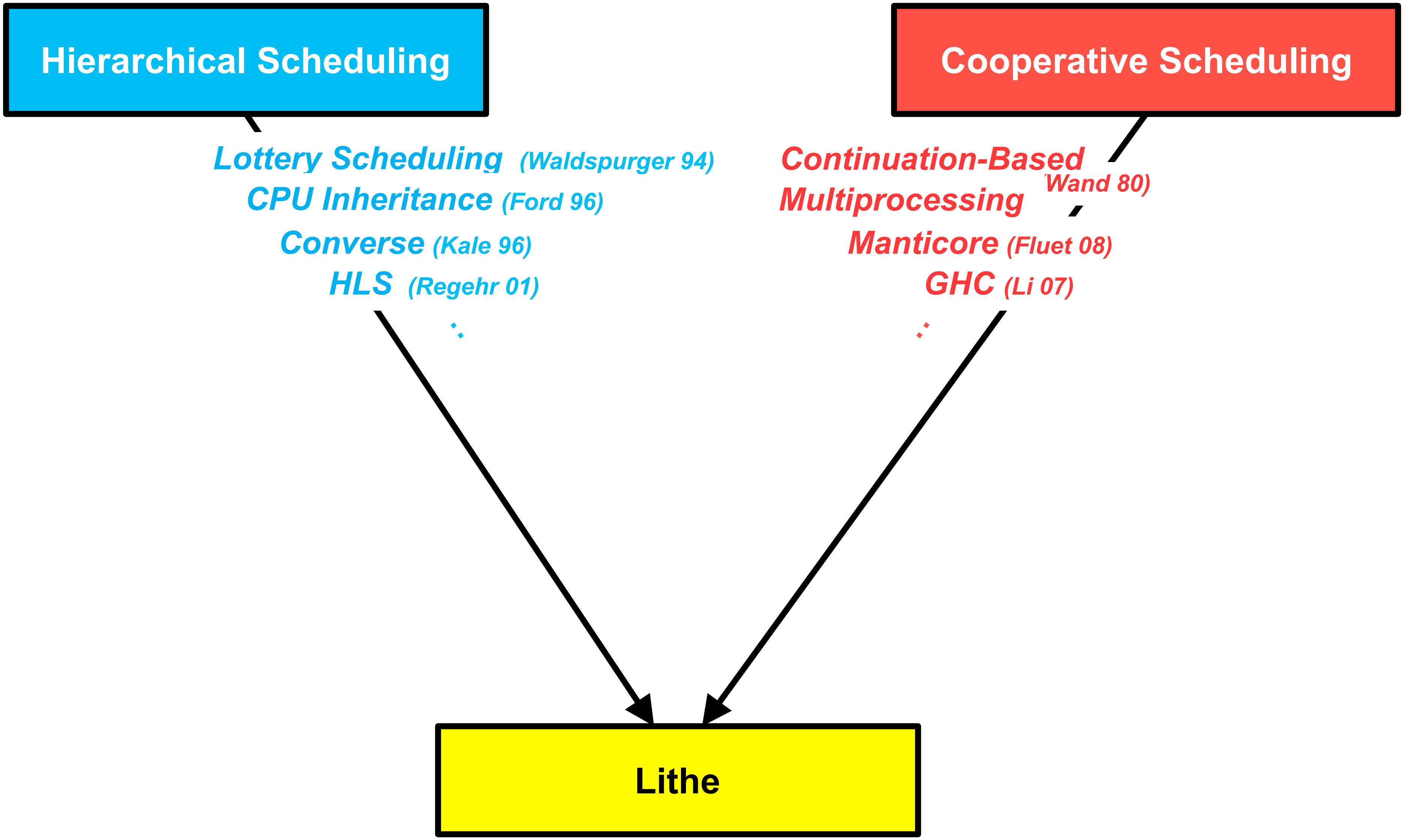
  }
  :
}
```



Transfer of control coupled with transfer of resources.

Confluence of Related Work



Hierarchical Scheduling

Lottery Scheduling (Waldspurger 94)

CPU Inheritance (Ford 96)

Converse (Kale 96)

HLS (Regehr 01)

⋮

Cooperative Scheduling

Continuation-Based Multiprocessing (Wand 80)

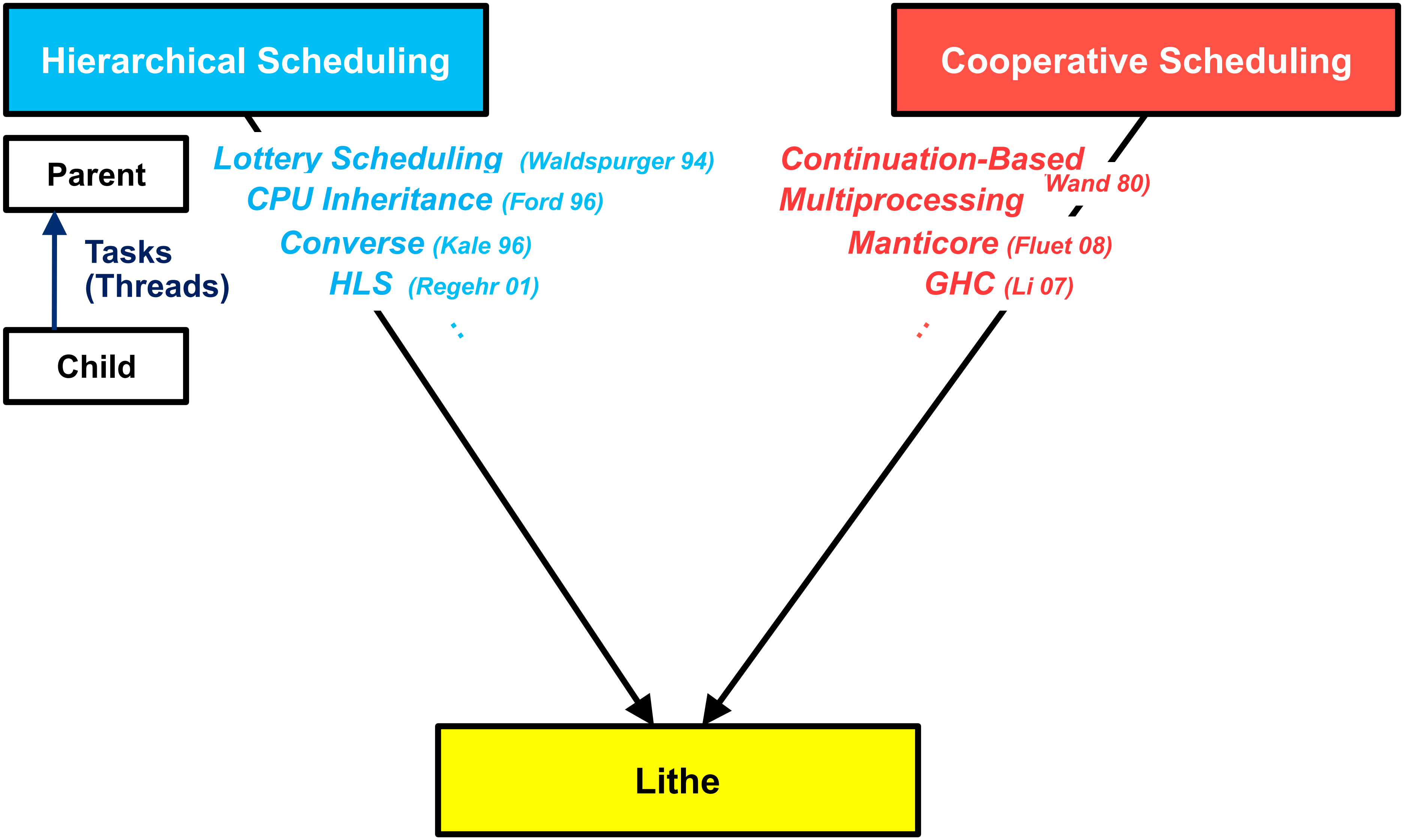
Manticore (Fluet 08)

GHC (Li 07)

⋮

Lithe

Confluence of Related Work



Hierarchical Scheduling

Parent

Tasks (Threads)

Child

Lottery Scheduling *(Waldspurger 94)*

CPU Inheritance *(Ford 96)*

Converse *(Kale 96)*

HLS *(Regehr 01)*

⋱

Cooperative Scheduling

Continuation-Based Multiprocessing Wand 80)

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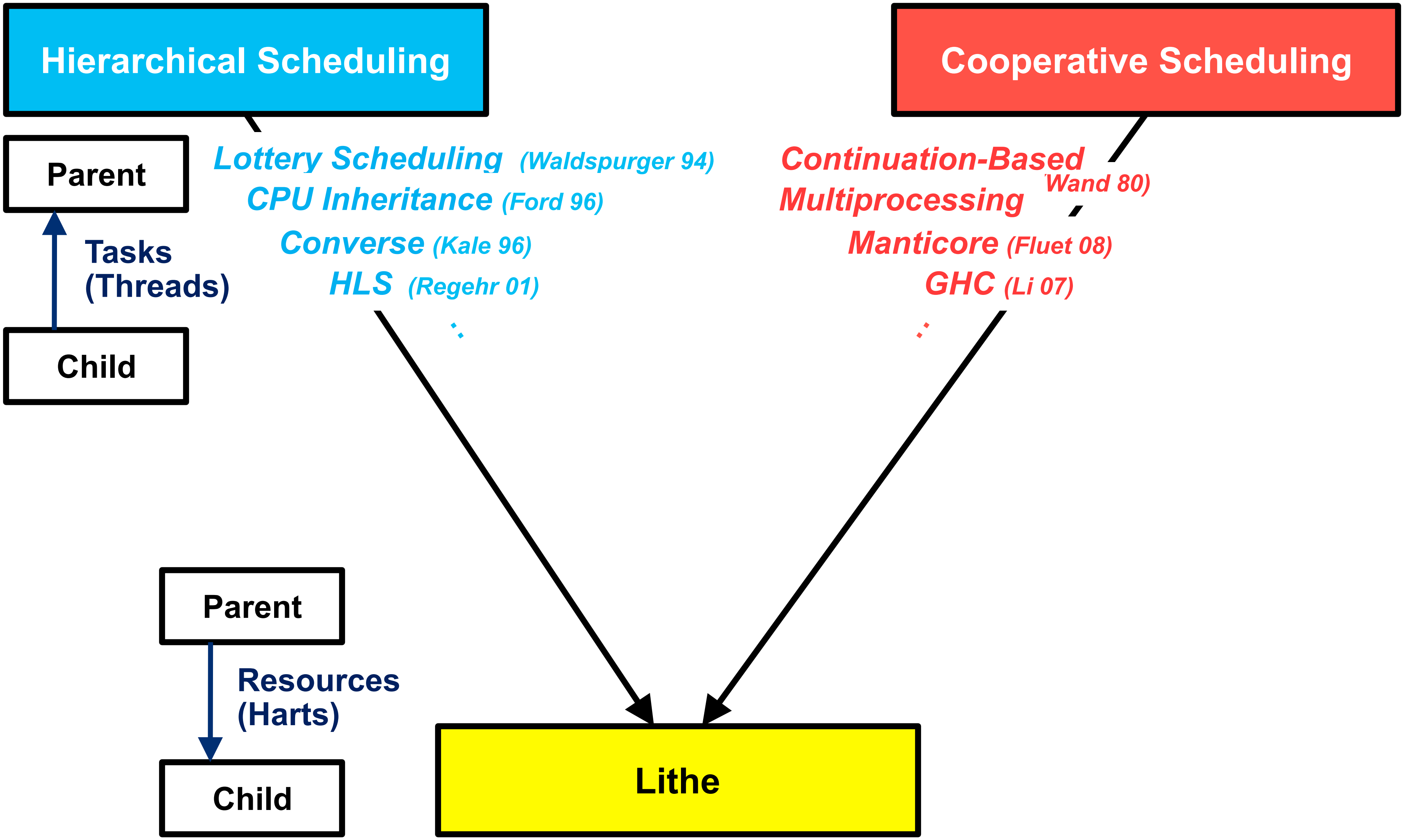
⋰

Lithe

Confluence of Related Work



Hierarchical Scheduling

Parent

Tasks (Threads)

Child

Lottery Scheduling (Waldspurger 94)

CPU Inheritance (Ford 96)

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⋱

Cooperative Scheduling

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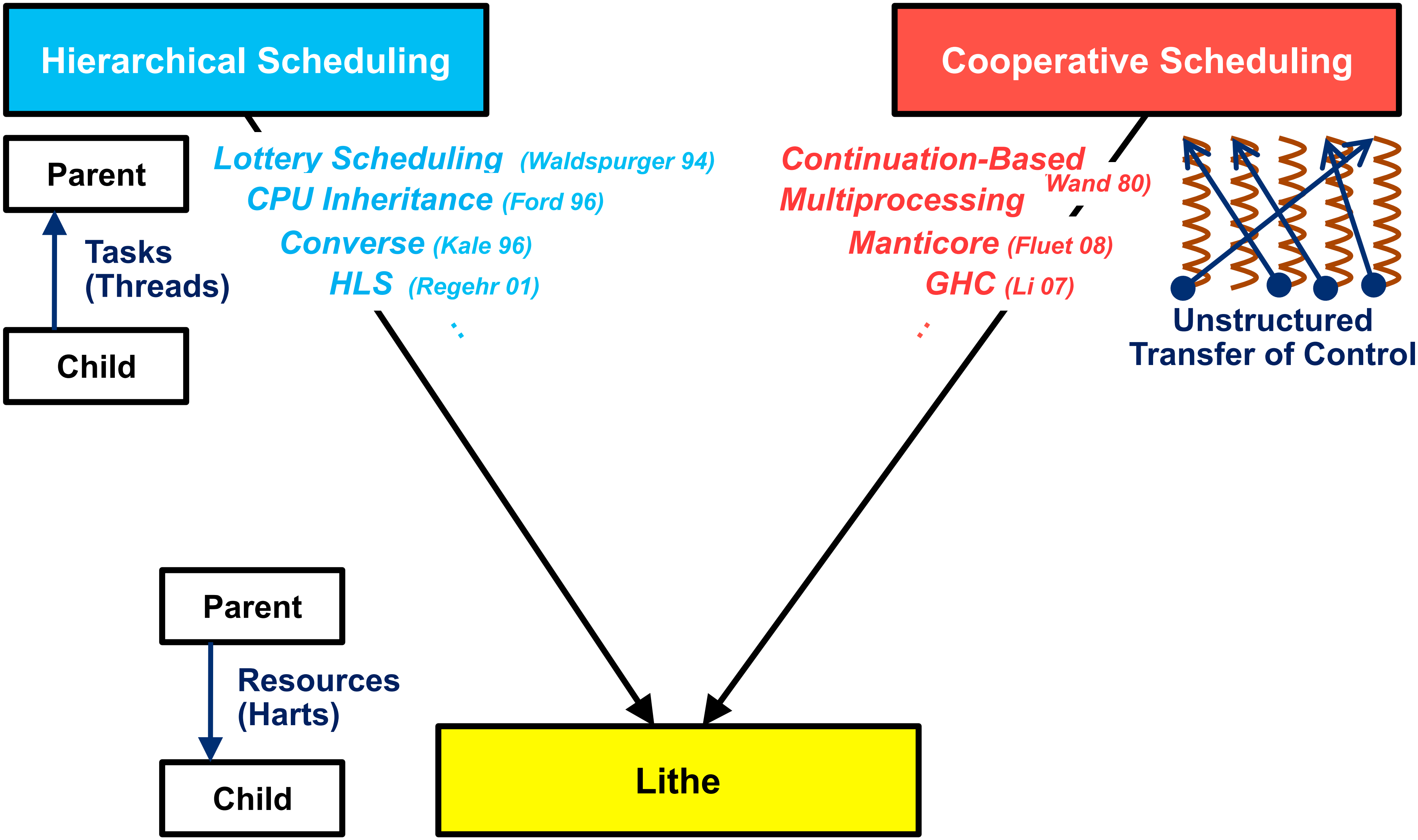
Parent

Resources (Harts)

Child

Lithe

Confluence of Related Work



Hierarchical Scheduling

Parent

Tasks (Threads)

Child

Lottery Scheduling (Waldspurger 94)

CPU Inheritance (Ford 96)

Converse (Kale 96)

HLS (Regehr 01)

Cooperative Scheduling

Continuation-Based Multiprocessing (Wand 80)

Manticore (Fluet 08)

GHC (Li 07)

Unstructured Transfer of Control

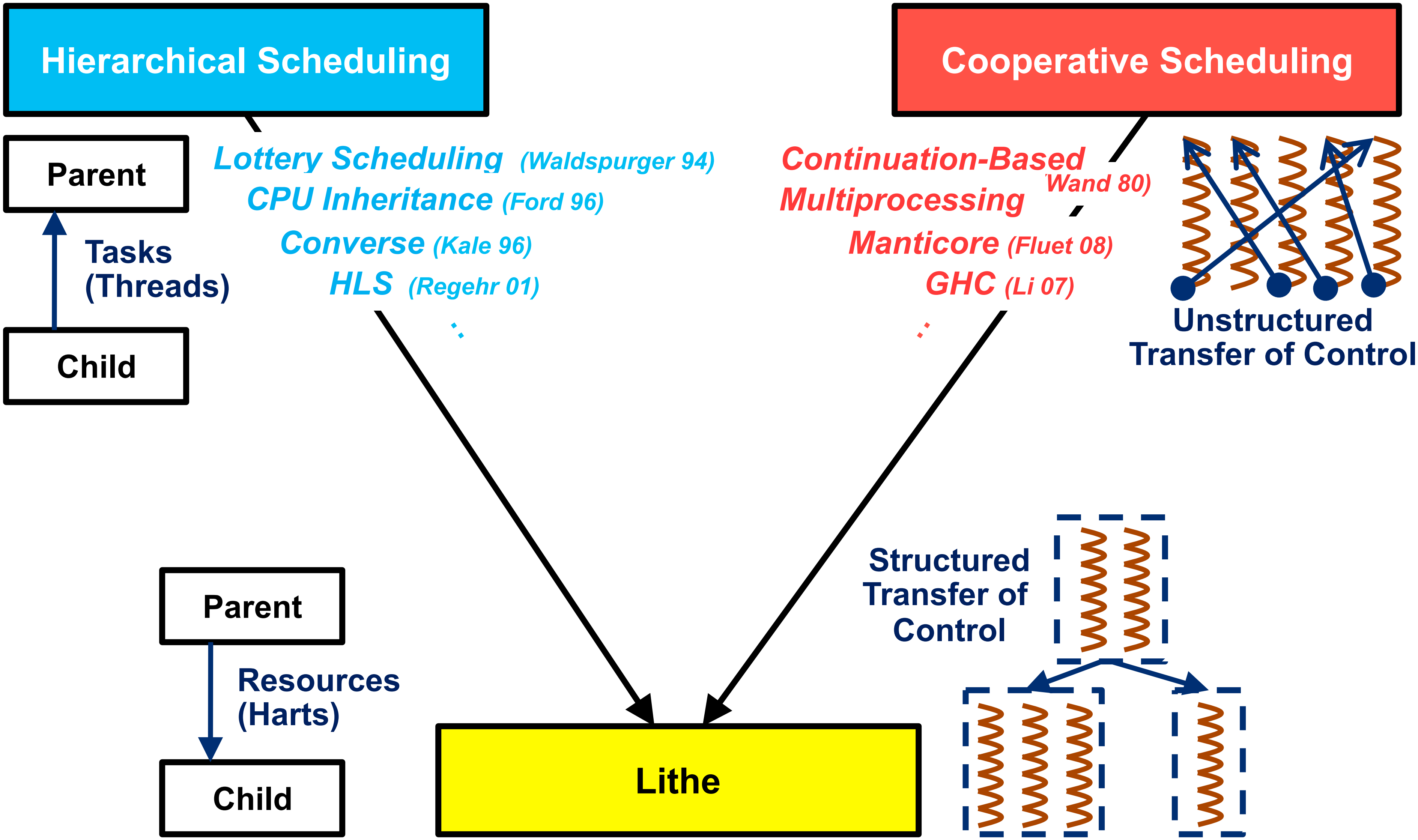
Parent

Resources (Harts)

Child

Lithe

Confluence of Related Work



Hierarchical Scheduling

Parent

Tasks (Threads)

Child

Lottery Scheduling *(Waldspurger 94)*

CPU Inheritance *(Ford 96)*

Converse *(Kale 96)*

HLS *(Regehr 01)*

⋮

Cooperative Scheduling

Continuation-Based Multiprocessing *(Wand 80)*

Manticore *(Fluet 08)*

GHC *(Li 07)*

⋮

Unstructured Transfer of Control

Parent

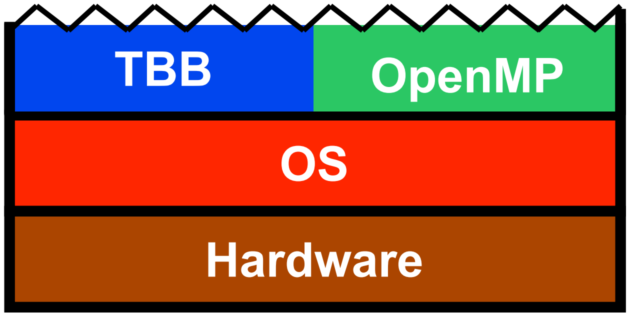
Resources (Harts)

Child

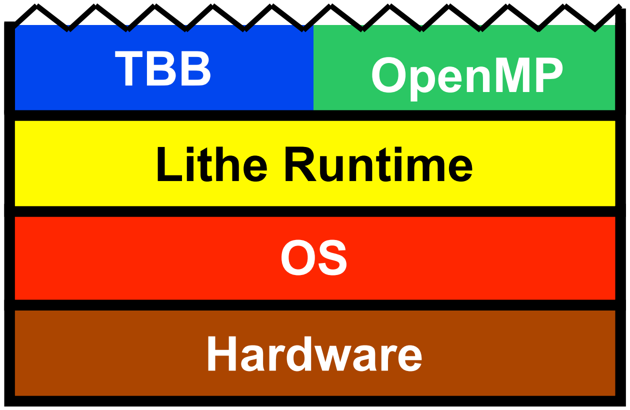
Lithe

Structured Transfer of Control

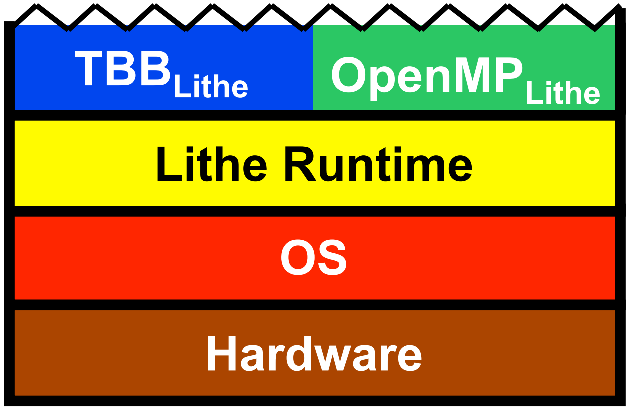
The Lithe Runtime



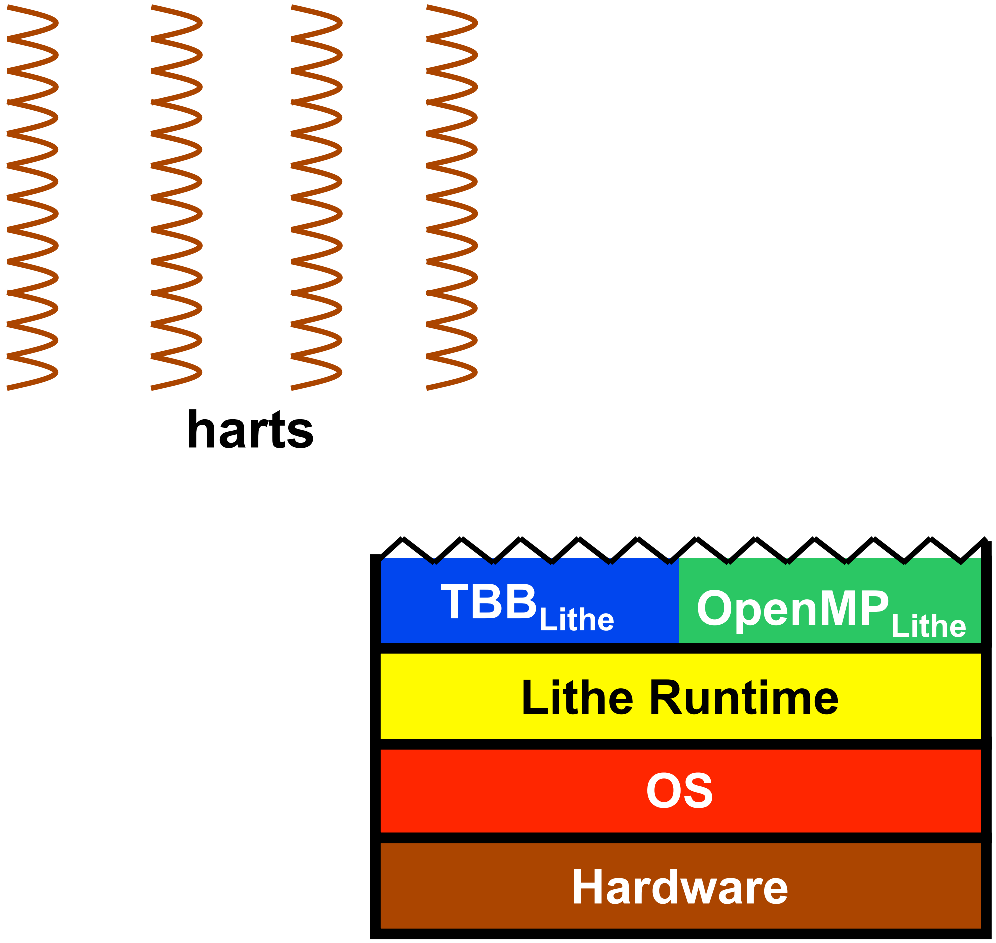
The Lithe Runtime



The Lithe Runtime



The Lithe Runtime



harts

$\text{TBB}_{\text{Lithe}}$ $\text{OpenMP}_{\text{Lithe}}$

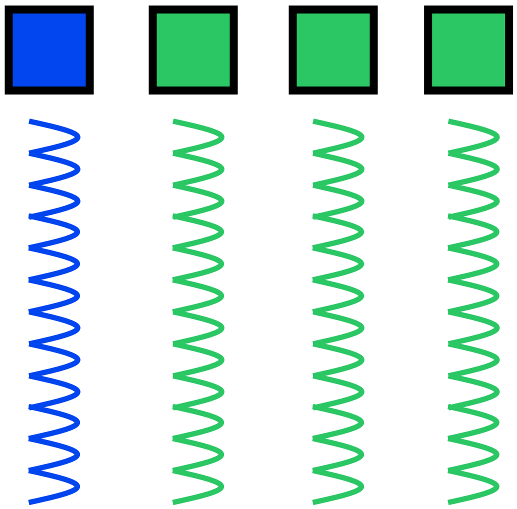
Lithe Runtime

OS

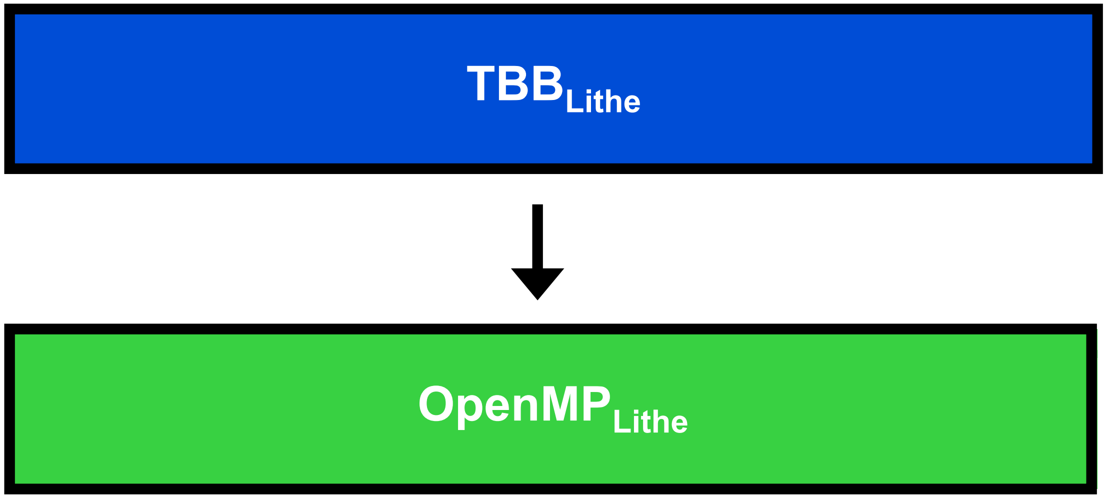
Hardware

The Lithe Runtime

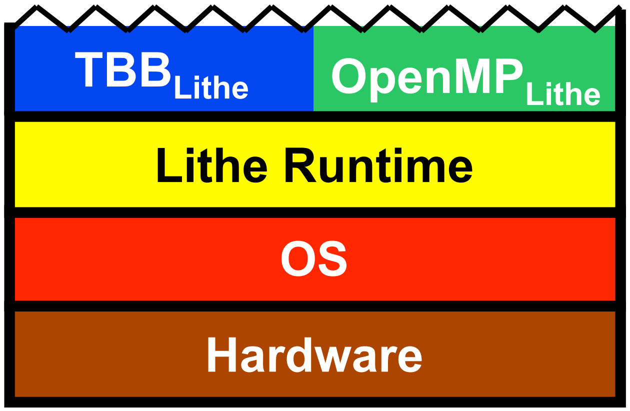
current scheduler



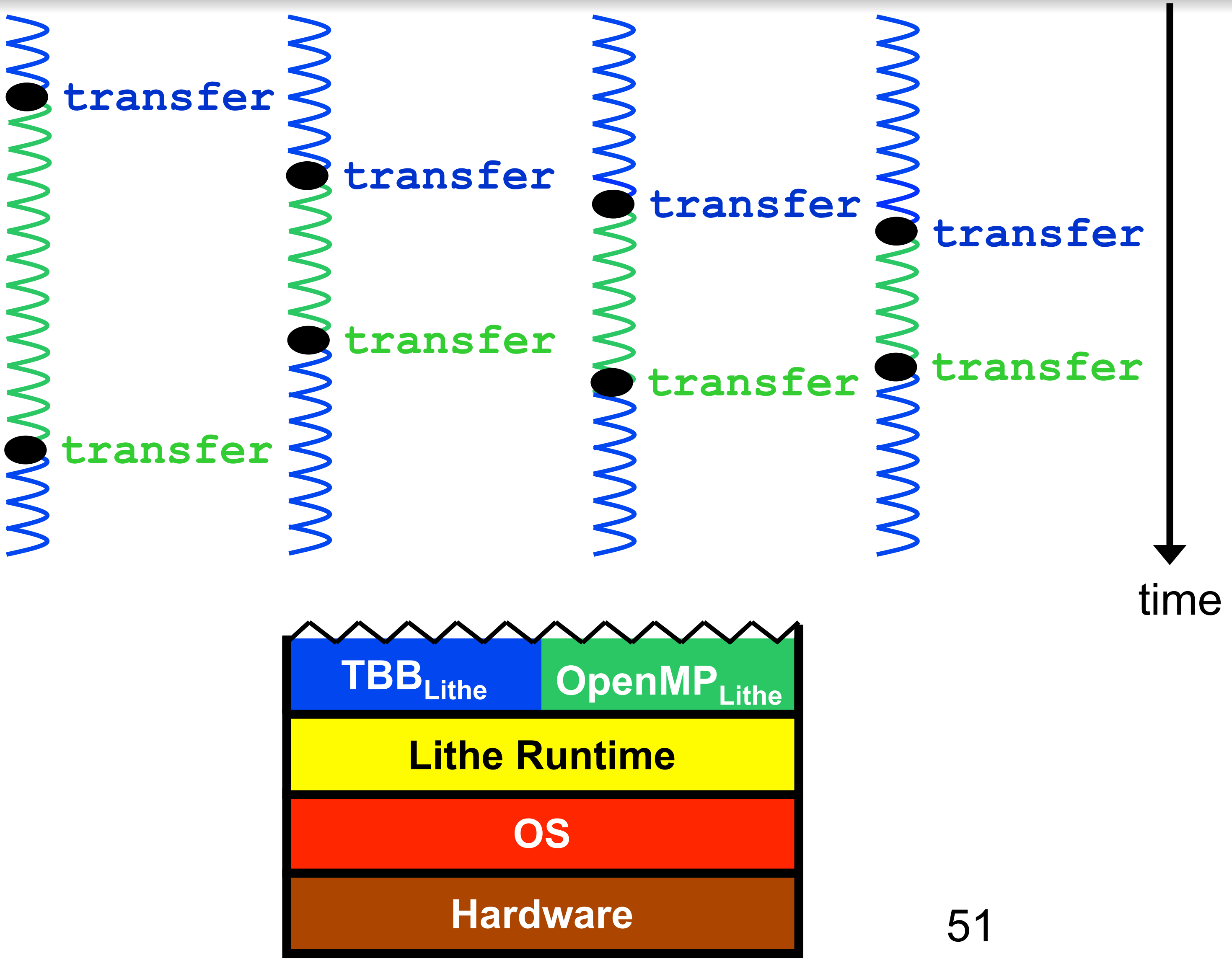
harts



scheduler hierarchy



The Lithe Runtime



transfer

transfer

transfer

transfer

transfer

transfer

transfer

transfer

time

$\text{TBB}_{\text{Lithe}}$ $\text{OpenMP}_{\text{Lithe}}$

Lithe Runtime

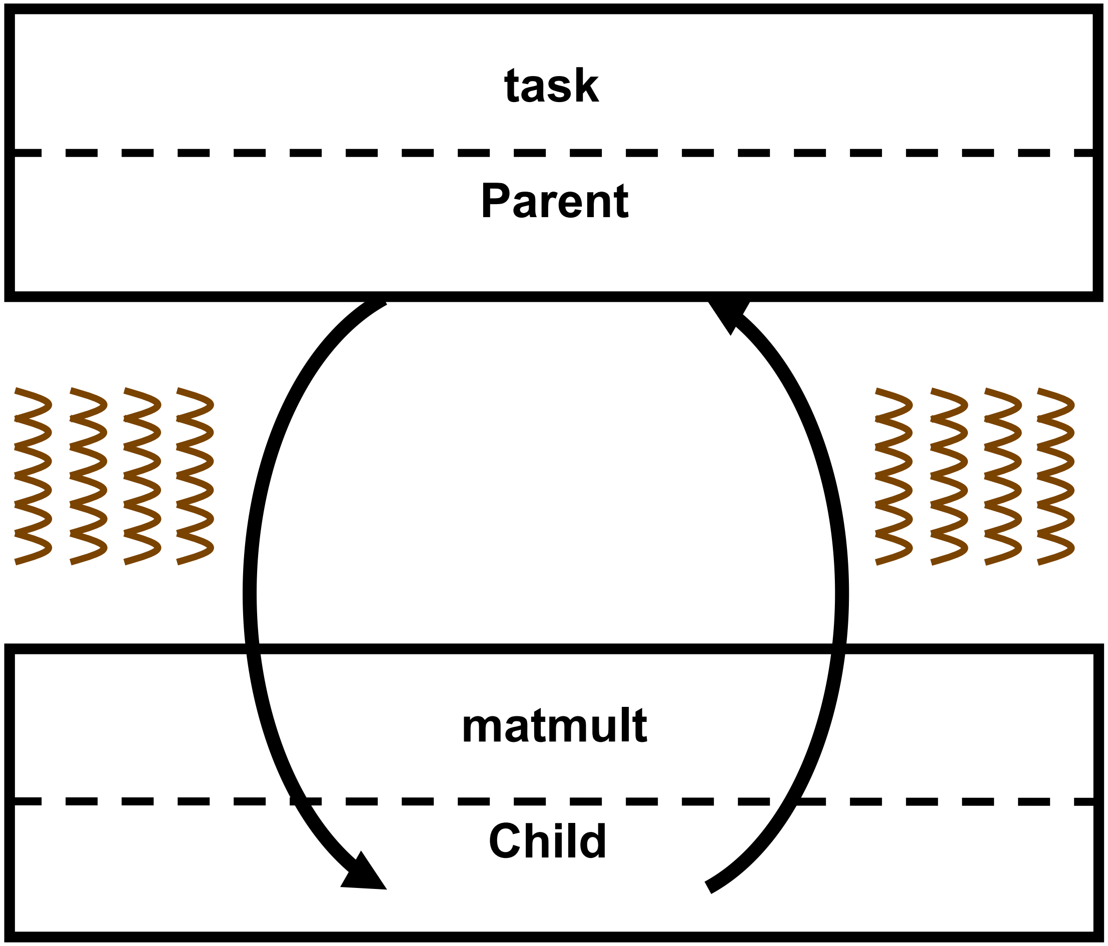
OS

Hardware

Standard API/Callback Interface

