Introduction to OpenMP

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目录

简介

什么是OpenMP?

- Open Multi-Processing
- OpenMP是一个应用程序接口（API）
  - 你可以简单理解为它是一个库
- 支持C, C++和Fortran
- 支持多种指令集和操作系统
- 由非营利性组织管理，由多家软硬件厂家参与，包括Arm, AMD, IBM, Intel, Cray, HP, Fujitsu, Nvidia等

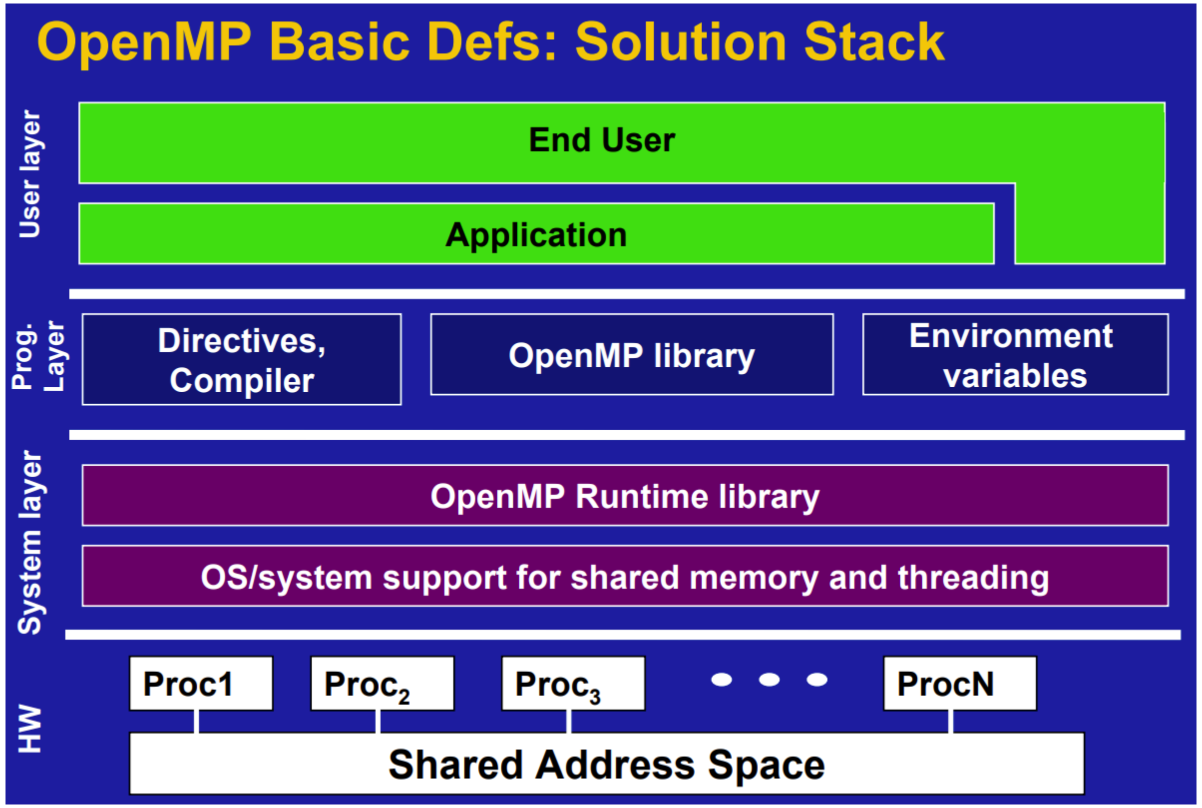
历史版本

- 可以在官网页面查询到openmp的历史版本和发布日期

日期	版本
October 1997	Fortran 1.0
October 1998	C/C++ 1.0
March 2002	C/C++ 2.0
May 2005	OpenMP 2.5
May 2008	OpenMP 3.0
July 2011	OpenMP 3.1
July 2013	OpenMP 4.0
November 2015	OpenMP 4.5
November 2018	OpenMP 5.0
November 2020	OpenMP 5.1
November 2021	OpenMP 5.2