```
task() {
  matmult() {

     :
    }
    :
}
```

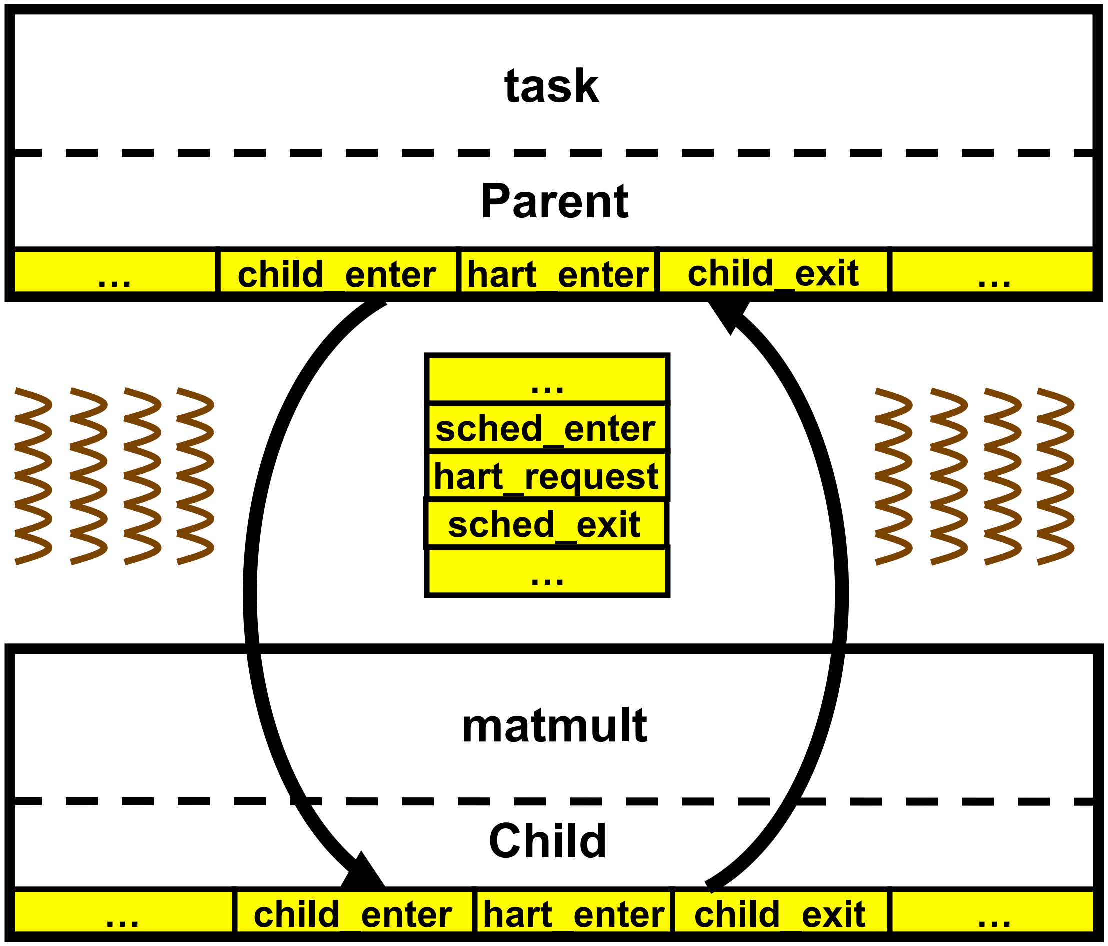


Separation of Interface and Implementation

Standard API/Callback Interface

```
task() {
  matmult() {

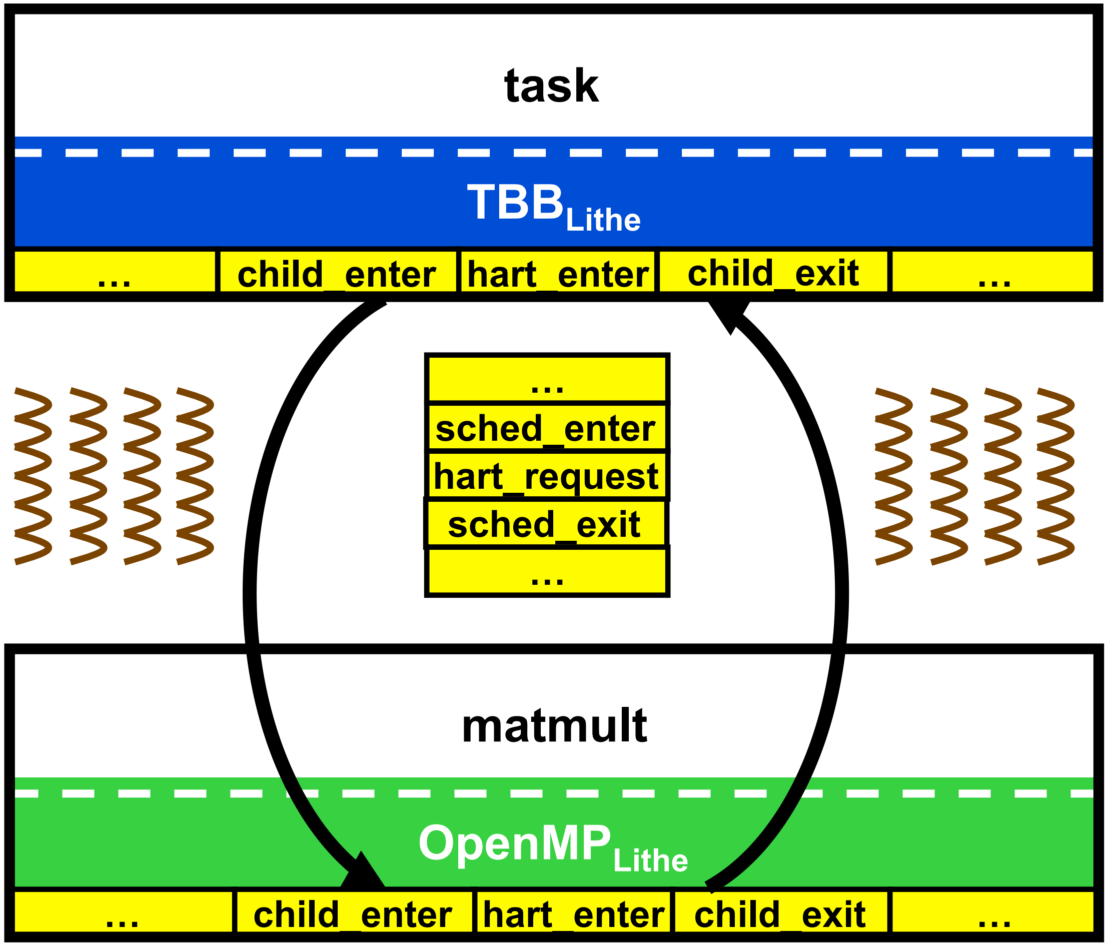
     :
    }
    :
}
```



Separation of Interface and Implementation

Standard API/Callback Interface

```
tbb::
task() {
  matmult() {
   #pragma OMP parallel
   :
  }
  :
}
```



task

$\text{TBB}_{\text{Lithe}}$

… | child_enter | hart_enter | child_exit | …

…

sched_enter

hart_request

sched_exit

…

matmult

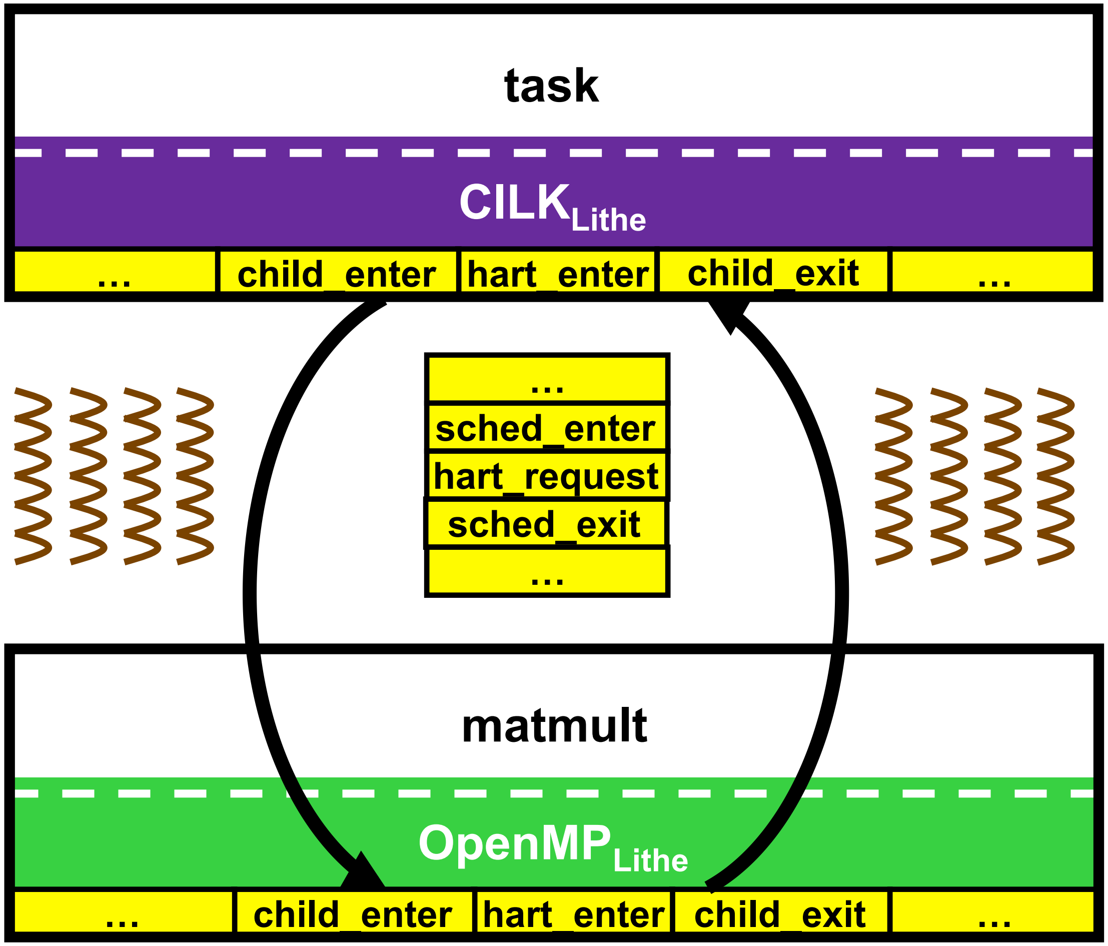
$\text{OpenMP}_{\text{Lithe}}$

… | child_enter | hart_enter | child_exit | …

Separation of Interface and Implementation

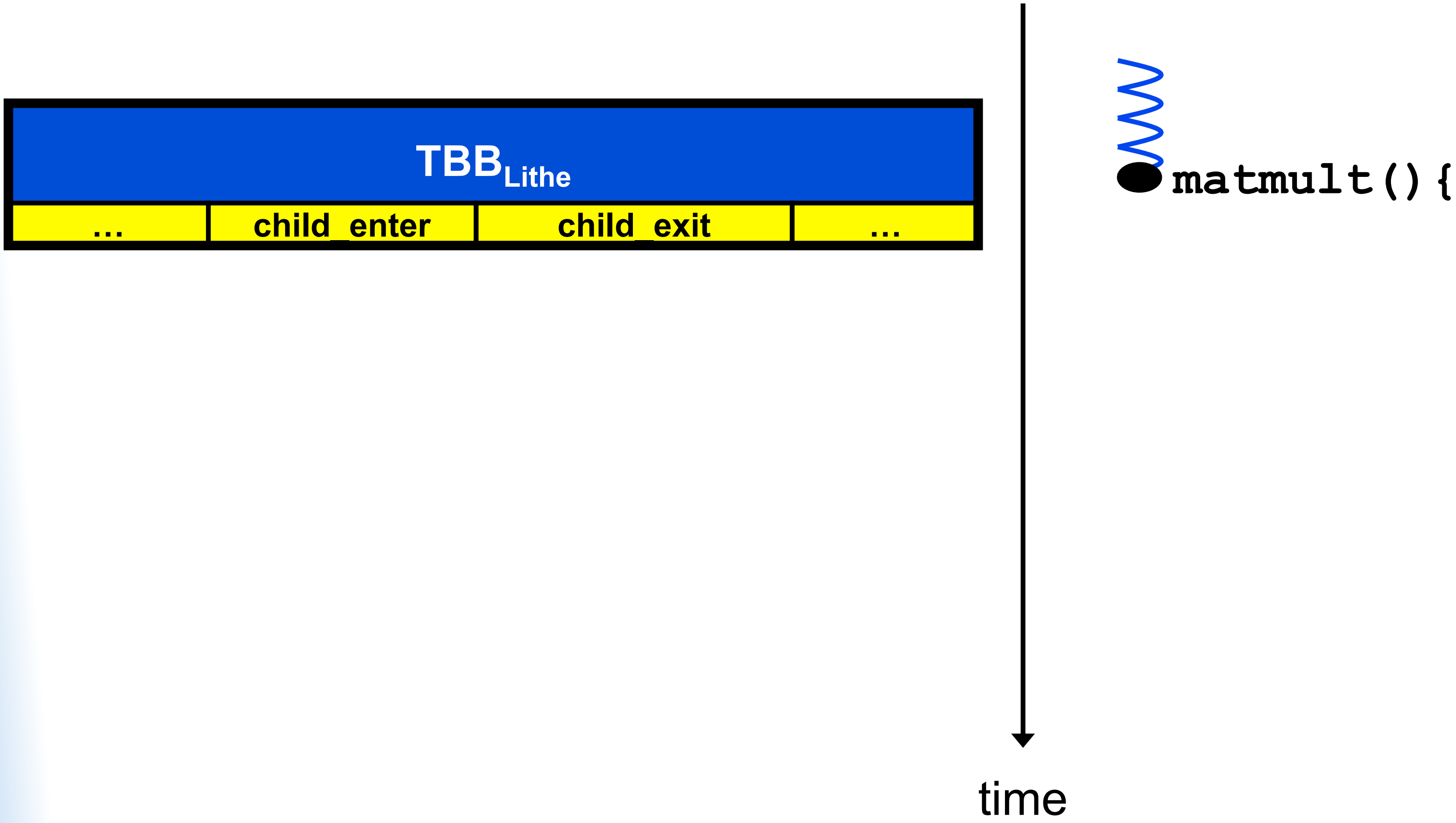
Standard API/Callback Interface