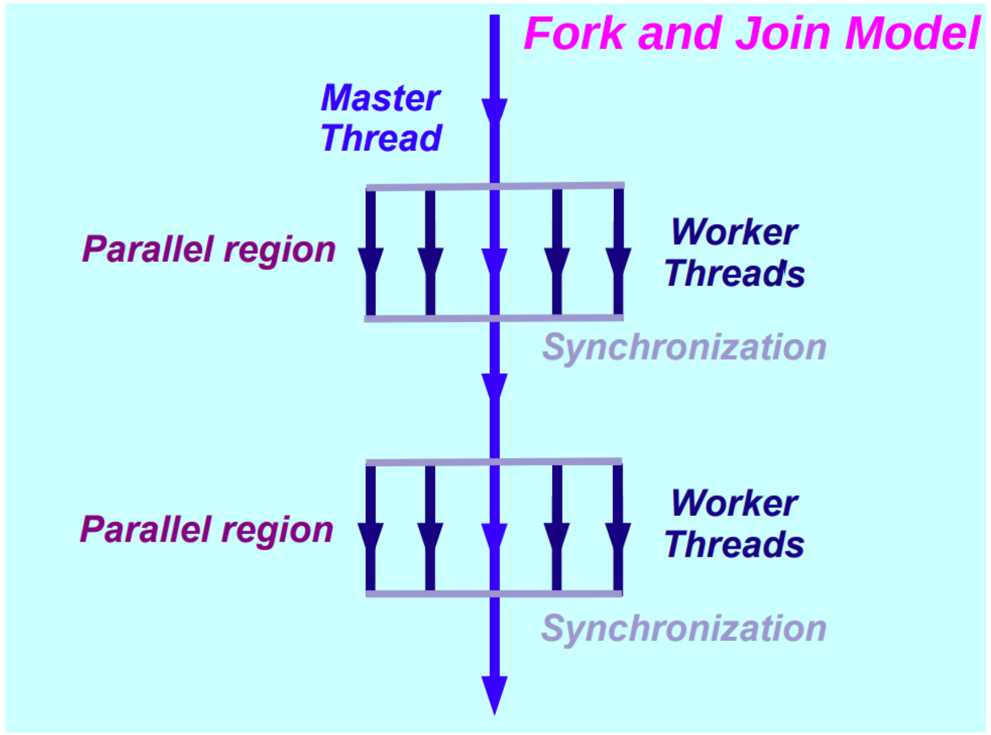
技术框架

- OpenMP library
- OpenMP Runtime library



执行模型：Fork-Join Model

- 单线程（initial thread）开始执行
- 进入并行区（parallel region）开始并行执行
- 在并行区结尾**进行同步**和结束线程，继续单线程执行程序

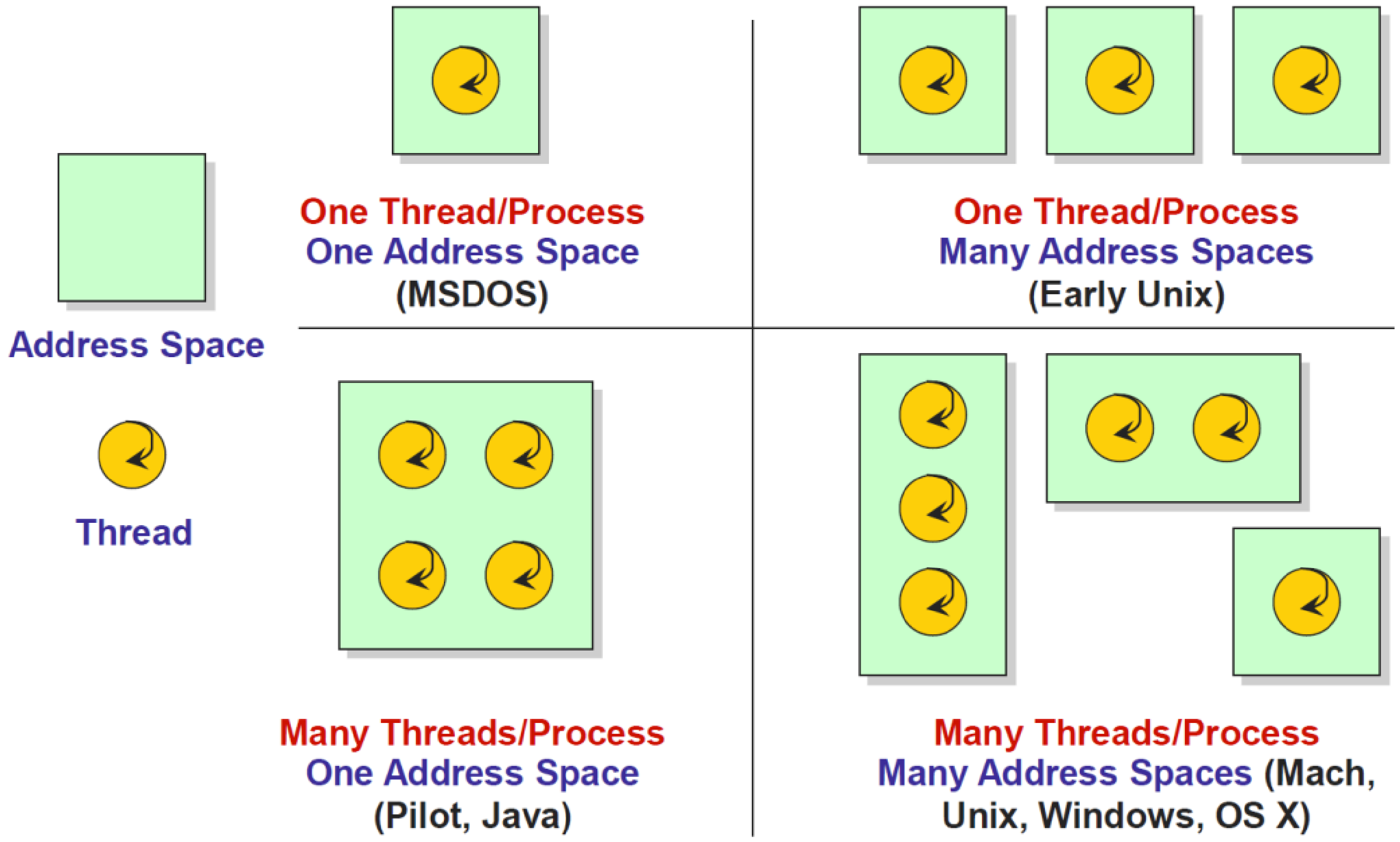


基础知识

进程和线程

- 进程
  - 每个进程有自己独立的地址空间
  - CPU在进程之间切换需要进行上下文切换
- 线程
  - 一个进程下的线程共享地址空间
  - CPU在线程之间切换开销较小