```
cilk
task() {
  matmult() {
    #pragma OMP parallel
     :
  }
  :
}
```



Separation of Interface and Implementation

Enter/Exit a Scheduler



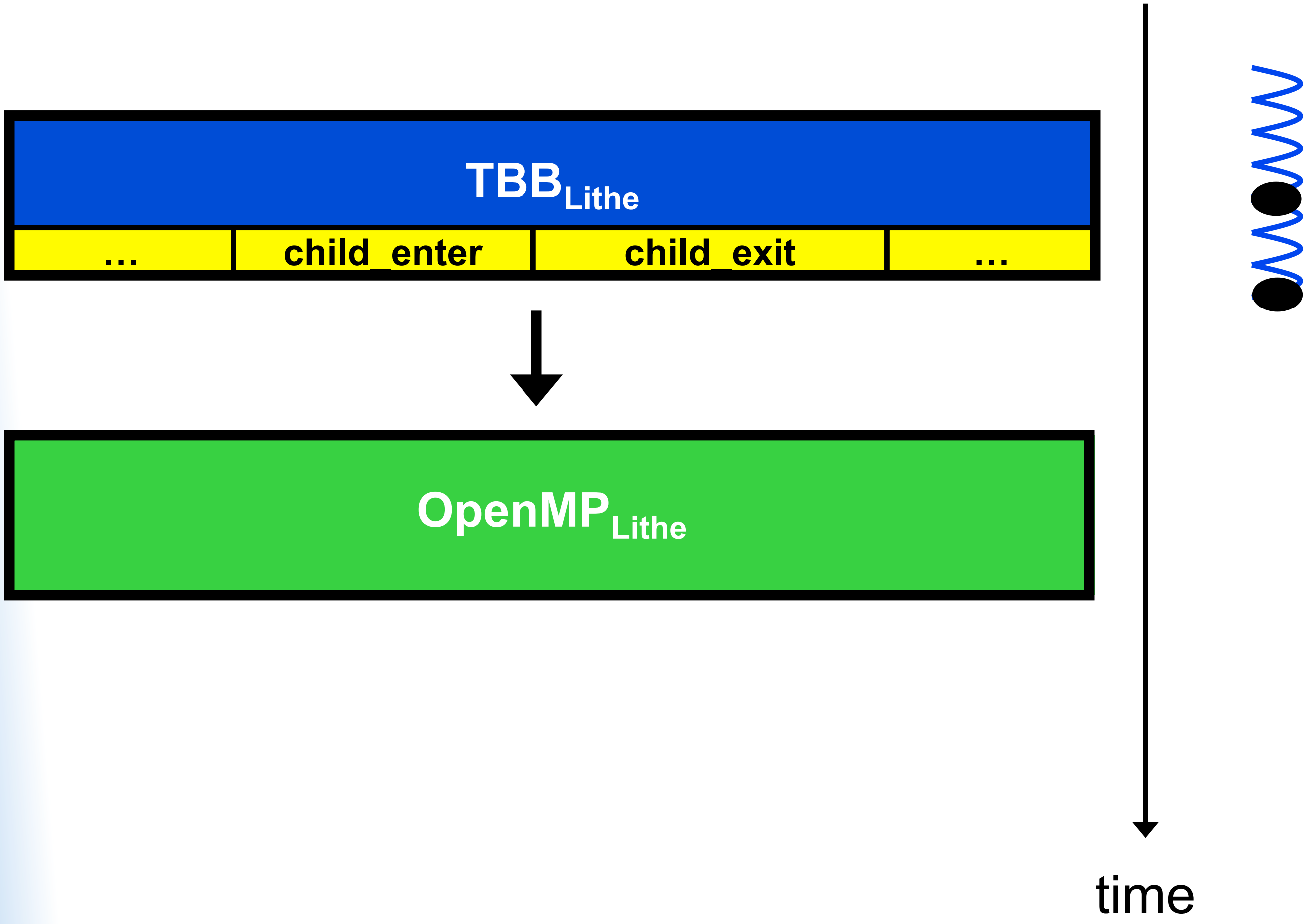
TBB$_{Lithe}$

… child_enter child_exit …

`matmult(){`

time

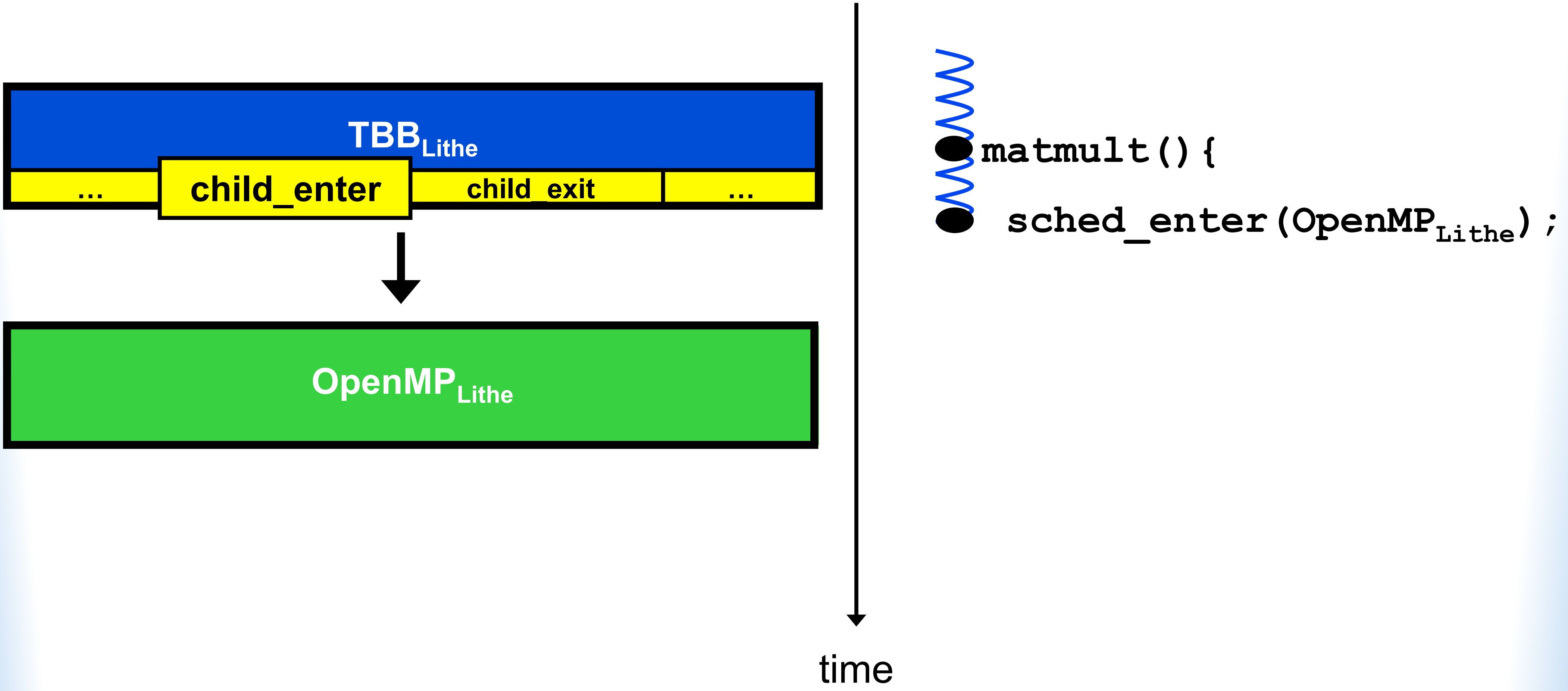
Enter/Exit a Scheduler



```
matmult(){
  sched_enter(OpenMP_Lithe);
```

`sched_enter()` **dynamically adds the new scheduler to the hierarchy.**

Enter/Exit a Scheduler

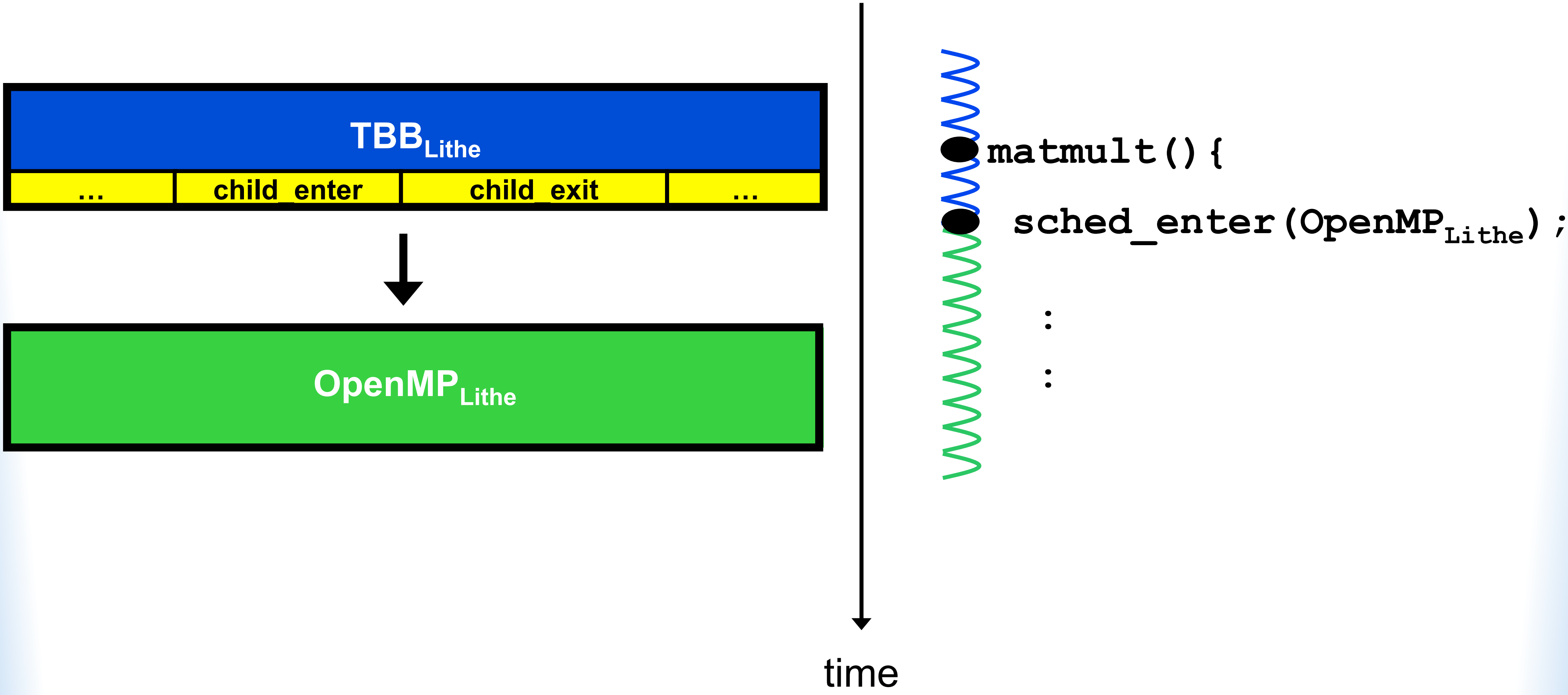


matmult(){

sched_enter(OpenMP$_{Lithe}$);

sched_enter() dynamically adds the new scheduler to the hierarchy.

Enter/Exit a Scheduler



```
matmult(){
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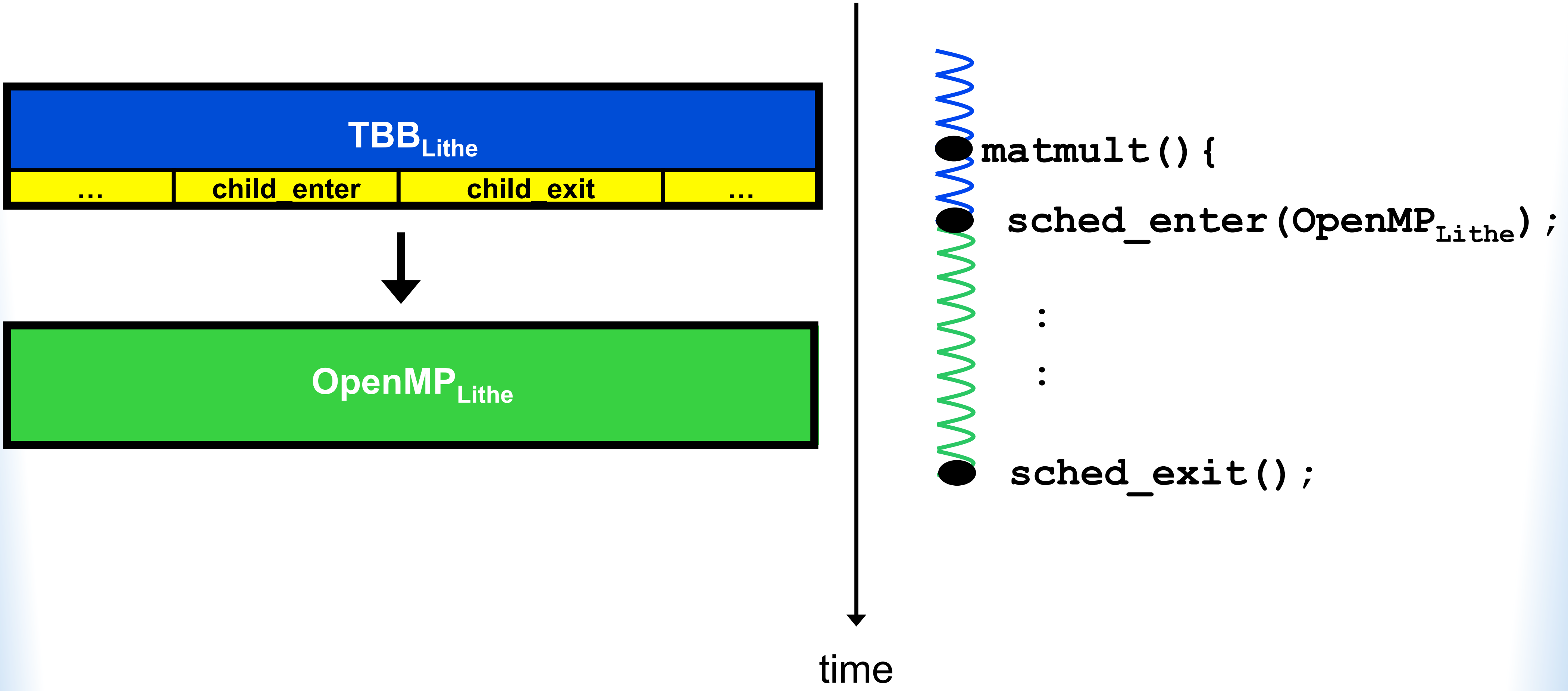
    :
    :
```

`sched_enter()` **dynamically adds the new scheduler to the hierarchy.**

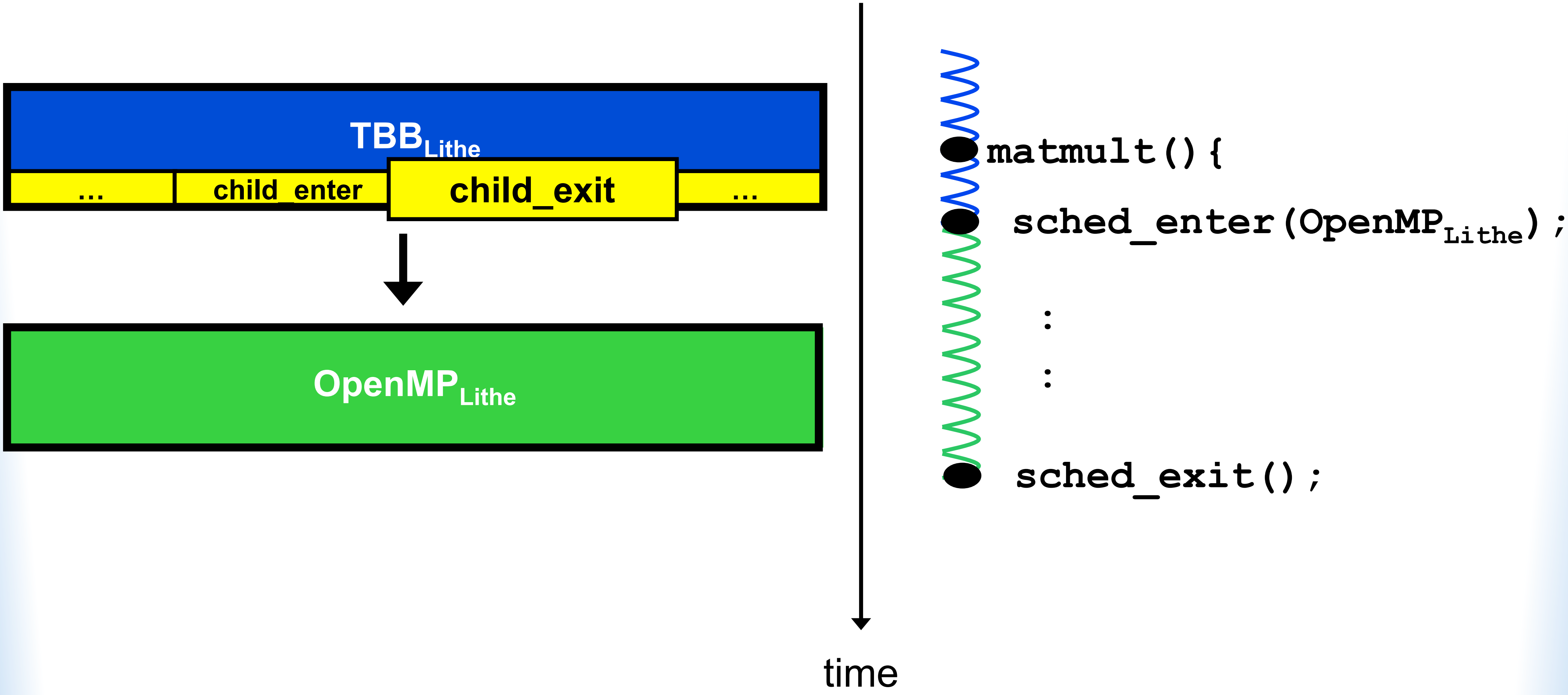
Enter/Exit a Scheduler



```
matmult(){
  sched_enter(OpenMPLithe);
     :
     :
  sched_exit();
```

`sched_enter()` **dynamically adds the new scheduler to the hierarchy.**
`sched_exit()` **dynamically removes a scheduler from the hierarchy.**

Enter/Exit a Scheduler



```
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`sched_enter()` **dynamically adds the new scheduler to the hierarchy.**
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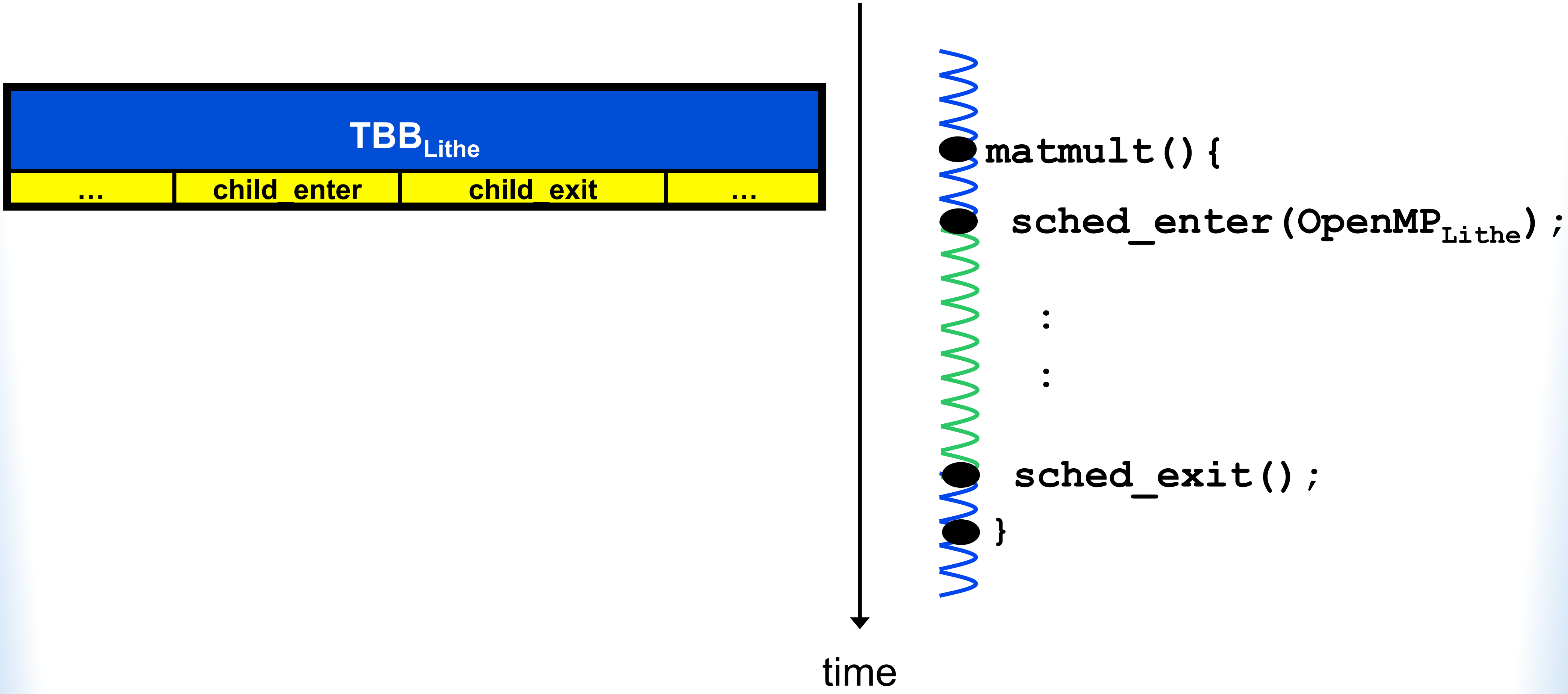
Enter/Exit a Scheduler



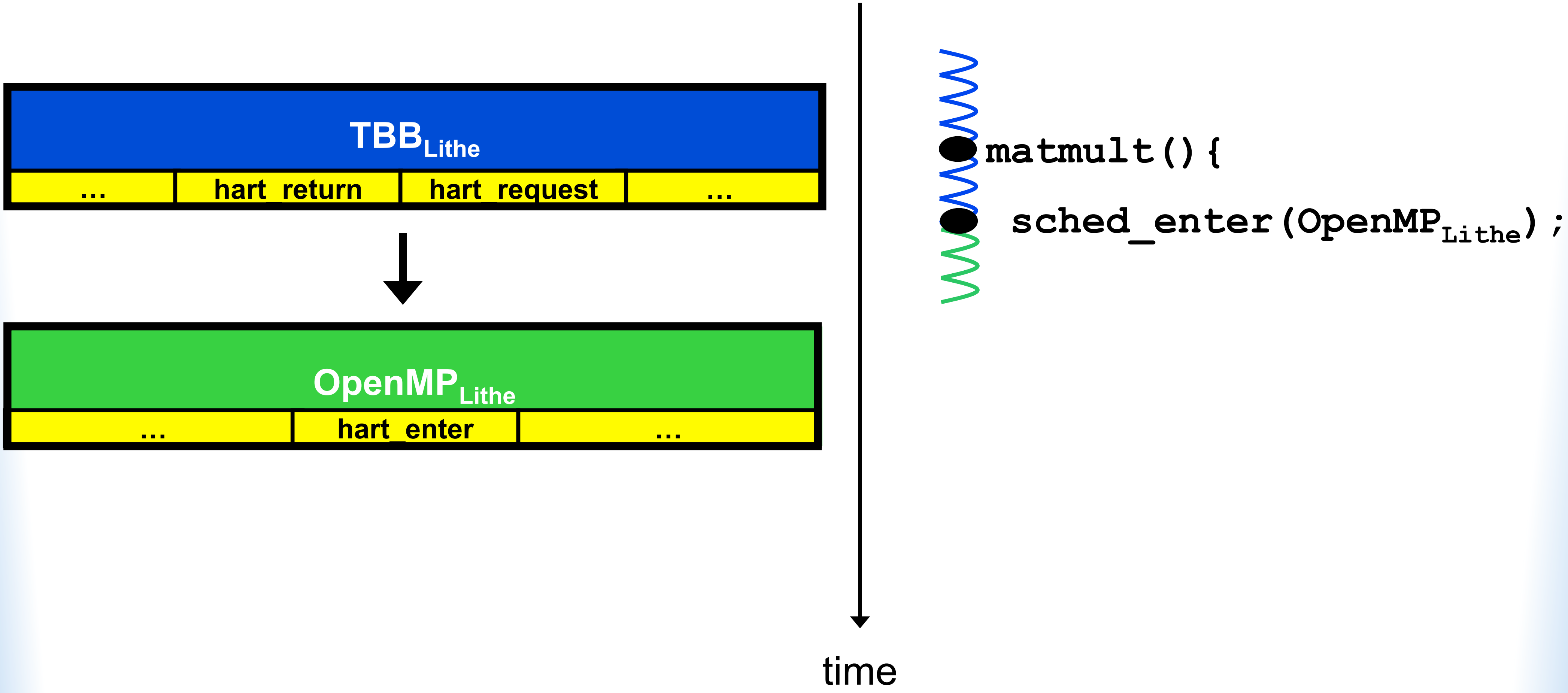
TBB_{Lithe}

… | child_enter | child_exit | …

```
matmult(){
  sched_enter(OpenMPLithe);
    :
    :
  sched_exit();
}
```

`sched_enter()` dynamically adds the new scheduler to the hierarchy.
`sched_exit()` dynamically removes a scheduler from the hierarchy.