操作系统的线程设计



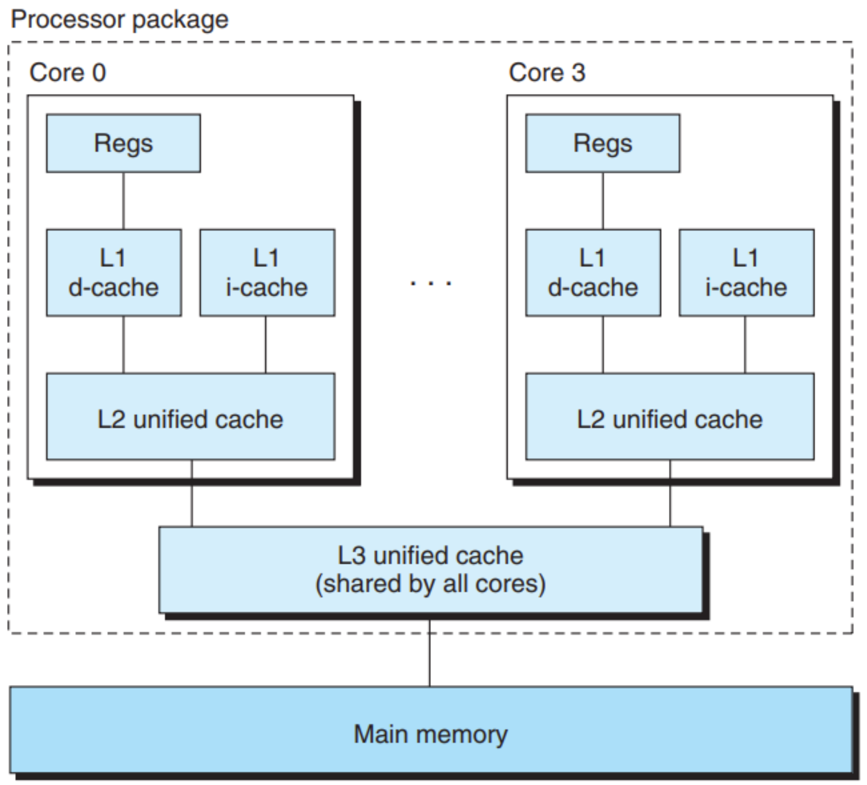
Address Space
Thread
One Thread/Process
One Address Space
(MSDOS)
One Thread/Process
Many Address Spaces
(Early Unix)
Many Threads/Process
One Address Space
(Pilot, Java)
Many Threads/Process
Many Address Spaces (Mach, Unix, Windows, OS X)

线程的硬件调度

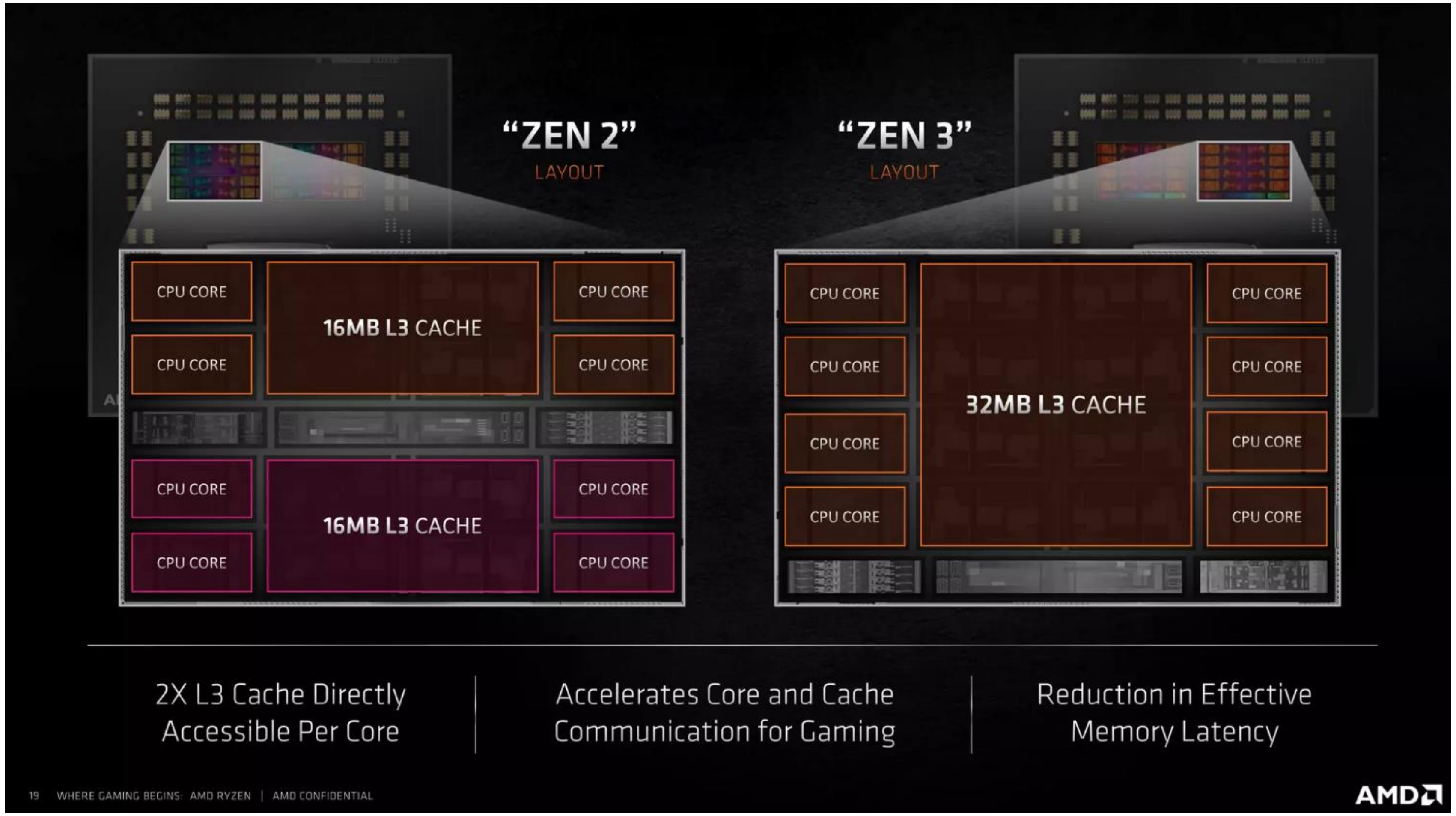
- 你可以简单理解，硬件和操作系统会自行将线程调度到CPU核心运行
- 所以当线程数目超过核心数，会出现多个线程抢占一个CPU核心，导致性能下降
- 超线程（hyper-threading）将单个CPU物理核心抽象为多个（目前通常为2个）逻辑核心，共享物理核心的计算资源

硬件的内存模型

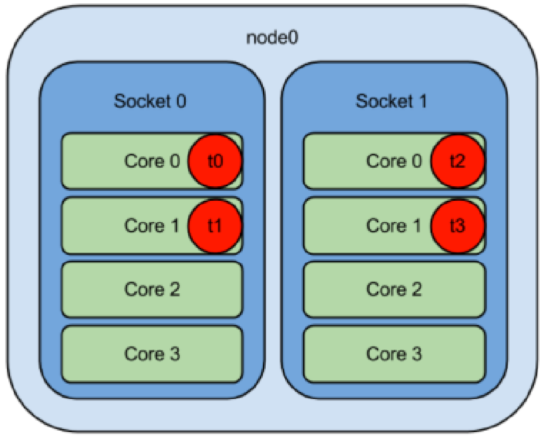
- CPU核心在主存之上有L1, L2, L3多级缓存
- L1, L2缓存是核心私有的
- 硬件和操作系统保证不同核心的缓存一致性（coherence）
- 被称为cache coherence non-uniform access architecture(ccNUMA)
- 缓存一致性会带来False Sharing的问题（之后会讲到）



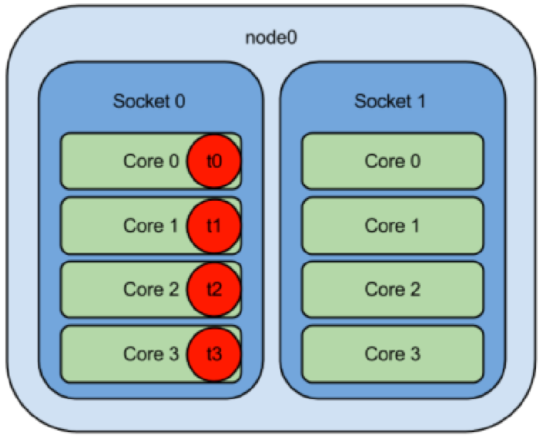
硬件的内存模型


"ZEN 2" LAYOUT
"ZEN 3" LAYOUT
CPU CORE
16MB L3 CACHE
16MB L3 CACHE
32MB L3 CACHE
2X L3 Cache Directly Accessible Per Core
Accelerates Core and Cache Communication for Gaming
Reduction in Effective Memory Latency
19 WHERE GAMING BEGINS: AMD RYZEN | AMD CONFIDENTIAL
AMD