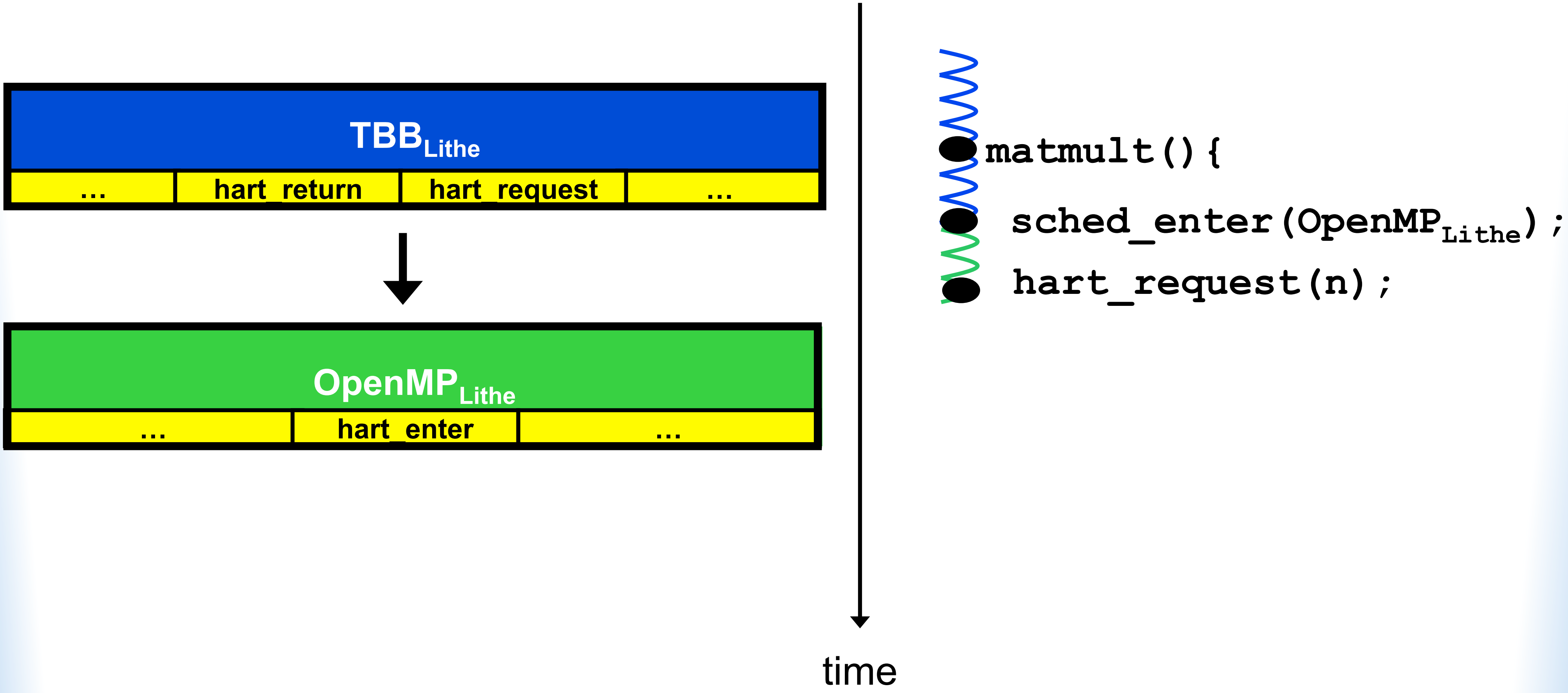
Request/Grant/Yield a Hart



```
matmult(){
  sched_enter(OpenMP_Lithe);
```

`hart_request()`,`hart_grant()`,`hart_yield()` **transfer harts between a parent and child.**

Request/Grant/Yield a Hart



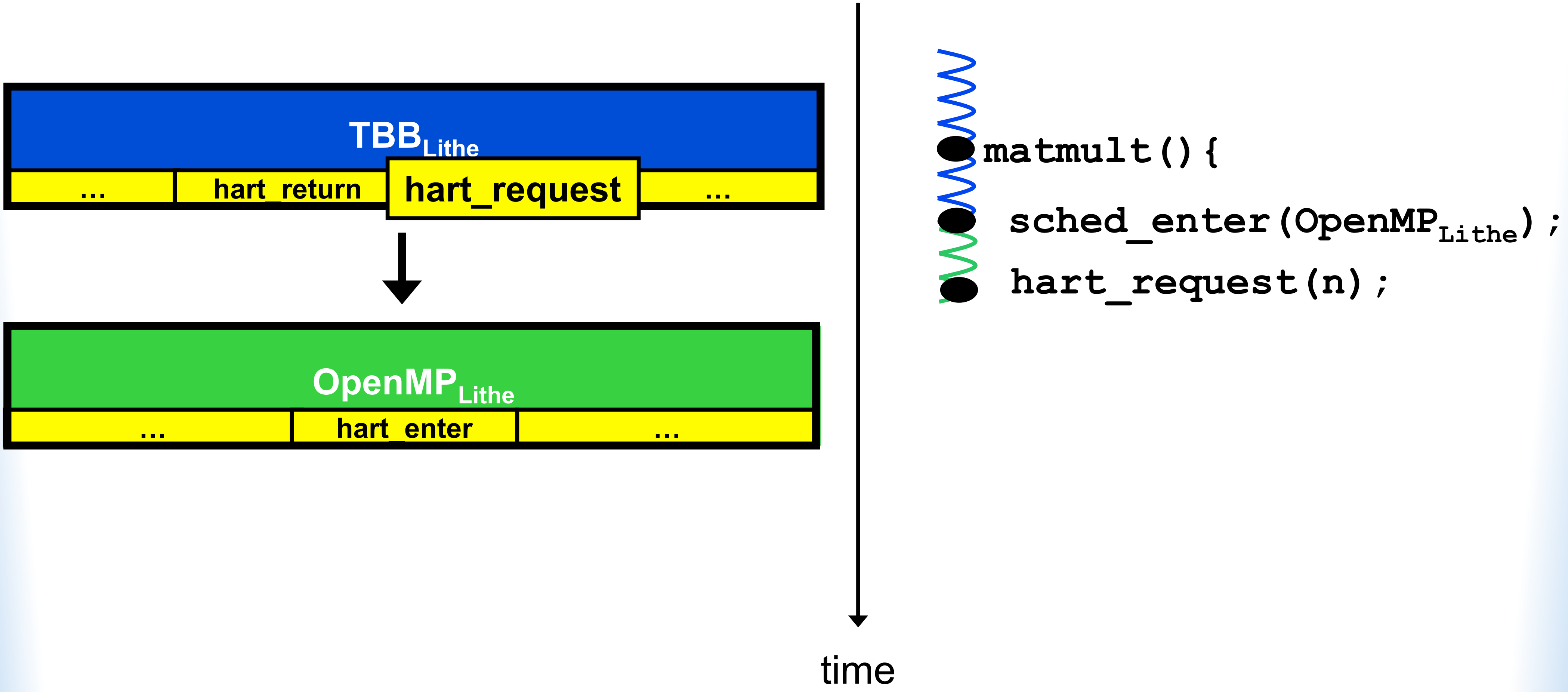
matmult(){

  sched_enter($\text{OpenMP}_{\text{Lithe}}$);

  hart_request(n);

hart_request(),hart_grant(),hart_yield()
transfer harts between a parent and child.

Request/Grant/Yield a Hart



```
matmult(){
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  hart_request(n);
```

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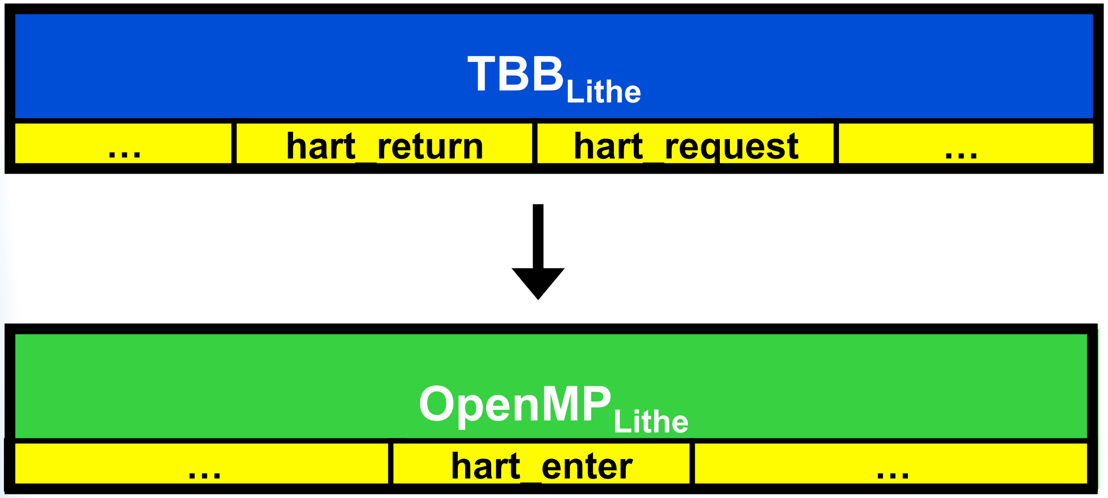
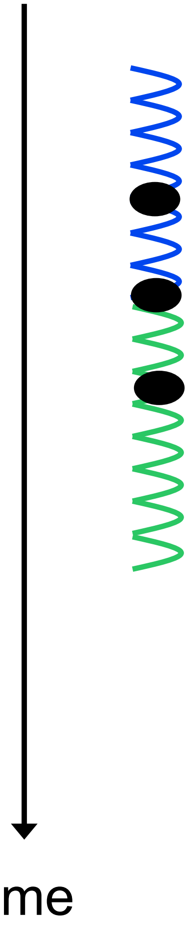
Request/Grant/Yield a Hart

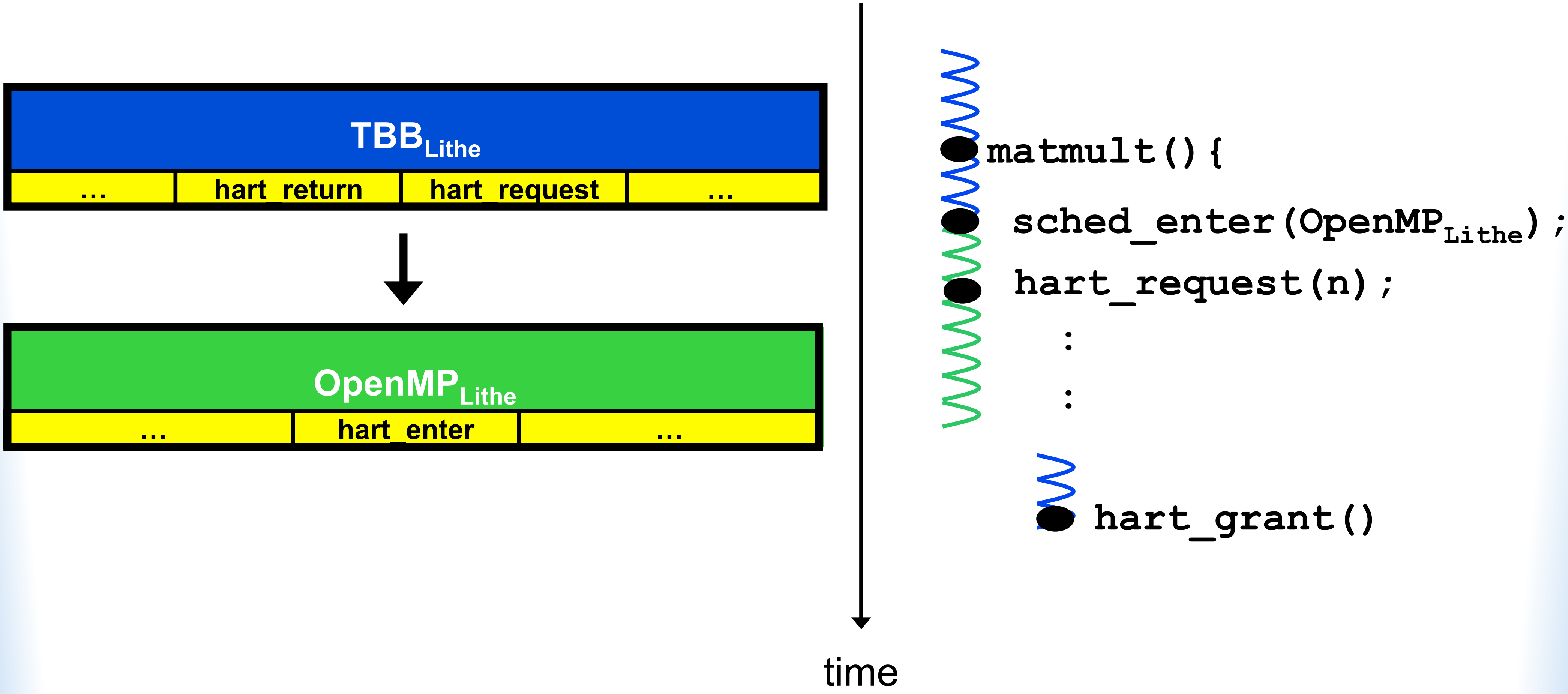




```
matmult(){
  sched_enter(OpenMP_Lithe);
  hart_request(n);
      :
      :
```

`hart_request(),hart_grant(),hart_yield()`
transfer harts between a parent and child.

Request/Grant/Yield a Hart



matmult(){

sched_enter(OpenMP$_{\text{Lithe}}$);

hart_request(n);

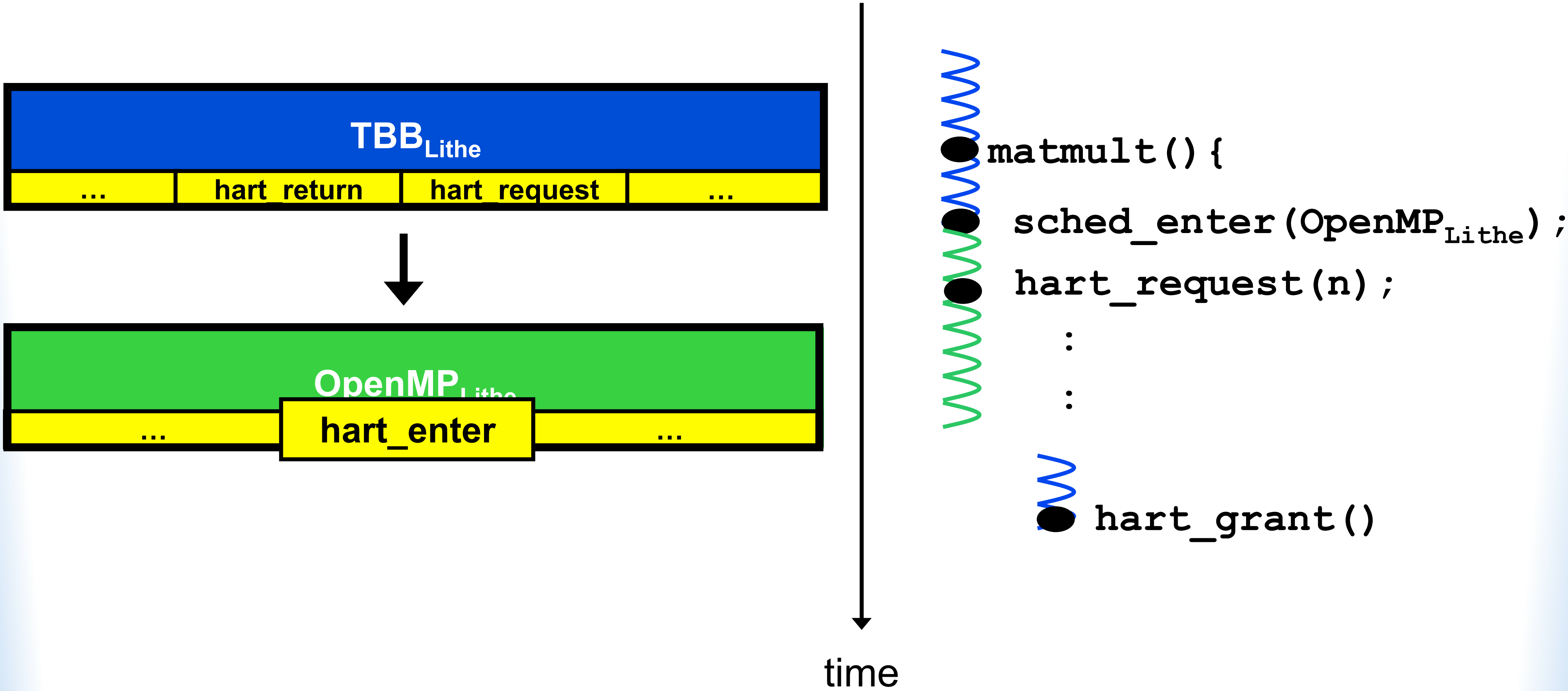
:

:

hart_grant()

hart_request(),hart_grant(),hart_yield()
transfer harts between a parent and child.

Request/Grant/Yield a Hart



$\text{TBB}_{\text{Lithe}}$

… | hart_return | hart_request | …

$\text{OpenMP}_{\text{Lithe}}$

… | hart_enter | …

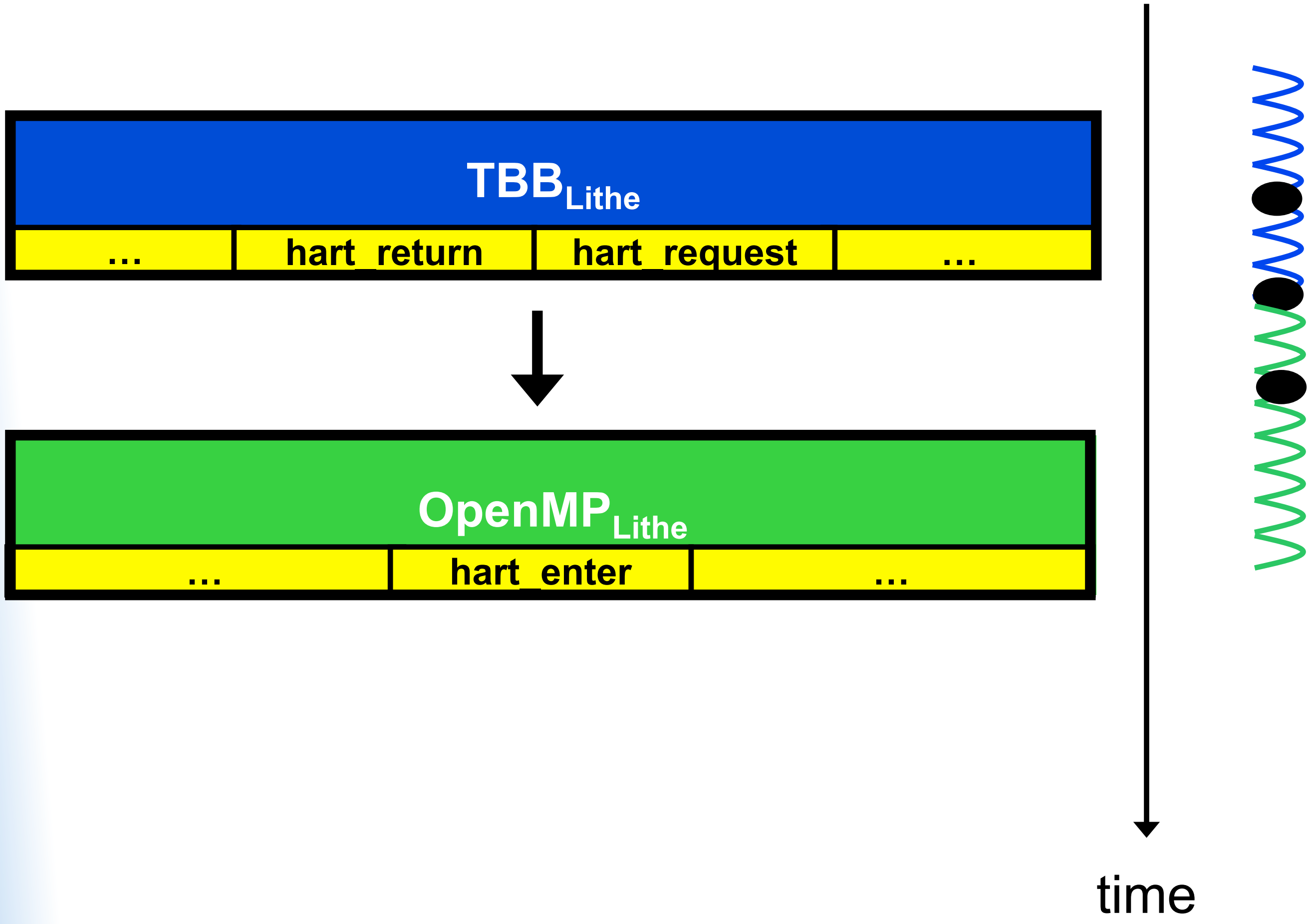
time

```
matmult(){
  sched_enter(OpenMP_Lithe);
  hart_request(n);
     :
     :

     hart_grant()
```

`hart_request(),hart_grant(),hart_yield()`
transfer harts between a parent and child.

Request/Grant/Yield a Hart



matmult(){

sched_enter(OpenMP$_{\text{Lithe}}$);

hart_request(n);

:

:

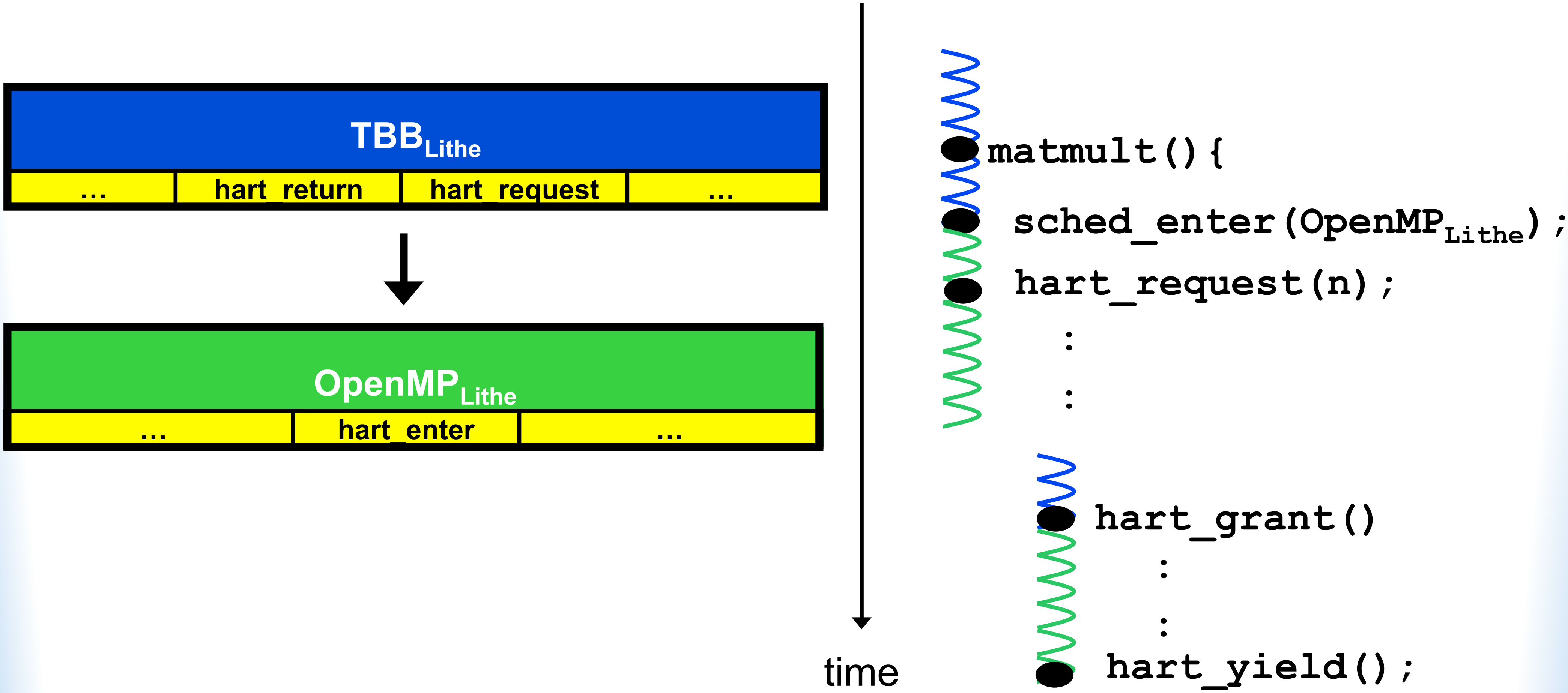
hart_grant()

:

:

hart_request(),hart_grant(),hart_yield() transfer harts between a parent and child.

Request/Grant/Yield a Hart



matmult(){

  sched_enter($\text{OpenMP}_{\text{Lithe}}$);

  hart_request(n);

    :

    :

      hart_grant()

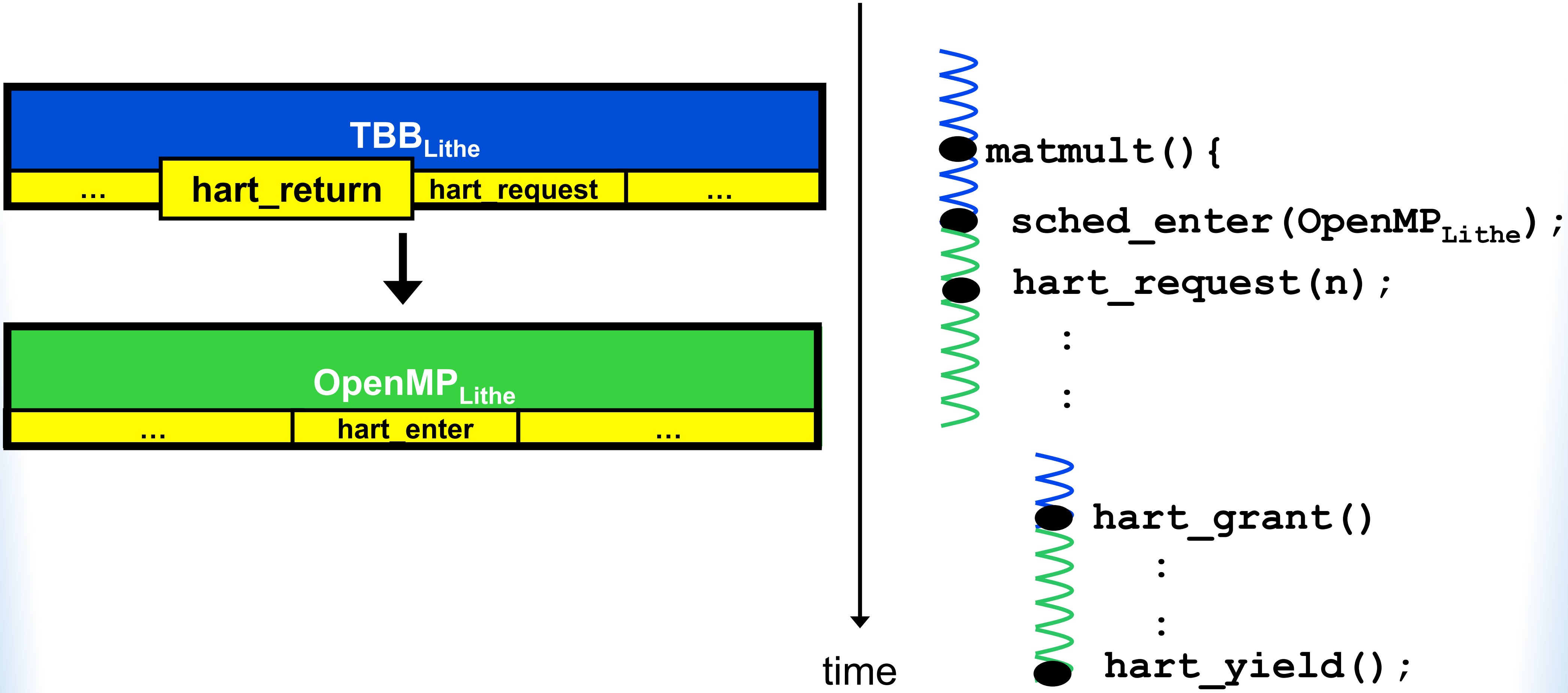
        :

        :

       hart_yield();

hart_request(),hart_grant(),hart_yield() transfer harts between a parent and child.

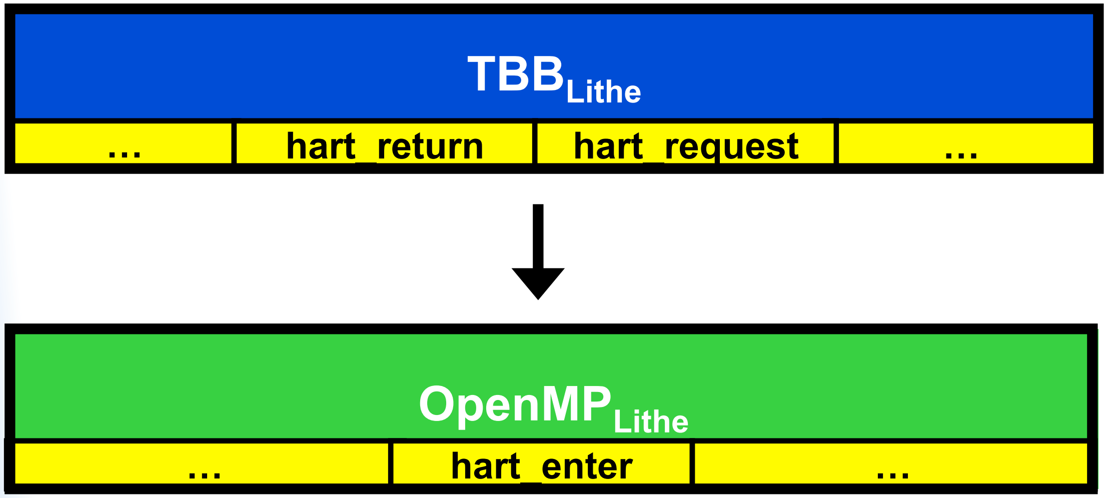
Request/Grant/Yield a Hart

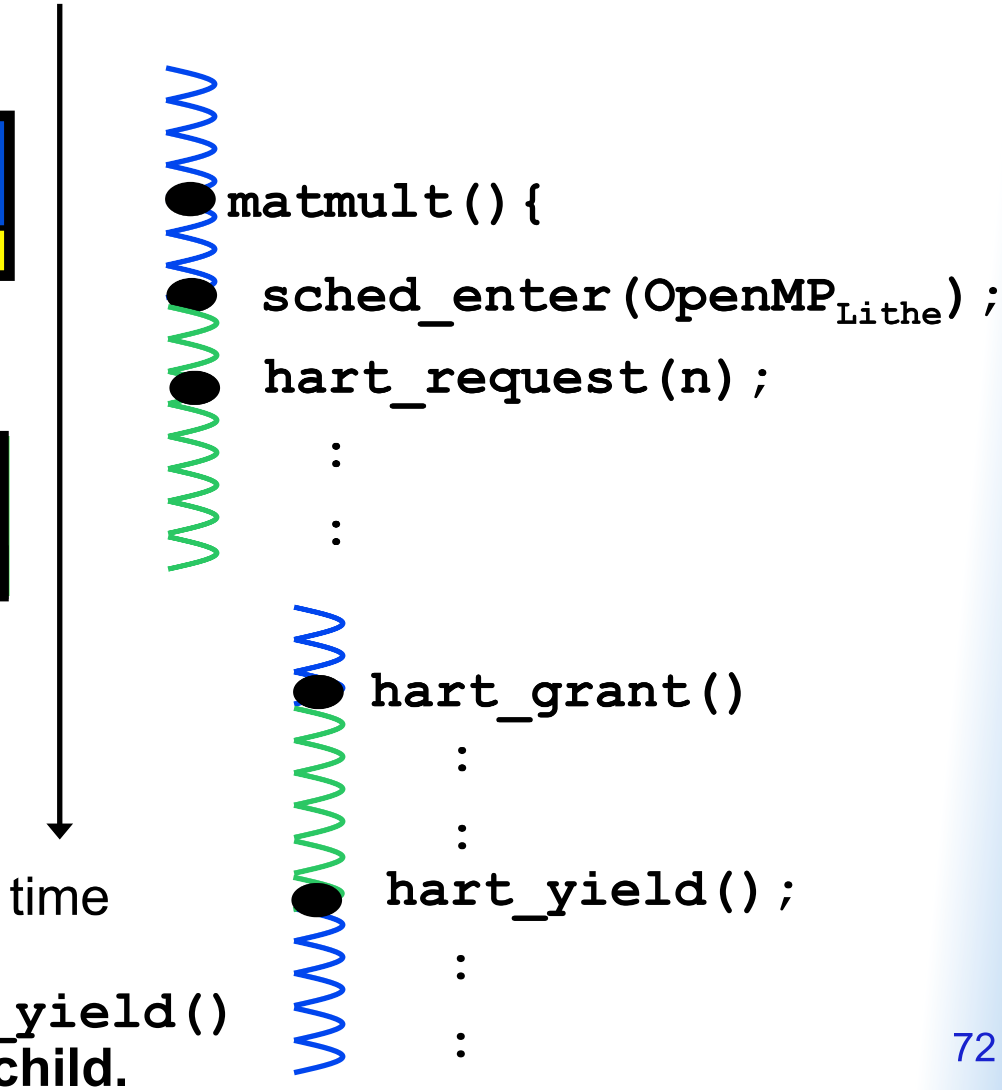


```
matmult(){
  sched_enter(OpenMPLithe);
  hart_request(n);
      :
      :
     hart_grant()
         :
         :
      hart_yield();
```

`hart_request(),hart_grant(),hart_yield()` **transfer harts between a parent and child.**

Request/Grant/Yield a Hart

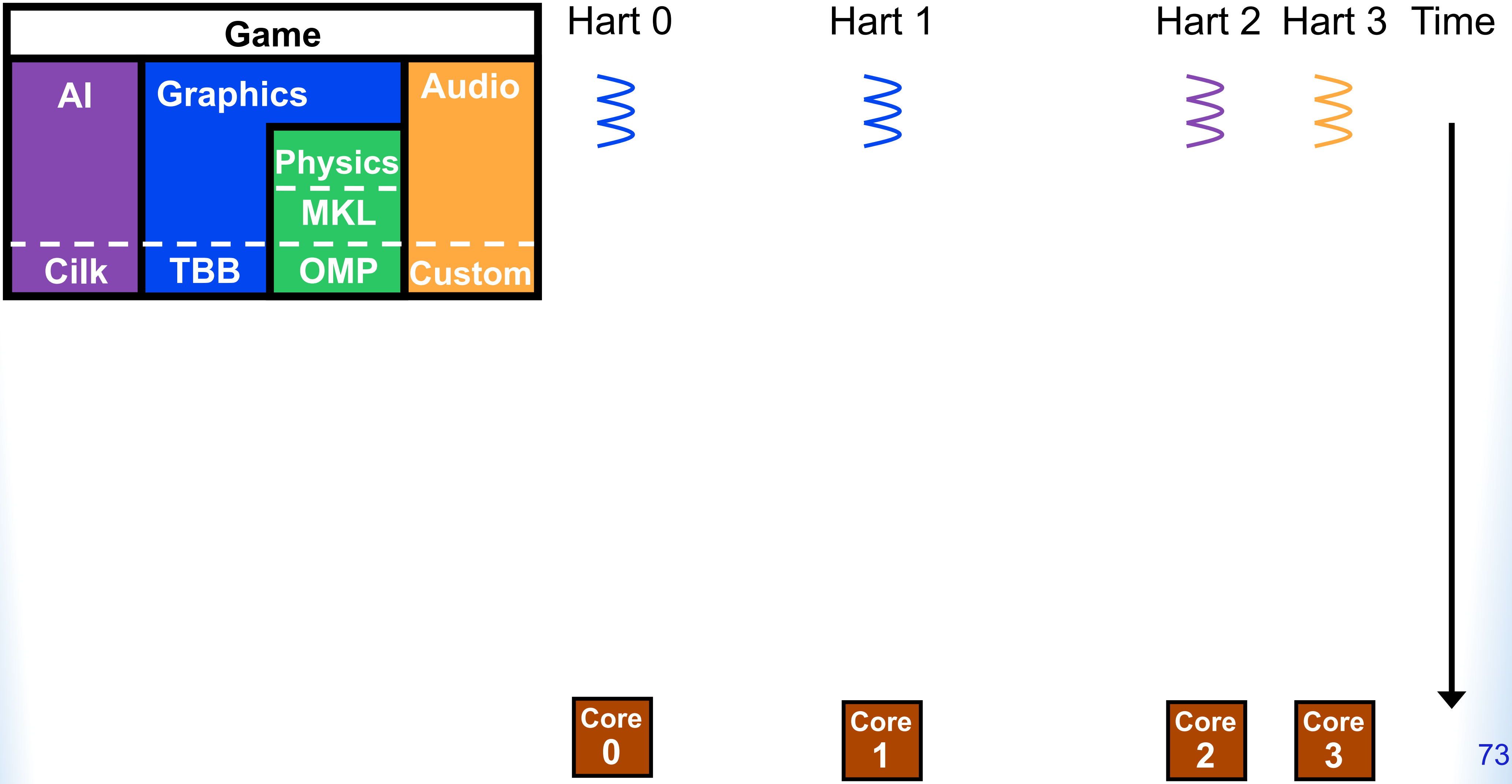




```
matmult(){
  sched_enter(OpenMPLithe);
  hart_request(n);
     :
     :
           hart_grant()
              :
              :
            hart_yield();
              :
              :
```

`hart_request(),hart_grant(),hart_yield()`
transfer harts between a parent and child.

Putting it All Together



Game

AI

Graphics

Physics

MKL

Audio

Cilk

TBB

OMP

Custom

Hart 0

Hart 1

Hart 2

Hart 3

Time

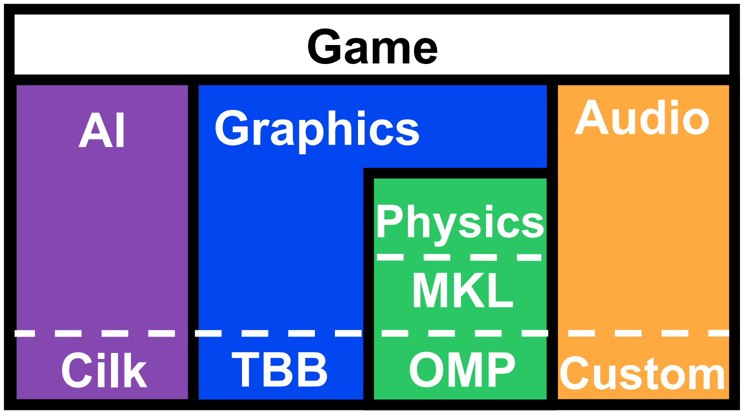
Core 0

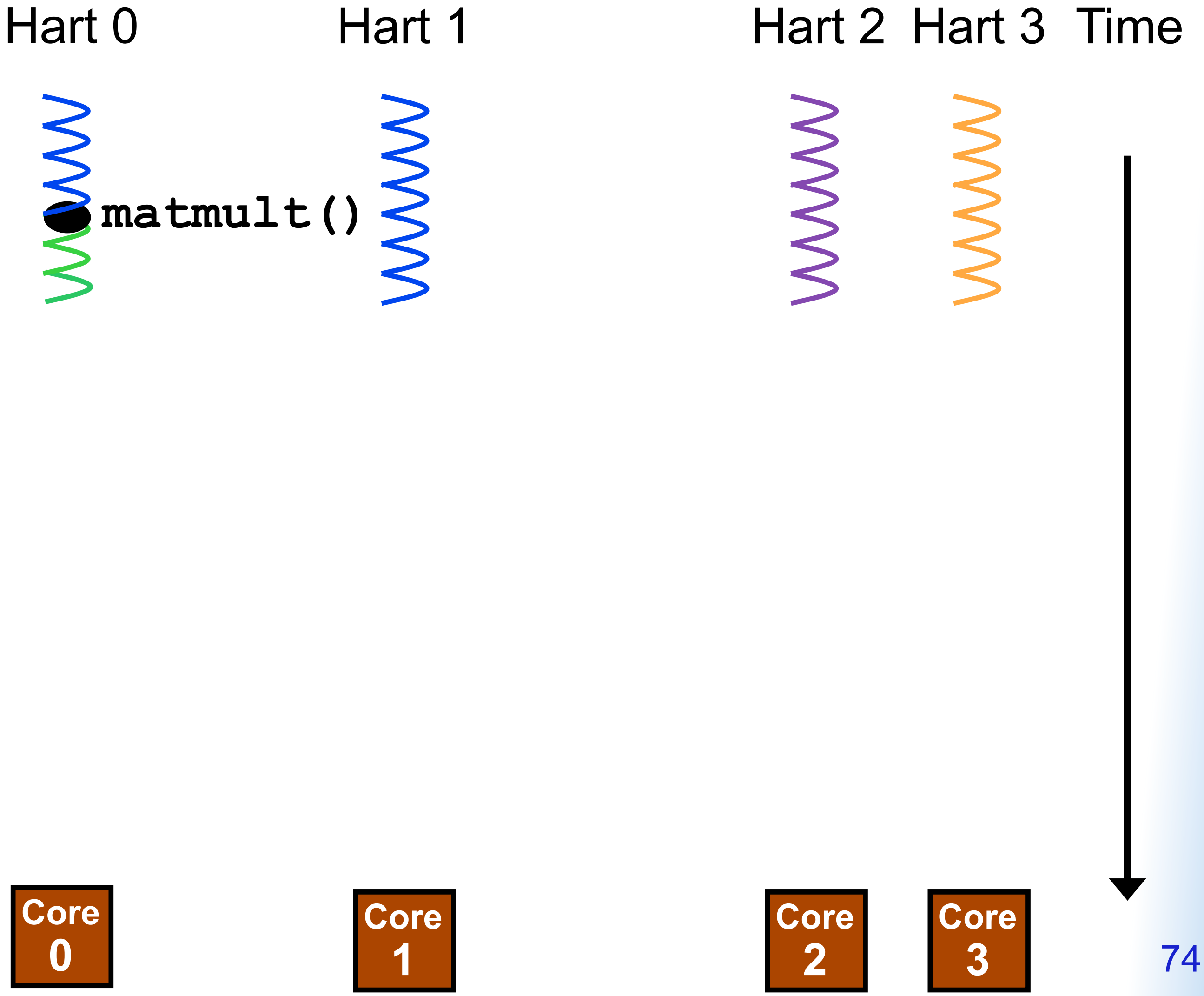
Core 1

Core 2

Core 3

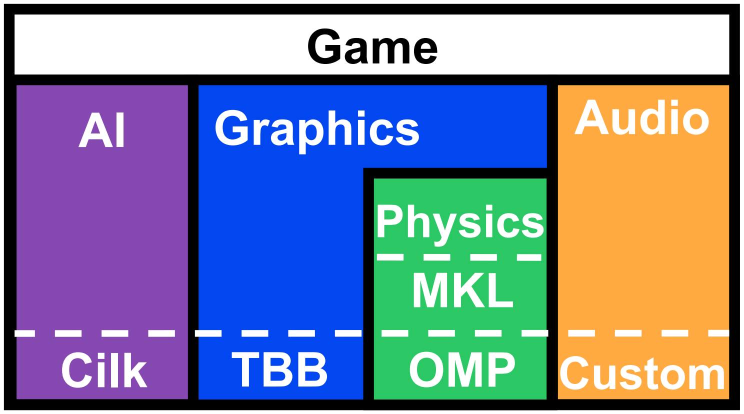
Putting it All Together

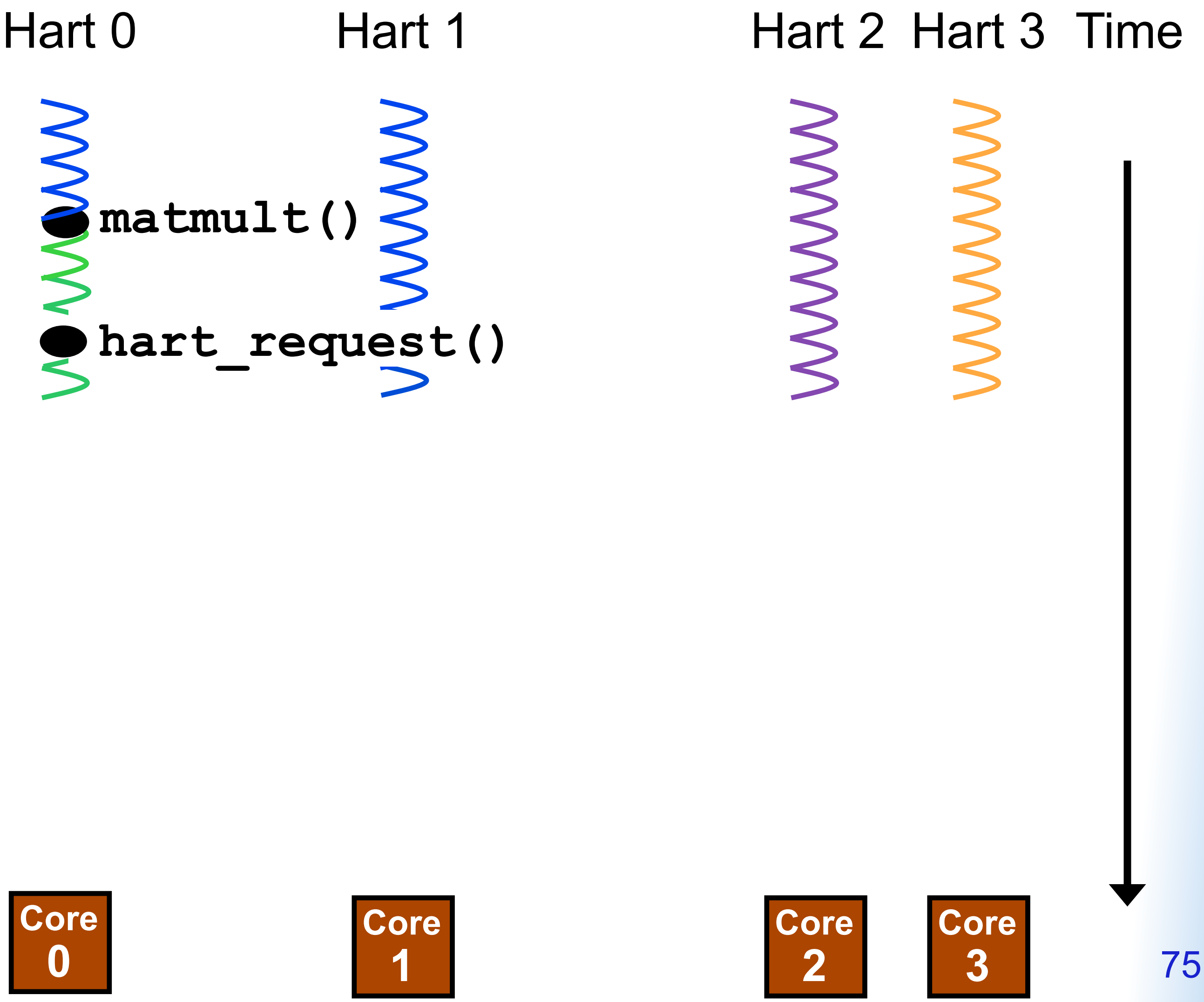




```
tbb::task() {
  matmult() {
   #pragma omp parallel
    :
  }
  :
}
```