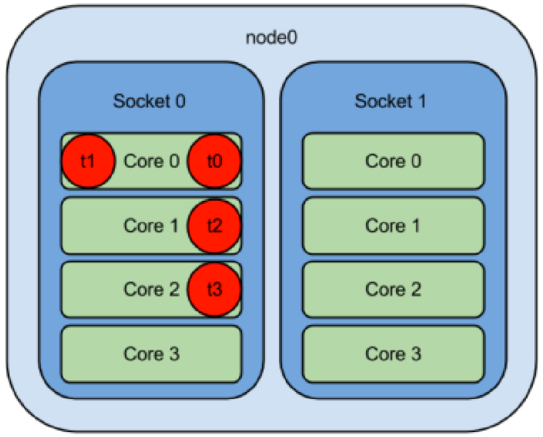
线程亲和性和线程绑定



scatter



compact



stupid

线程亲和性和线程绑定

- openmp支持控制线程的绑定
  - 环境变量OMP_PROC_BIND/从句proc_bind(master|close|spread)：控制线程绑定与否，以及线程对于绑定单元（称为 place）分布
- 参考文档以及相关官方手册

OpenMP编程

安装

- 含在Ubuntu提供的build-essential包中
- 如何查看openmp版本?

```
echo |cpp -fopenmp -dM |grep -i open
# #define _OPENMP 201511
```

编译使用

- 可以直接在编译语句添加-fopenmp，如：

```
g++ -O2 -std=c++14 -fopenmp hello.cpp -o hello
```

- 如果使用cmake构建项目：
  - gcc加入-Wunknown-pragmas会在编译时报告没有处理的#pragma语句

```
find_package(OpenMP)
add_compile_options(-Wunknown-pragmas)

add_executable(hello src/hello.cpp)
target_link_libraries(hello OpenMP::OpenMP_CXX)
```

Hello

第一个OpenMP程序

Hello

```
#include <iostream>
#include <omp.h>

int main() {
#pragma omp parallel num_threads(8)
  {
    int tid = omp_get_thread_num();
    int num_threads = omp_get_num_threads();
    printf("Hello from thread %d of %d\n", tid, num_threads);
  }
  return 0;
}
```

```
Hello from thread 0 of 8
Hello from thread 4 of 8
Hello from thread 5 of 8
Hello from thread 3 of 8
Hello from thread 6 of 8
Hello from thread 1 of 8
Hello from thread 2 of 8
Hello from thread 7 of 8
```

Hello

```
#include <iostream>
#include <omp.h>

int main() {
#pragma omp parallel num_threads(8)
  {
    int tid = omp_get_thread_num();
    int num_threads = omp_get_num_threads();
    printf("Hello from thread %d of %d\n", tid, num_threads);
  }
  return 0;
}
```

- 同一类openmp制导语句称为一种构造 (construct)
- 形式为#pragma omp <directive name> <clause>
- 使用{}标记作用的代码块

设置线程数

```
#include <iostream>
#include <omp.h>

int main() {
#pragma omp parallel num_threads(8)
  {
    int tid = omp_get_thread_num();
    int num_threads = omp_get_num_threads();
    printf("Hello from thread %d of %d\n", tid, num_threads);
  }
  return 0;
}
```

- 优先级由低到高
  - 什么也不做，系统选择运行线程数
  - 设置环境变量export OMP_NUM_THREADS=4
  - 代码中使用库函数void omp_set_num_threads(int)
  - 通过制导语句从句num_threads(integer-expression)
  - if从句判断串行还是并行执行

一些常用库函数

```
// 设置并行区运行的线程数
void omp_set_num_threads(int)
// 获得并行区运行的线程数
int omp_get_num_threads(void)
// 获得线程编号
int omp_get_thread_num(void)
// 获得openmp wall clock时间 (单位秒)
double omp_get_wtime(void)
// 获得omp_get_wtime时间精度
double omp_get_wtick(void)
```

parallel构造

#pragma omp parallel

支持的从句

- if(scalar_expression)：决定是否以并行的方式执行并行区
  - 表达式为真 (非零)：按照并行方式执行并行区
  - 否则：主线程串行执行并行区
- num_threads(integer_expression)：指定并行区的线程数