Putting it All Together





```
tbb::task() {
  matmult() {
    #pragma omp parallel
     :
  }
  :
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```
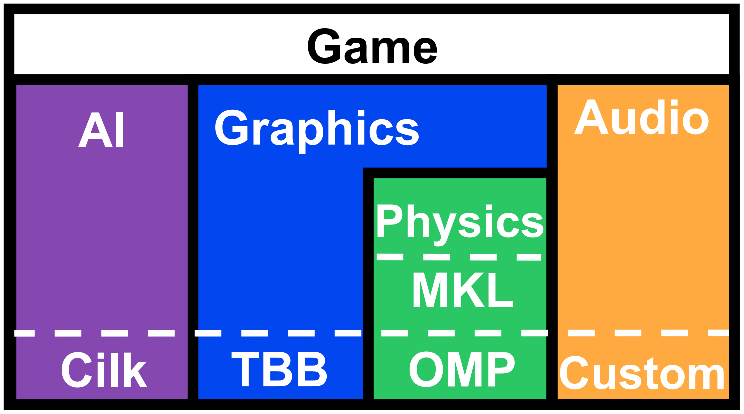
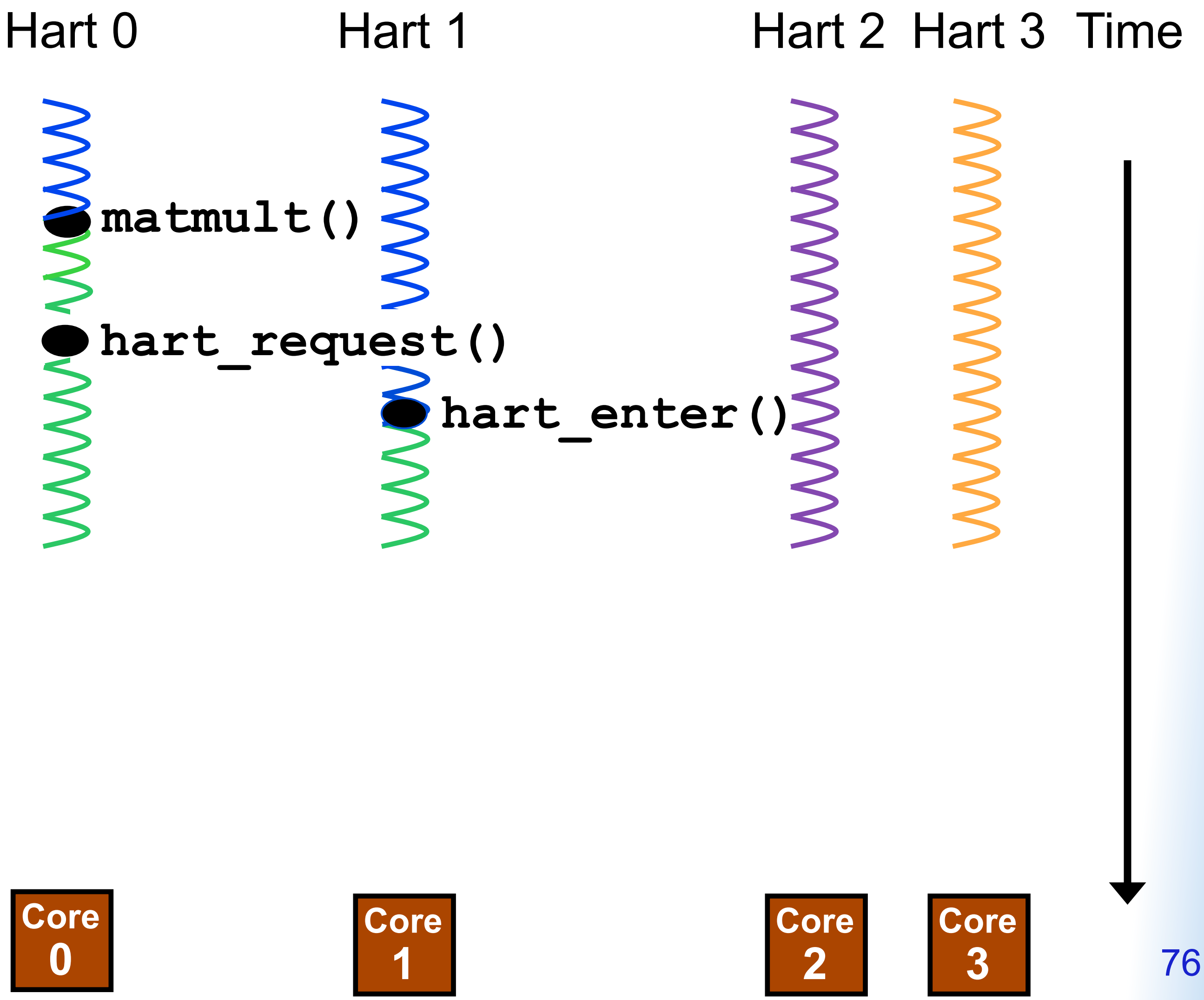

Putting it All Together





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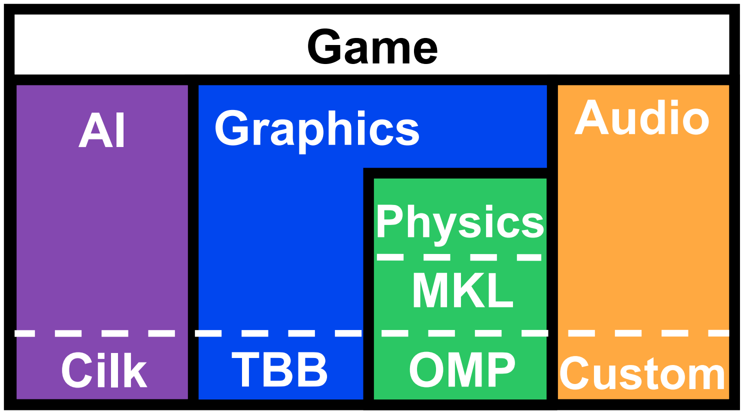
Putting it All Together



Game

AI

Graphics

Audio

Physics

MKL

Cilk

TBB

OMP

Custom

```
tbb::task() {
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  :
}
```
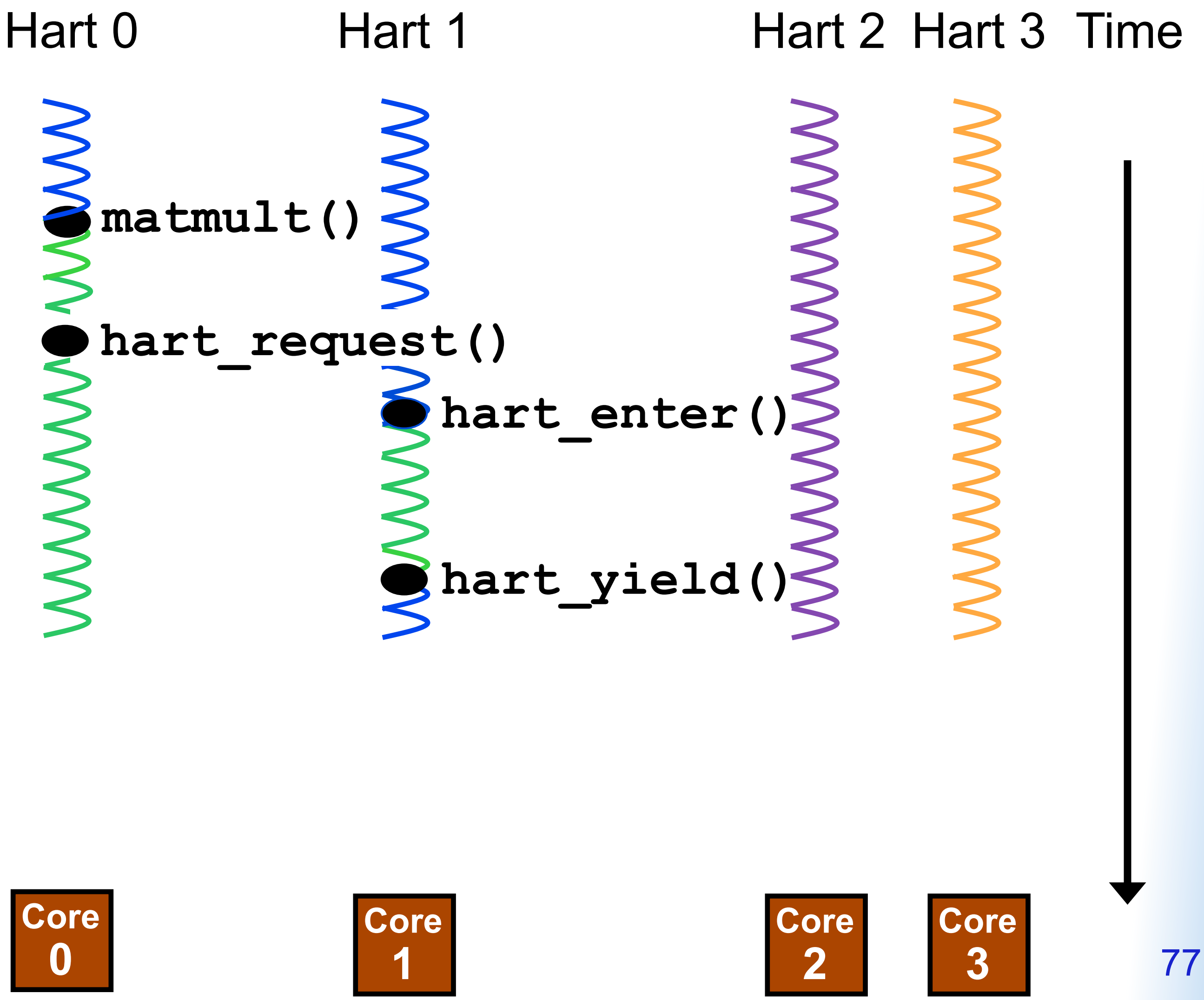



Hart 0

Hart 1

Hart 2

Hart 3

Time

matmult()

hart_request()

hart_enter()

hart_yield()

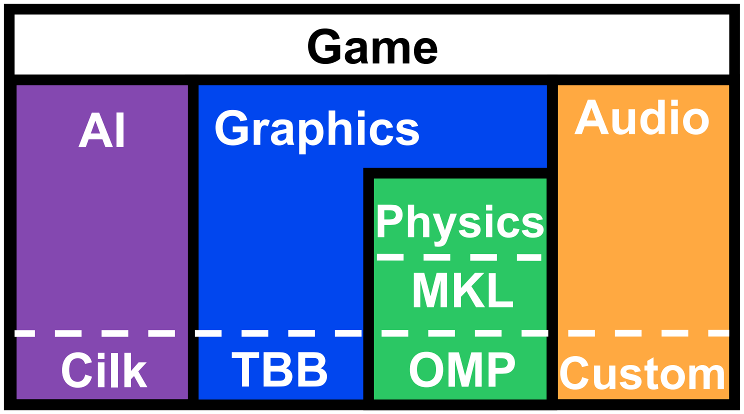
Core 0

Core 1

Core 2

Core 3

Putting it All Together



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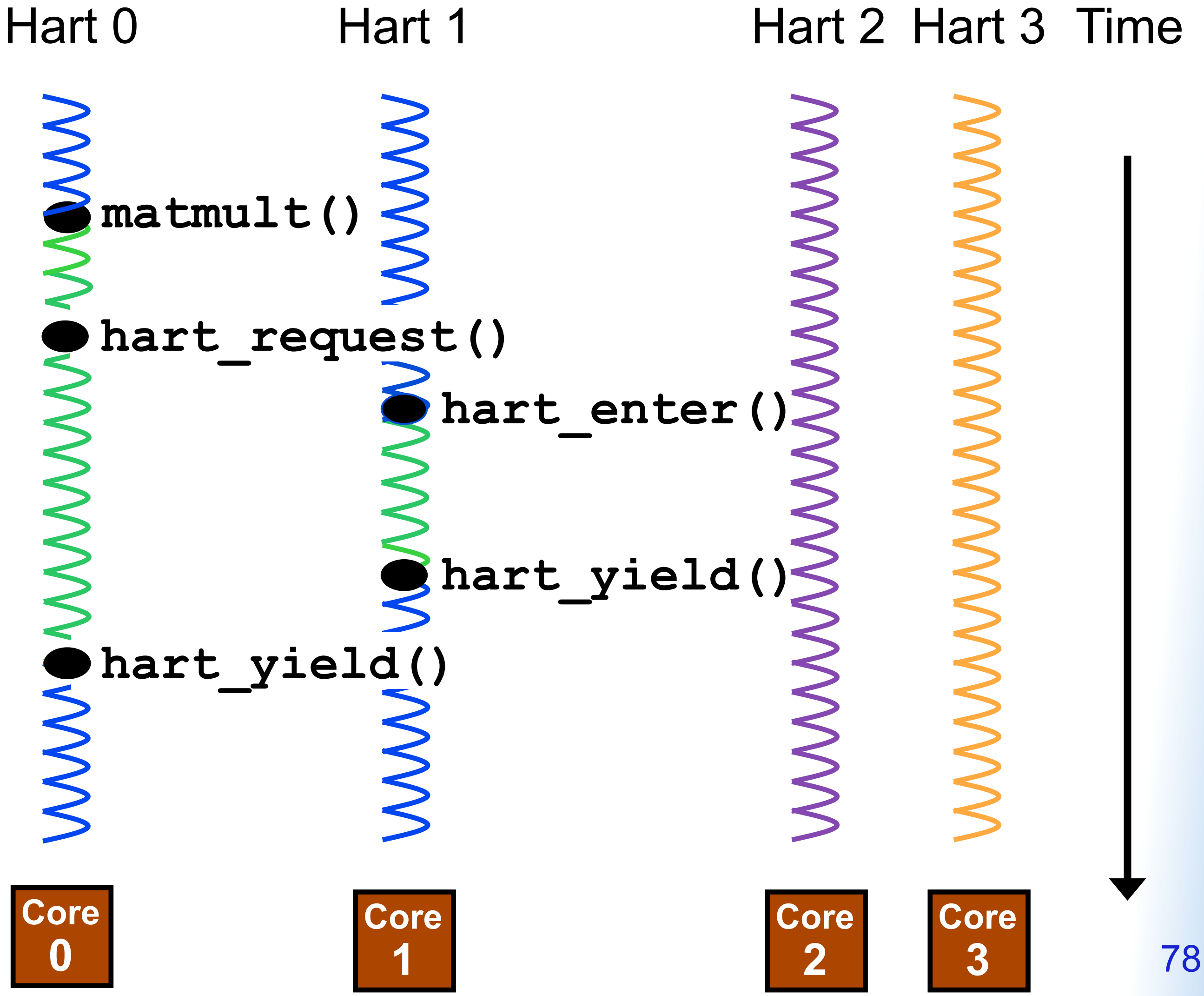
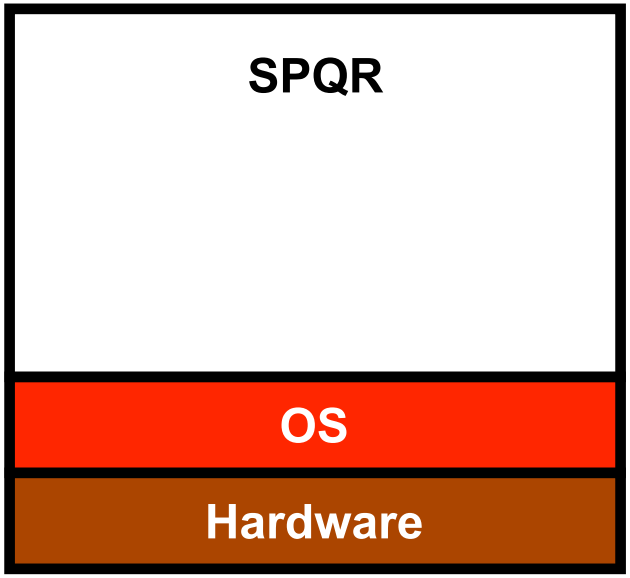


Real World Example

Sparse QR Factorization
(Tim Davis, Univ of Florida)

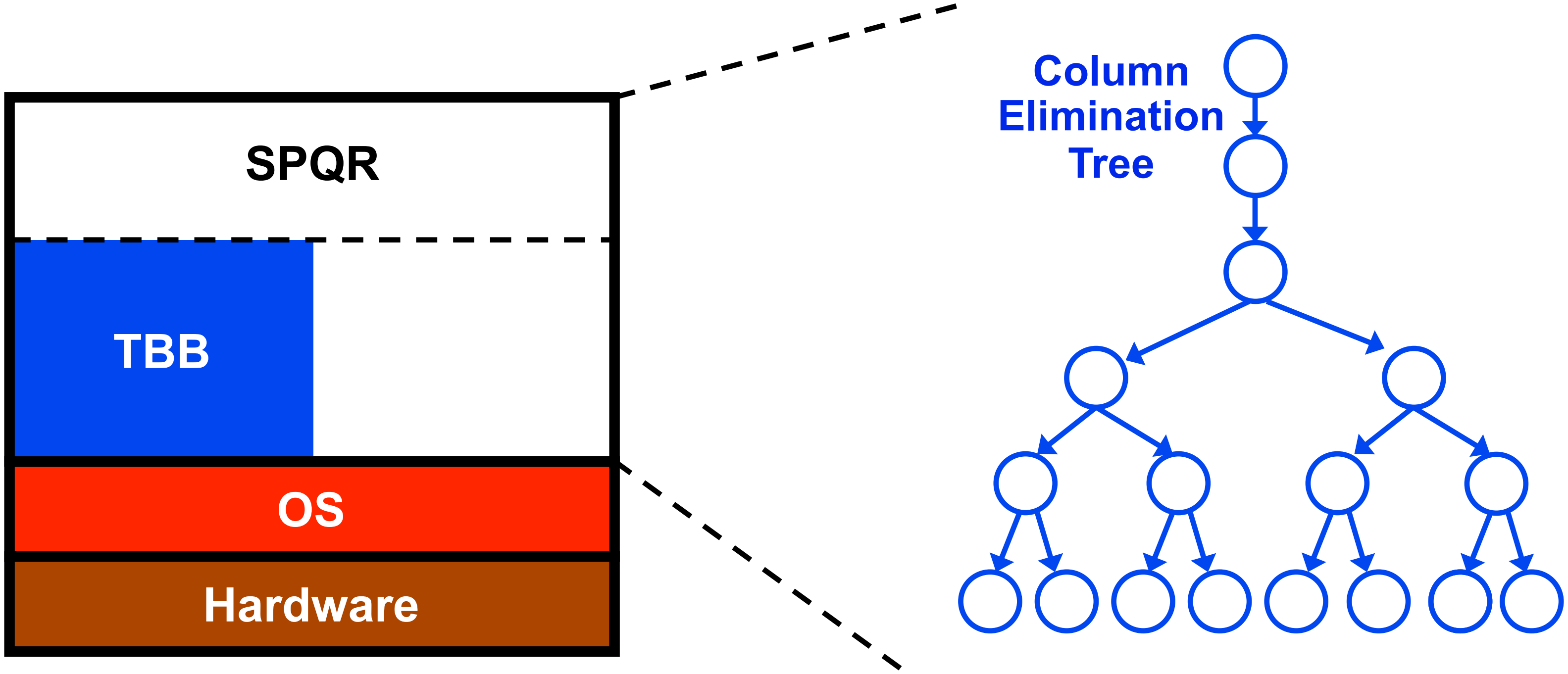


System Stack

Real World Example

Sparse QR Factorization

(Tim Davis, Univ of Florida)



SPQR

TBB

OS

Hardware

Column Elimination Tree

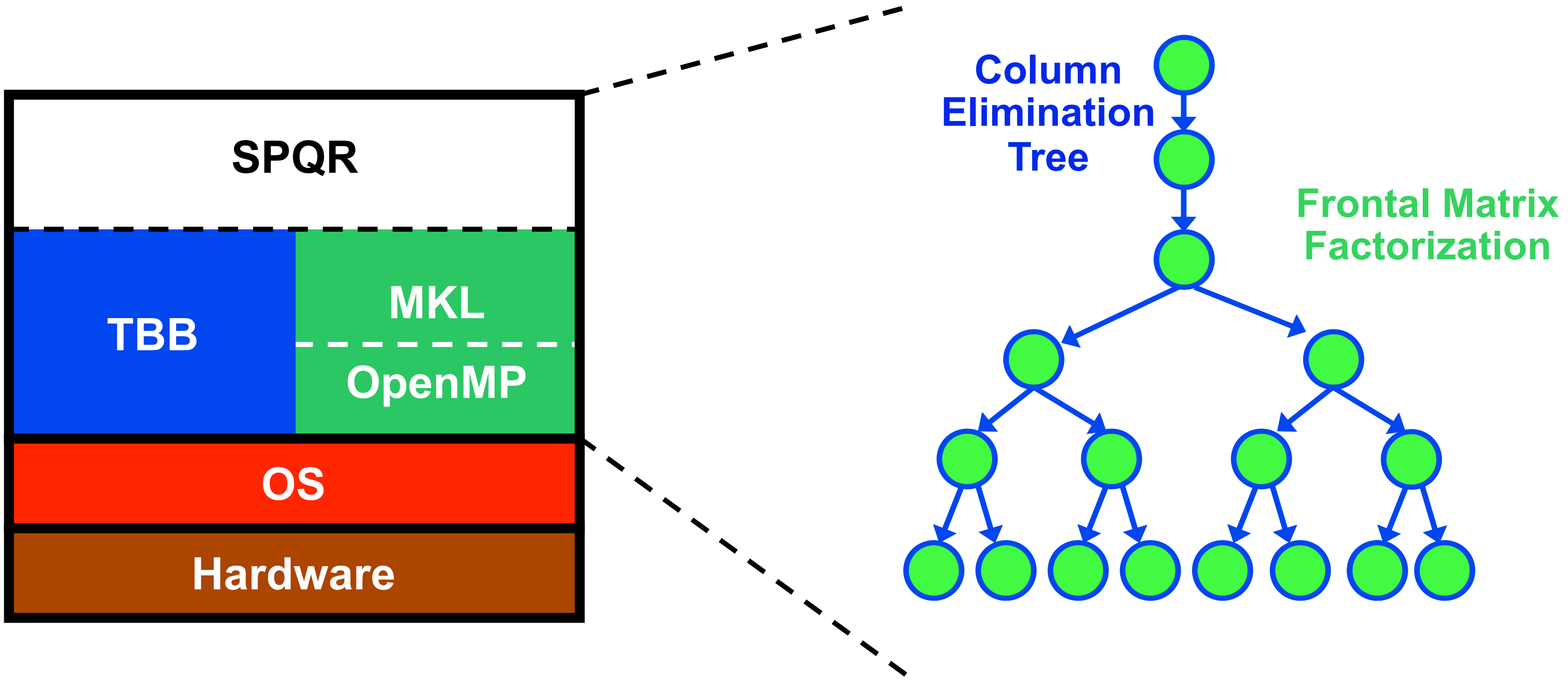
System Stack

Software Architecture

Real World Example

Sparse QR Factorization

(Tim Davis, Univ of Florida)



SPQR

TBB

MKL

OpenMP

OS

Hardware

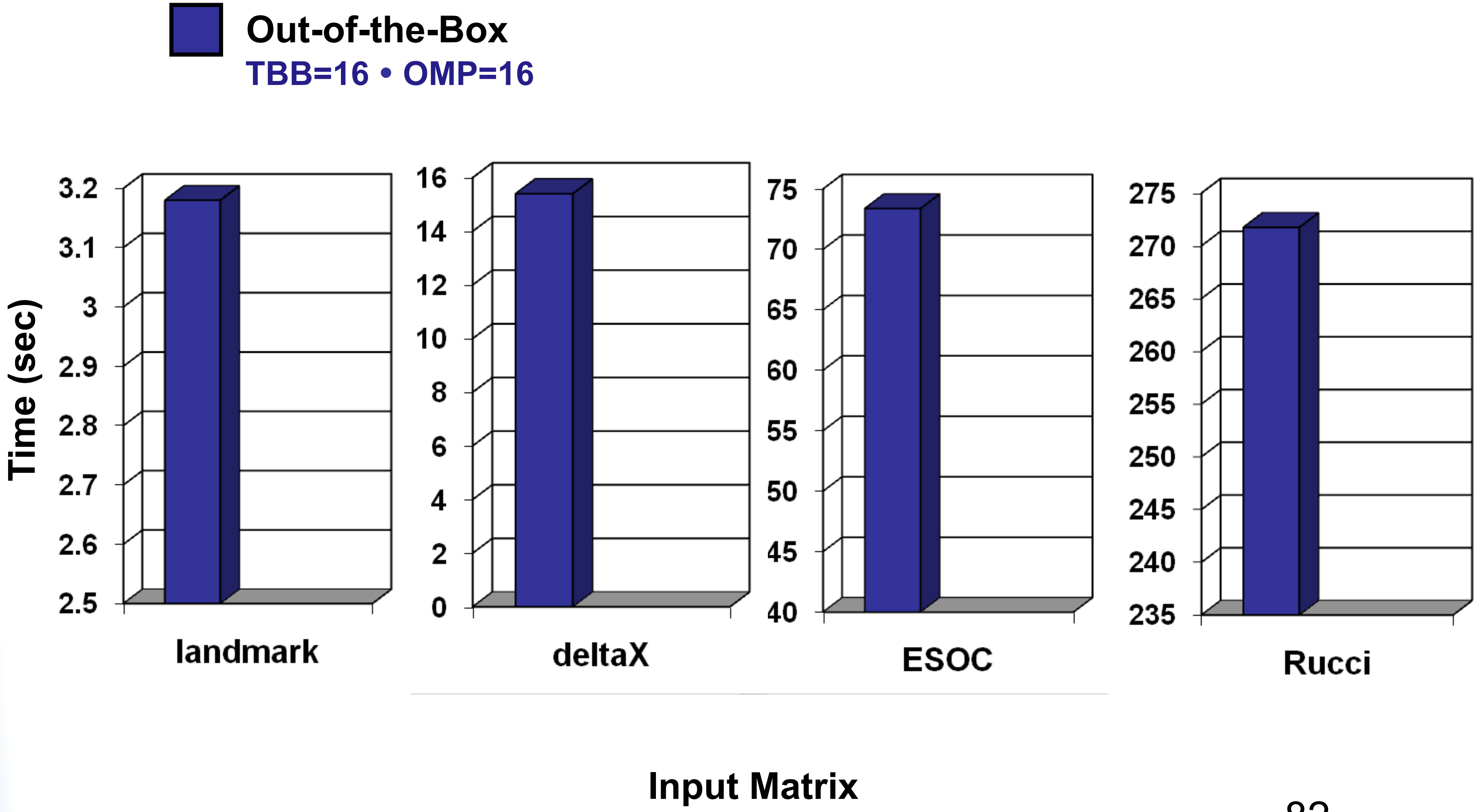
Column Elimination Tree

Frontal Matrix Factorization

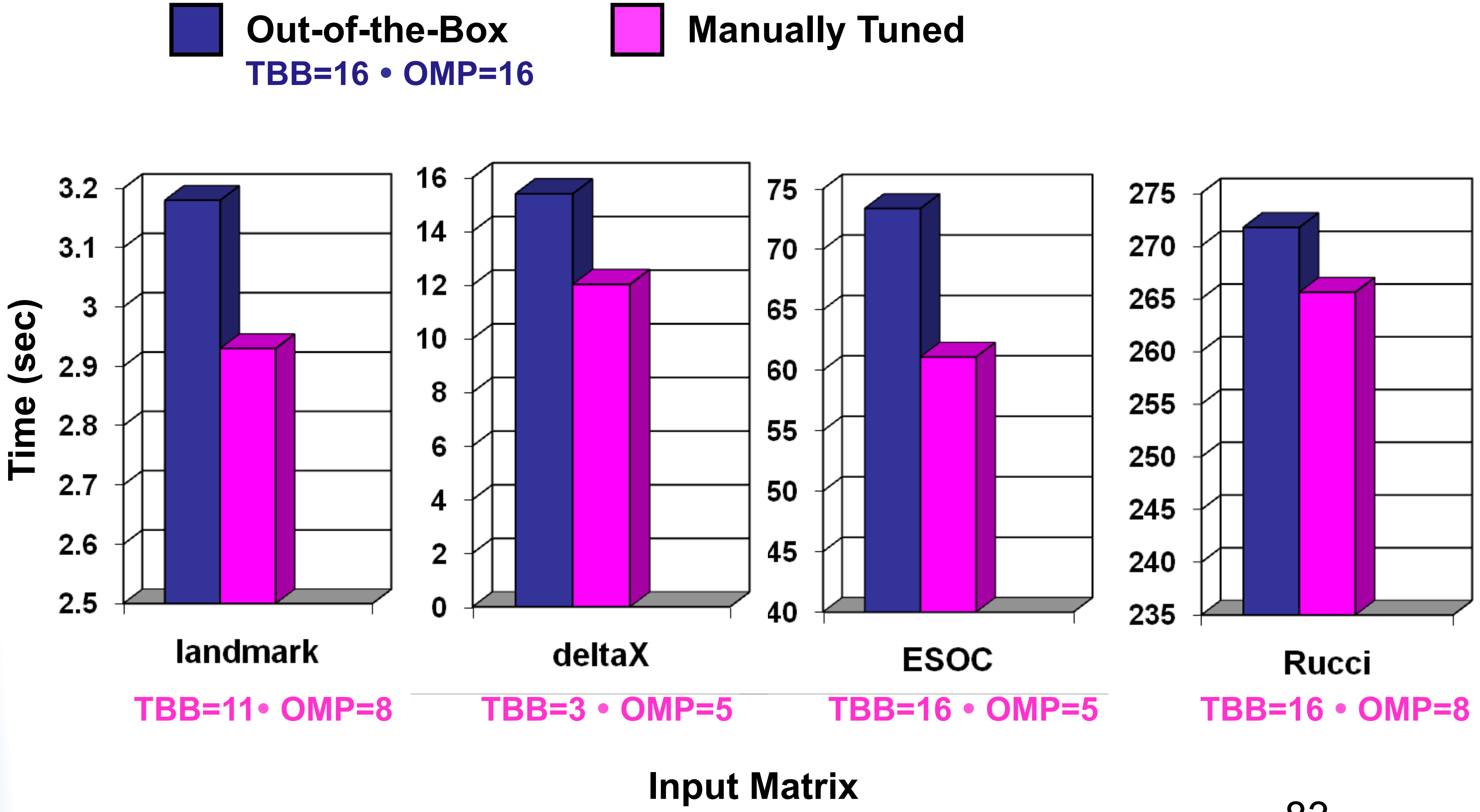
System Stack

Software Architecture

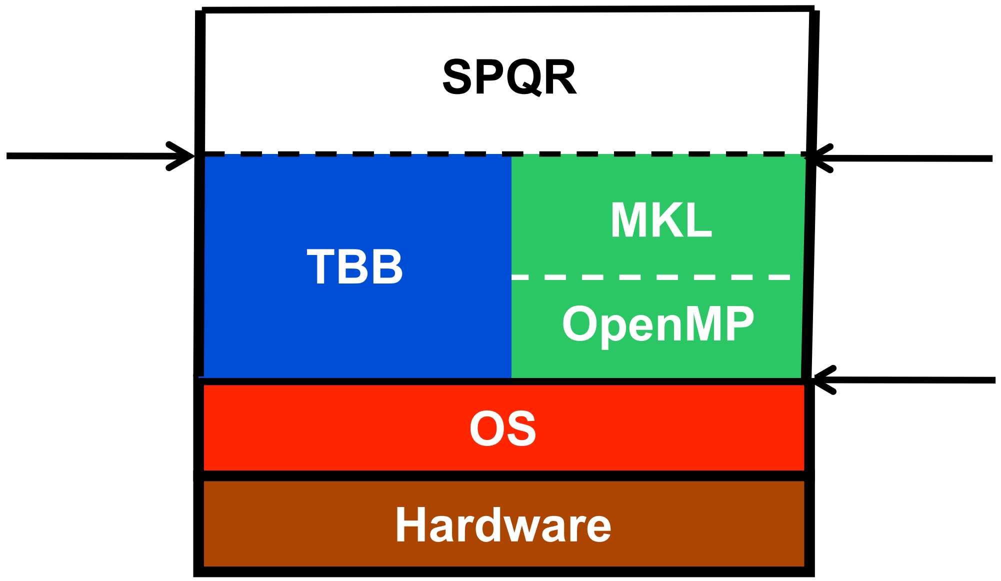
Performance of SPQR on 16-Core machine



Performance of SPQR on 16-Core machine

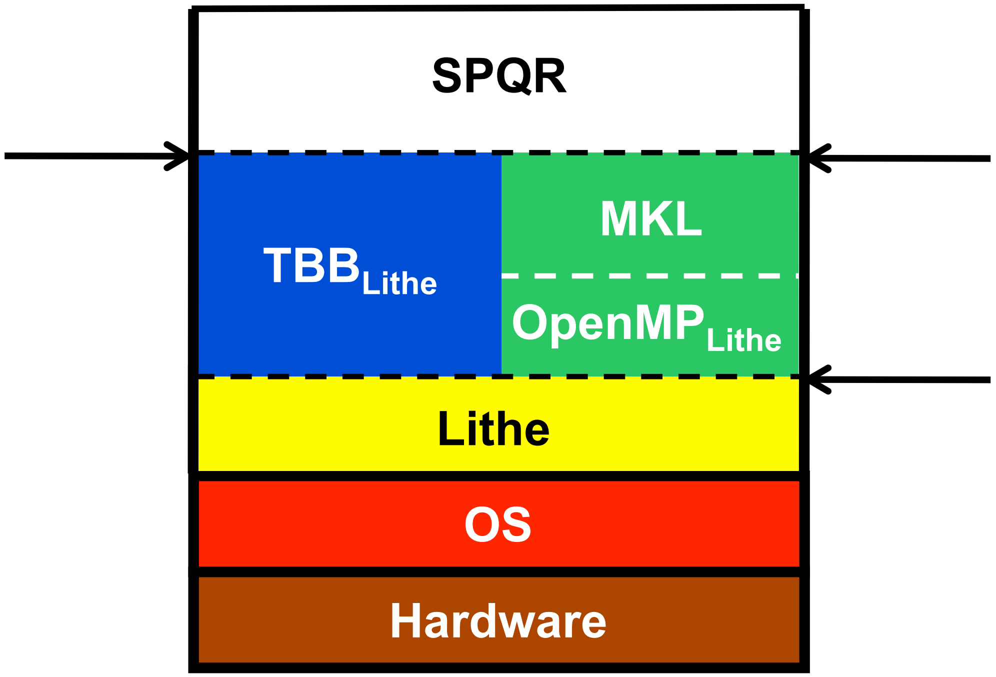


SPQR with Lithe



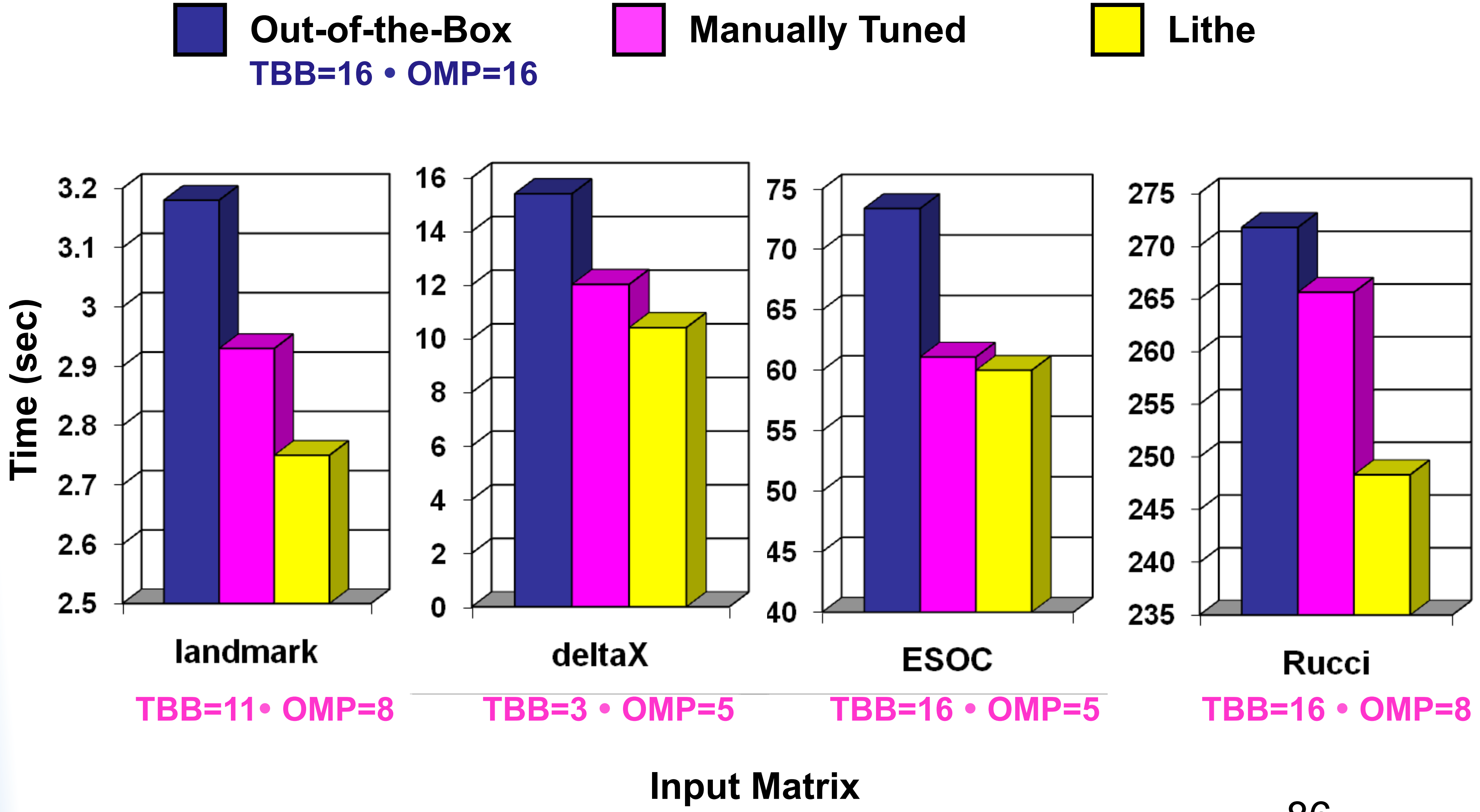
- Library interfaces remain the same
- Zero lines of high-level code changed (SPQR, MKL)

SPQR with Lithe



- Library interfaces remain the same
- Zero lines of high-level code changed (SPQR, MKL)
- Just link in Lithe runtime + Lithe versions of libraries (TBB, OpenMP)

Performance of SPQR with Lithe



Out-of-the-Box: TBB=16 • OMP=16

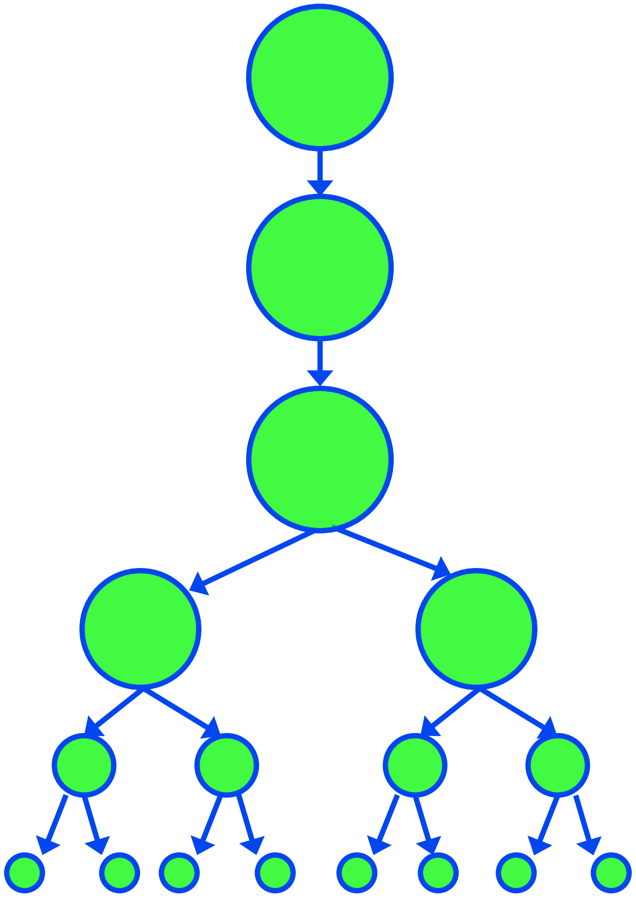
landmark: TBB=11• OMP=8

deltaX: TBB=3 • OMP=5

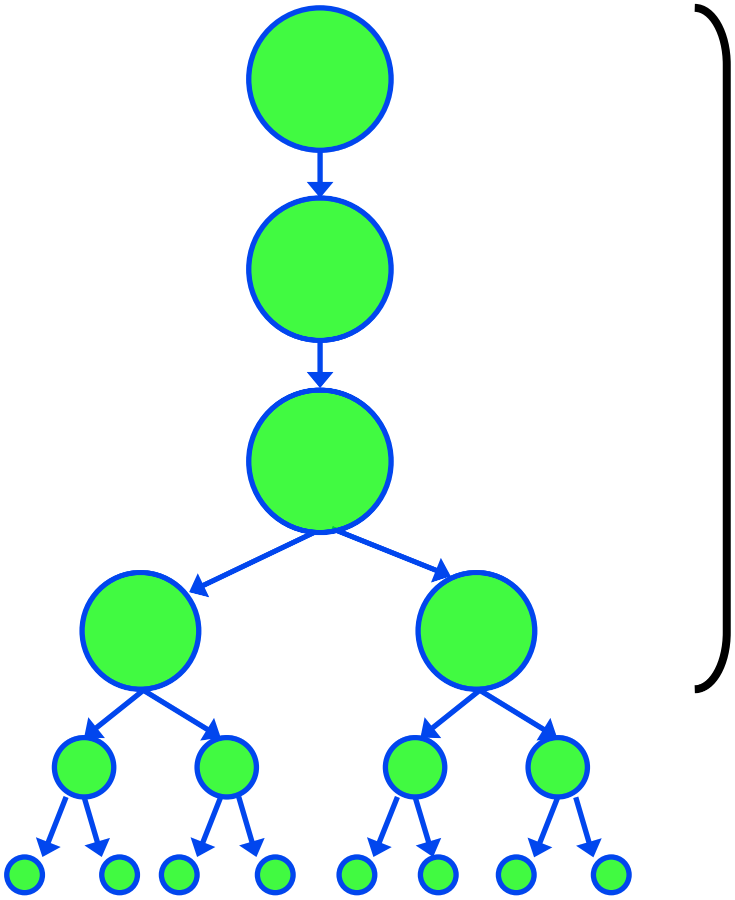
ESOC: TBB=16 • OMP=5

Rucci: TBB=16 • OMP=8

Lithe Enables Flexible Sharing of Resources

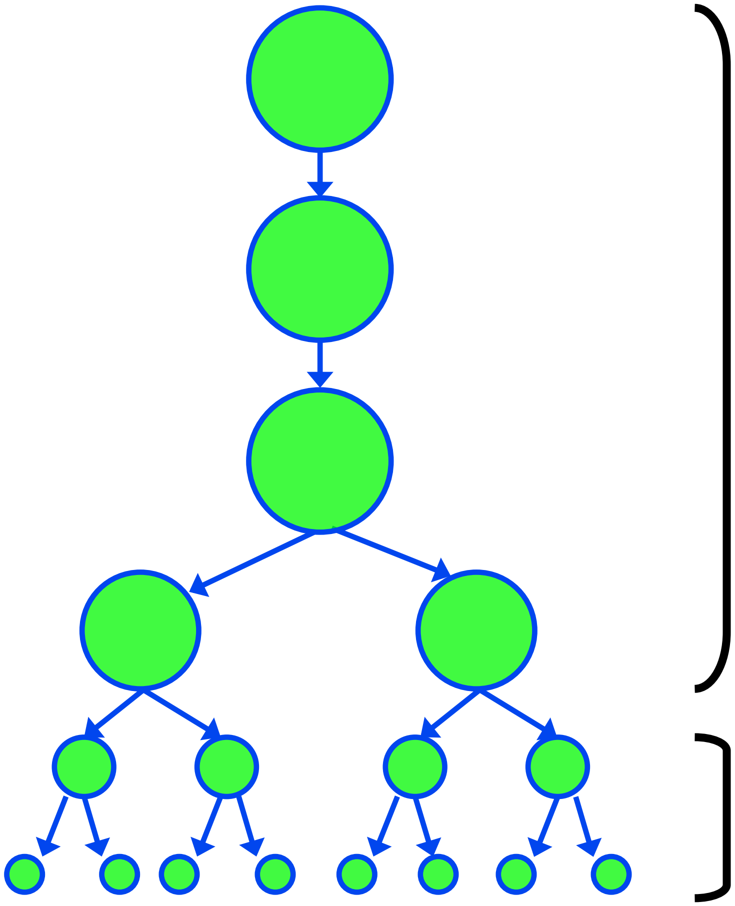


Lithe Enables Flexible Sharing of Resources



Give resources to OpenMP

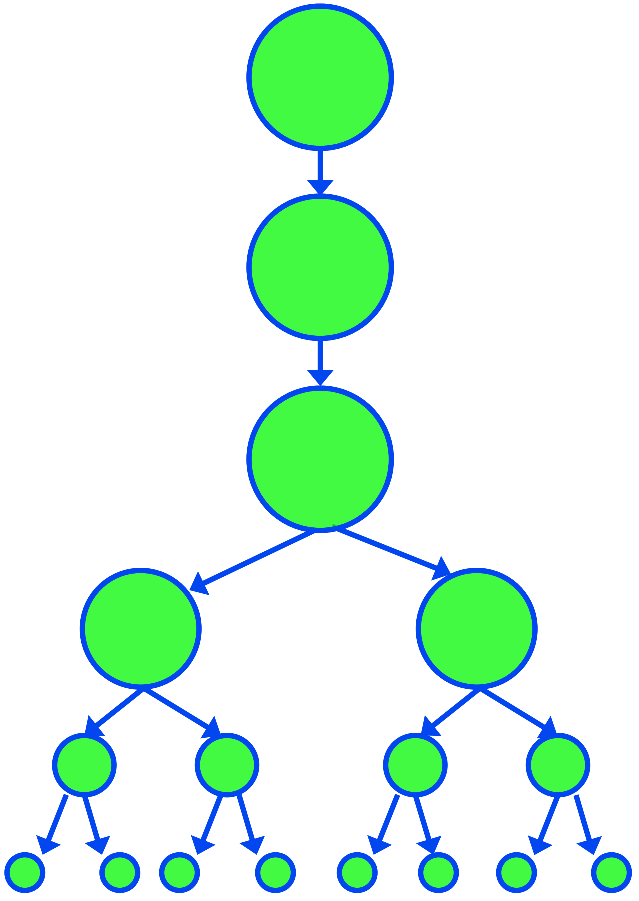
Lithe Enables Flexible Sharing of Resources



Give resources to OpenMP

Give resources to TBB

Lithe Enables Flexible Sharing of Resources

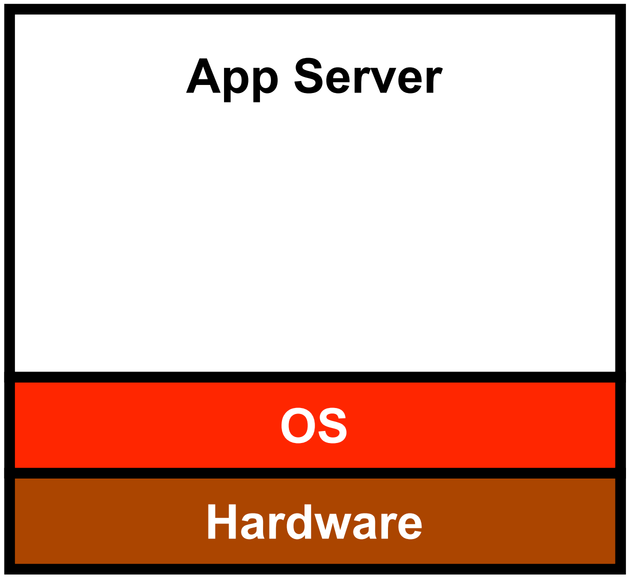


Give resources to OpenMP

Give resources to TBB

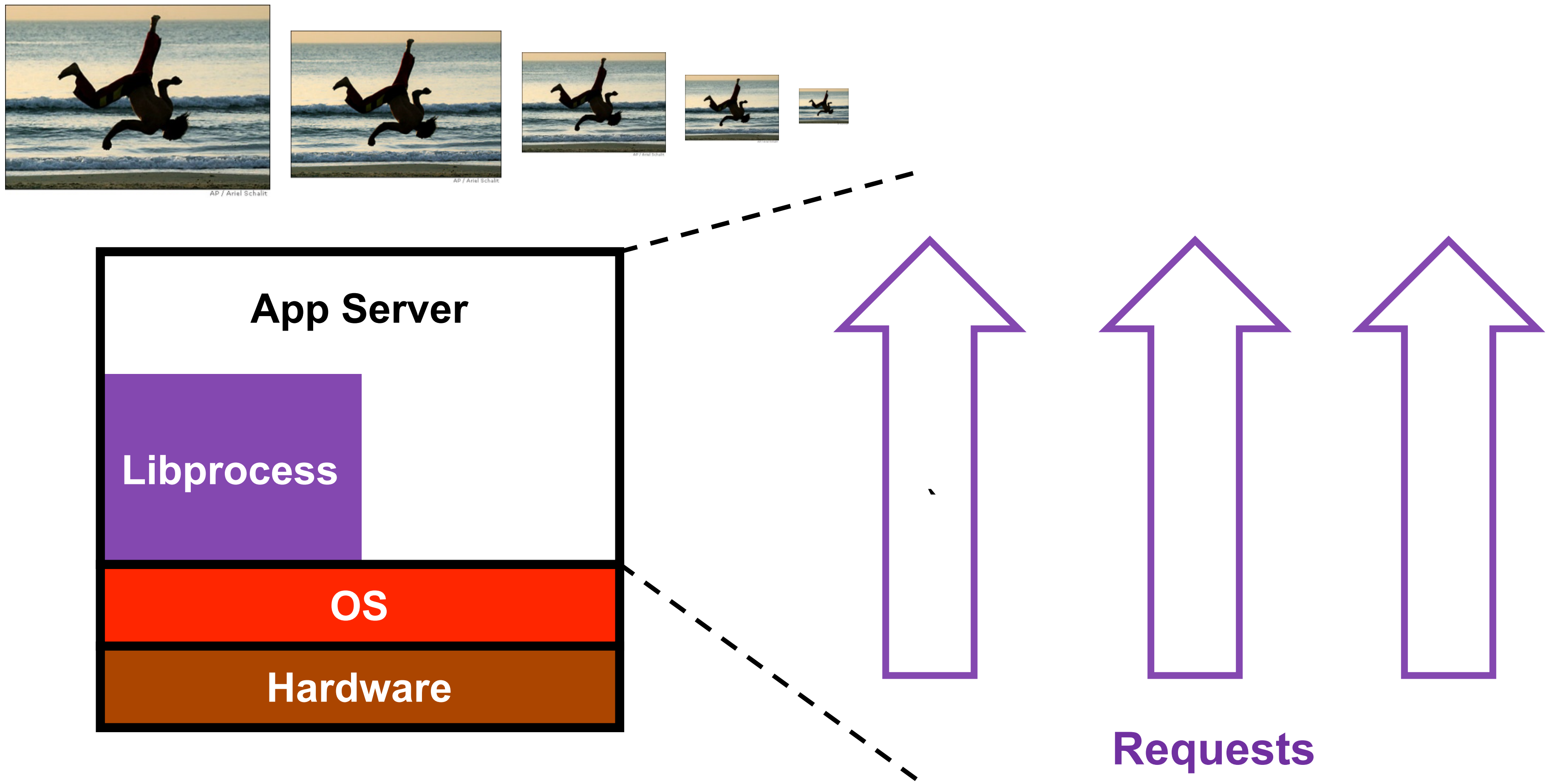
Manual tuning is stuck with 1 TBB/OMP config throughout run.

Flickr-Like Image Processing App Server



System Stack

Flickr-Like Image Processing App Server



AP / Ariel Schalit

App Server

Libprocess

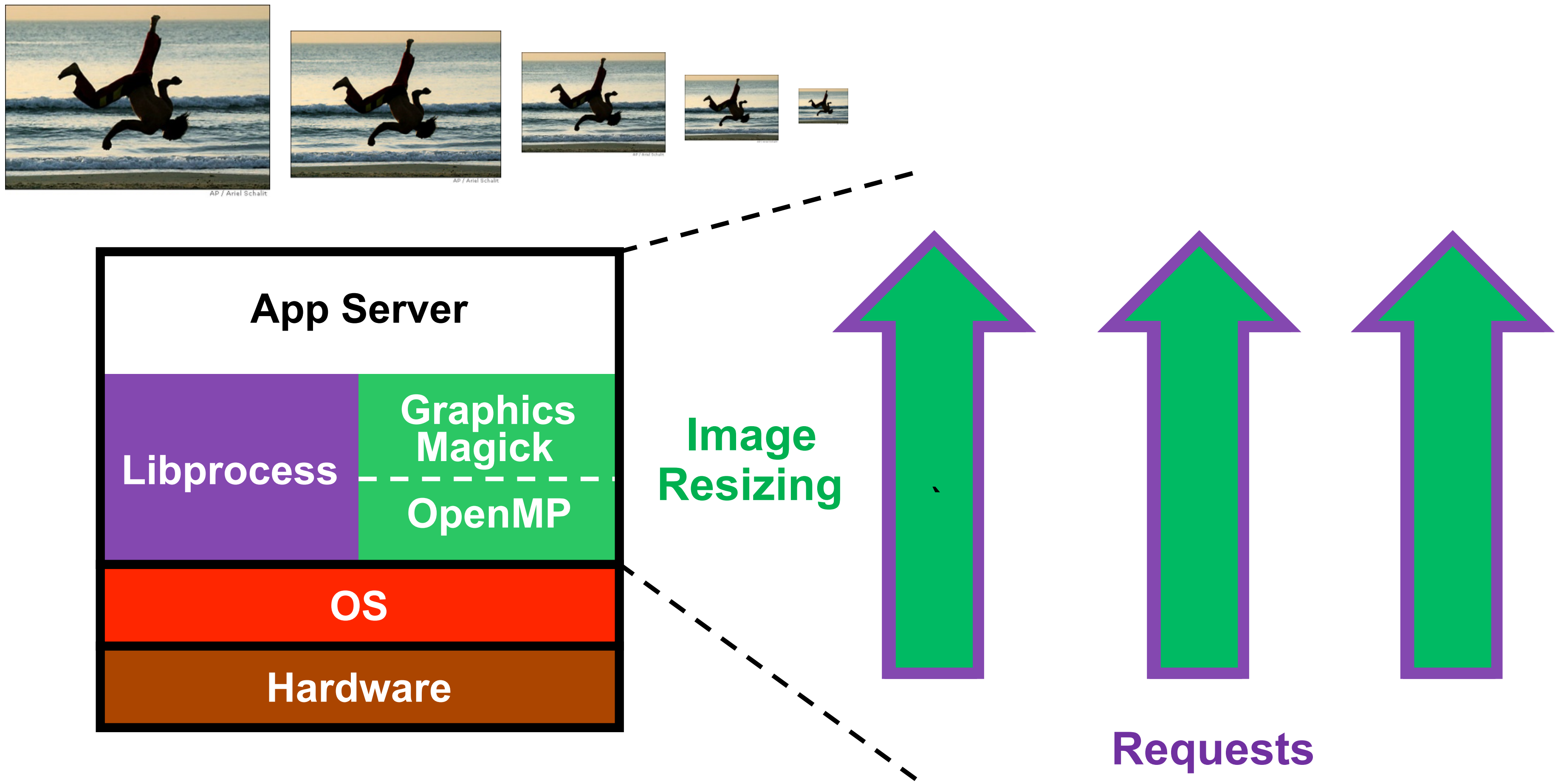
OS

Hardware

Requests

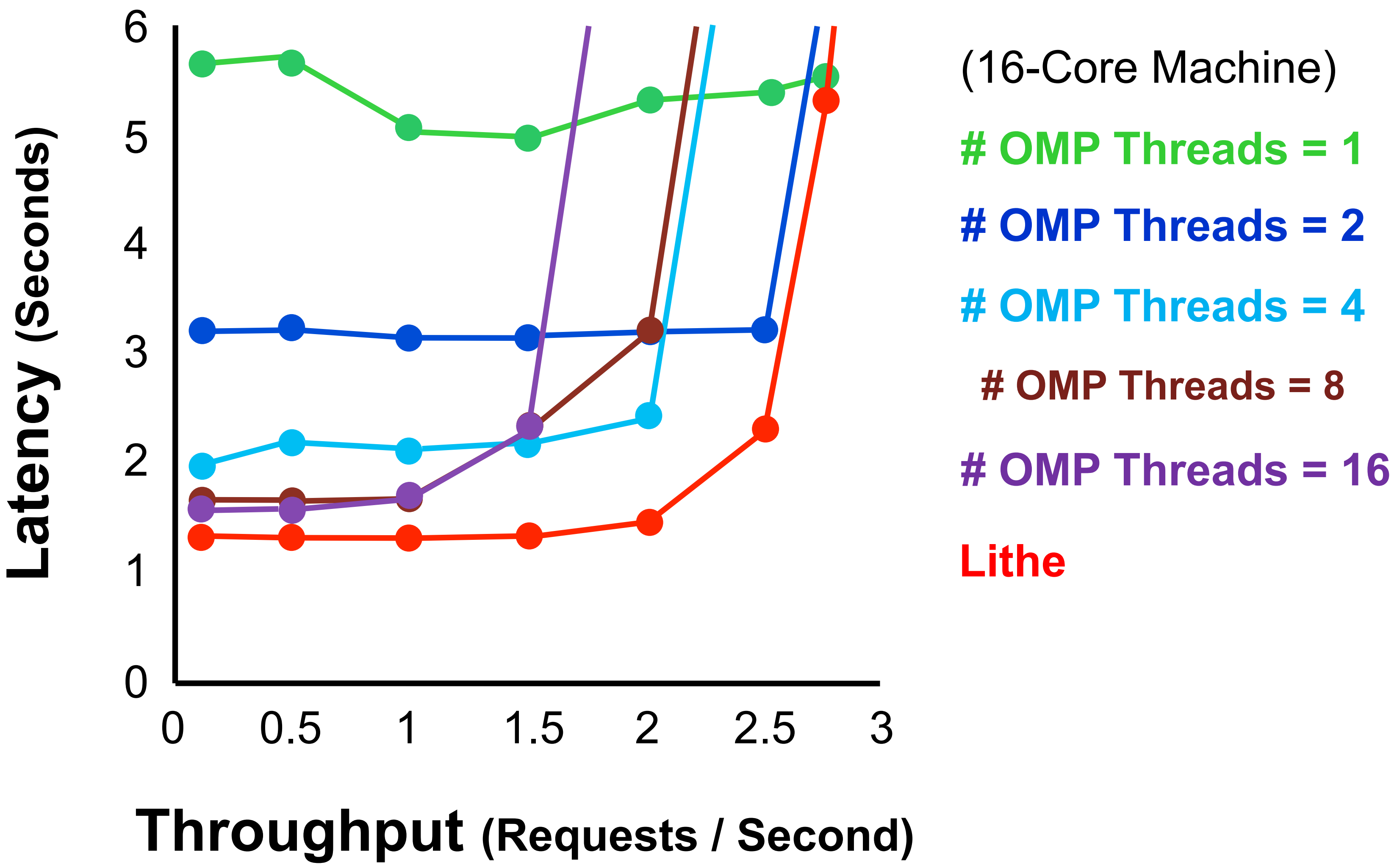
System Stack

Flickr-Like Image Processing App Server



System Stack

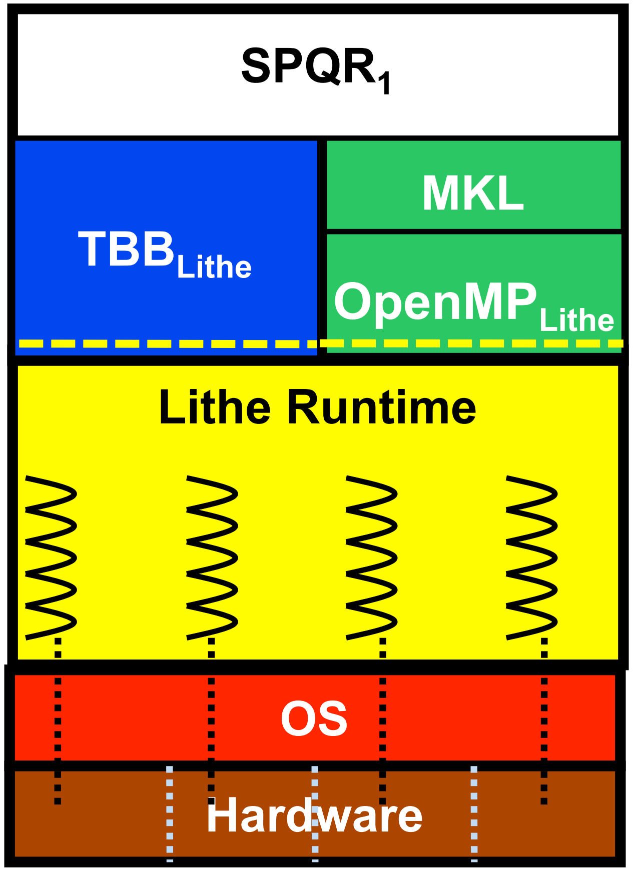
Performance of App Server



Future Directions

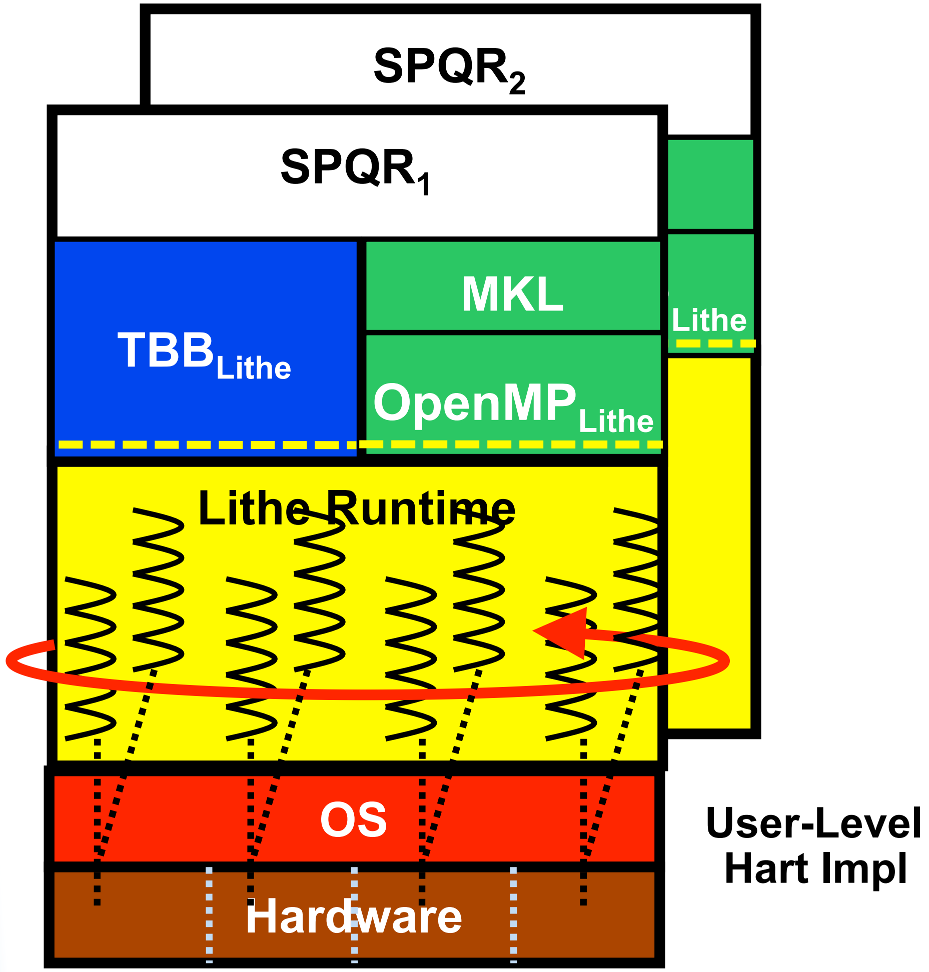
- OS Support for Lithe
  - Akaros, Tessellation
- Preemptive Version of Lithe
  - Direct support for MPI
  - Integrate with GASNet
- Other ways to integrate with the DEGAS stack?

OS Support for Lithe

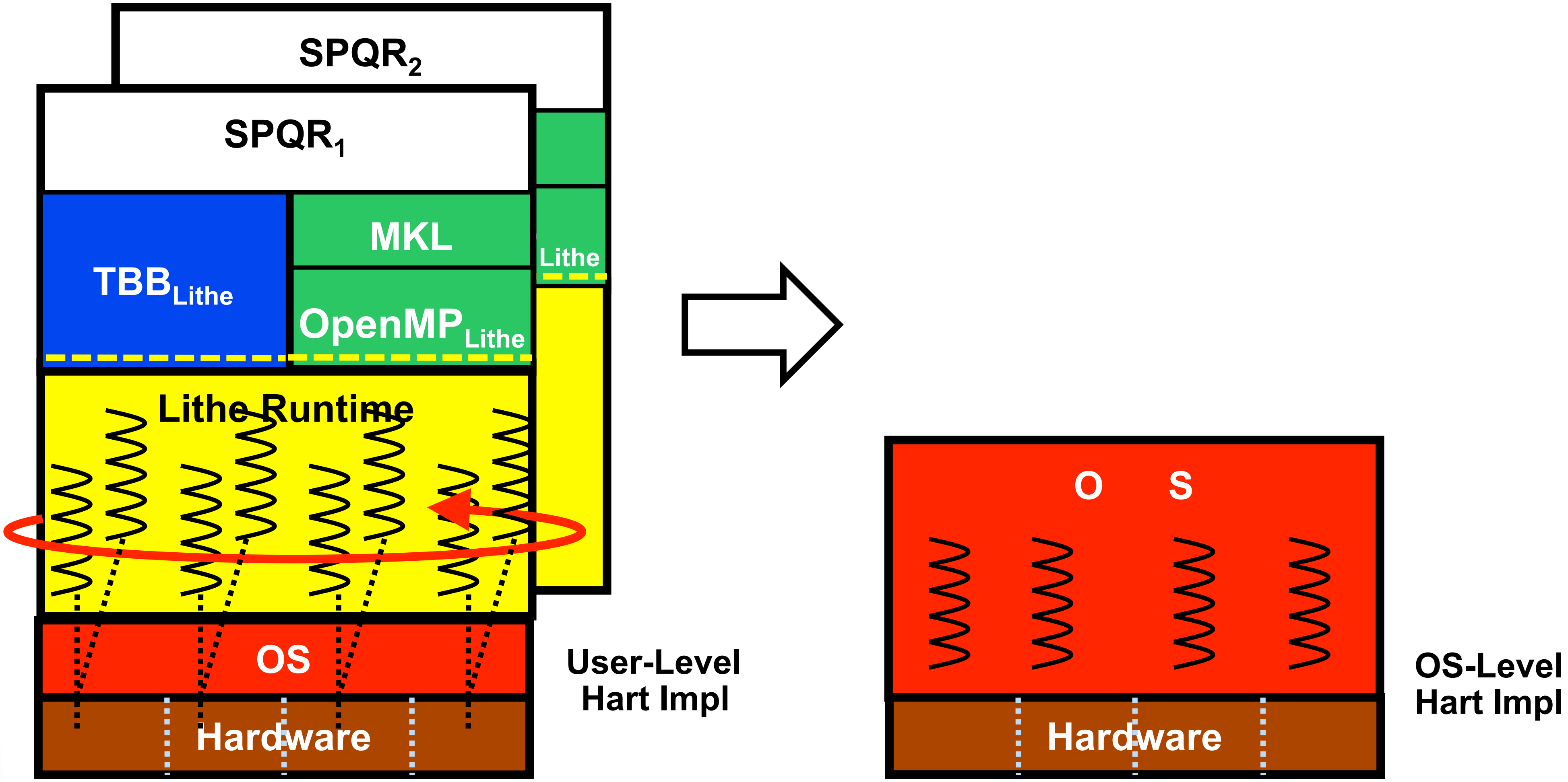


User-Level
Hart Impl

OS Support for Lithe



OS Support for Lithe



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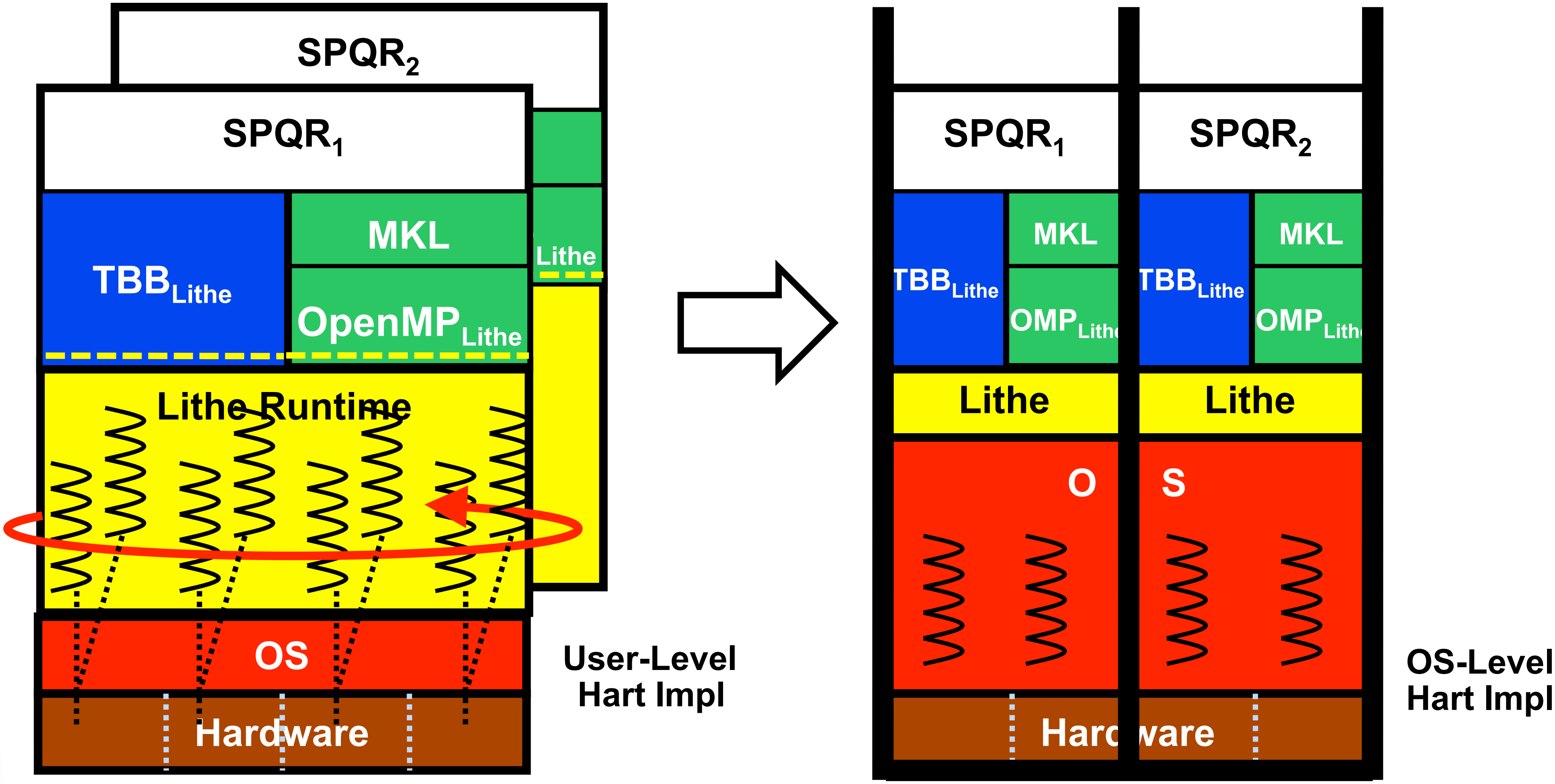
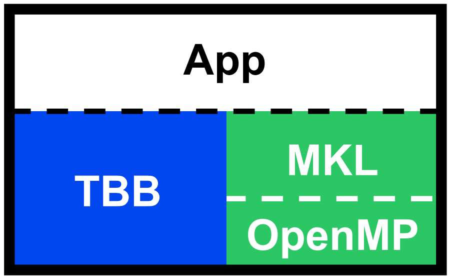
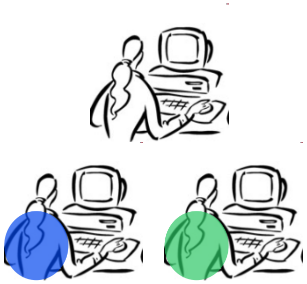


Conclusion

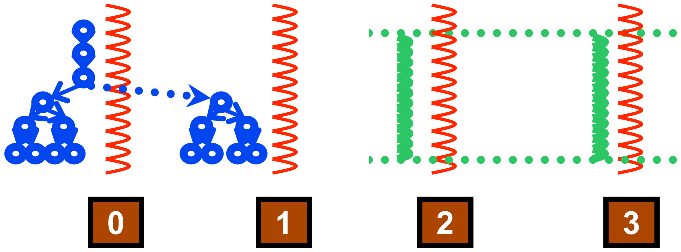
- Composability essential for parallel programming to become widely adopted




functionality

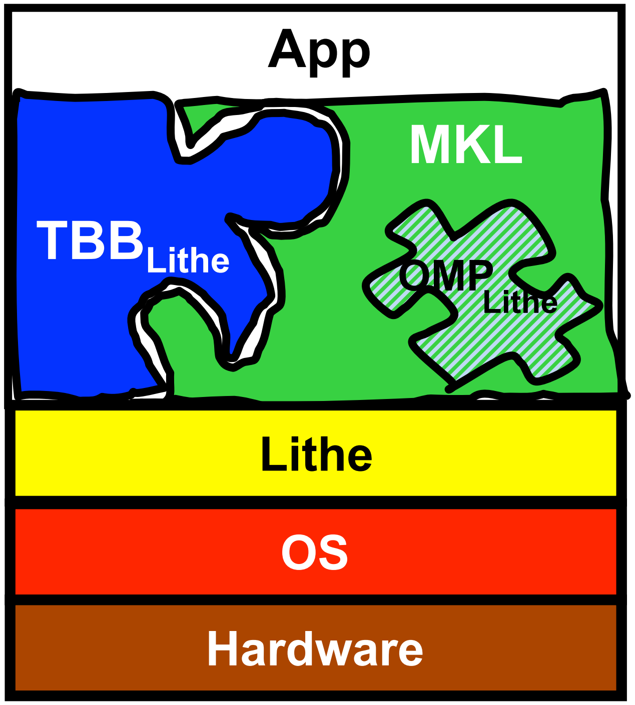
resource management

- Parallel libraries need to share resources cooperatively



- Main Contributions
  - **Harts:** better resource model for parallel programming
  - **Lithe:** framework for using and sharing harts

Questions?



http://lithe.eecs.berkeley.edu