支持的从句

- default(shared|none)：指定默认
  - shared：默认为共享变量
  - none：无默认变量类型，每个变量都需要另外指定
- shared(list)：指定共享变量列表变量类型
  - 共享变量在内存中只有一份，所有线程都可以访问
  - 请保证共享访问不会冲突
  - 不特别指定并行区变量**默认为shared**

支持的从句

- private(list)：指定私有变量列表
  - 每个线程生成一份与该私有变量同类型的数据对象
  - 变量需要**重新初始化**
- firstprivate(list)
  - 同private
  - 对变量根据主线程中的数据进行初始化

样例代码

```c
int cnt;
cnt = 1;
#pragma omp parallel num_threads(4)
{
  int tid = omp_get_thread_num();
  for (int i = 0; i < 4; i++) {
    cnt += 1;
  }
  results[tid] = cnt;
}

cnt = 1;
#pragma omp parallel num_threads(4) private(cnt)
{
  int tid = omp_get_thread_num();
  for (int i = 0; i < 4; i++) {
    cnt += 1;
  }
  results[tid] = cnt;
}

cnt = 1;
#pragma omp parallel num_threads(4) firstprivate(cnt)
{
  int tid = omp_get_thread_num();
  for (int i = 0; i < 4; i++) {
    cnt += 1;
  }
  results[tid] = cnt;
}
```

```
no clause: 5 9 17 13
private(not init): 4 -187939698 -187939698 -187939698
firstprivate: 5 5 5 5
```

for构造

#pragma omp for

样例代码

```cpp
#pragma omp parallel num_threads(8)
{
  int tid = omp_get_thread_num();
  int num_threads = omp_get_num_threads();
#pragma omp for ordered
  for (int i = 0; i < num_threads; i++) {
    // do something
    // #pragma omp ordered
    // #pragma omp critical
    std::cout << "Hello from thread " << tid << std::endl;
  }
}
```

```
#no synchronization
Hello from thread 0Hello from thread
Hello from thread 4
Hello from thread Hello from thread Hello from thread 7
Hello from thread 1
2
Hello from thread 5
6
3

# ordered
Hello from thread 0
Hello from thread 1
Hello from thread 2
Hello from thread 3
Hello from thread 4
Hello from thread 5
Hello from thread 6
Hello from thread 7

# critical
Hello from thread 5
Hello from thread 4
Hello from thread 1
Hello from thread 7
Hello from thread 6
Hello from thread 3
Hello from thread 2
Hello from thread 0
```

格式要求

- 在并行区内对for循环进行线程划分，且for循环满足格式要求
  - init-expr：需要是var=lb形式，类型也有限制
  - test-expr：限制为var relational-opb或者b relational-op var
  - incr-expr：仅限加减法
- 详细参考OpenMP API 4.5 Specification, p53

parallel for

- 常常将parallel和for合并为parallel for制导语句

	parallel	for	parallel for
if	√		√
num_threads	√		√
default	√		√
copyin	√		√
private	√	√	√
firstprivate	√	√	√
shared	√	√	√
reduction	√	√	√
lastprivate		√	√
Schedule		√	√
ordered		√	√
collapse		√	√
nowait		√	

支持的从句

- lastprivate(list)
  - 同private
  - 执行最后一个循环的线程的私有数据取出赋值给主线程的变量
- nowait：取消代码块结束时的栅栏同步（barrier）
- collapse(n)：应用于n重循环，合并（展开）循环
  - 注意循环之间是否有数据依赖
- ordered：声明有潜在的顺序执行部分
  - 使用#pragma omp ordered标记顺序执行代码（搭配使用）
  - ordered区内的语句任意时刻仅由最多一个线程执行

支持的从句

- schedule(type [, chunk])：控制调度方式
  - static：chunk大小固定（默认n/p）
  - dynamic：动态调度，chunk大小固定（默认为1）
  - guided：chunk大小动态缩减
  - runtime：由系统环境变量OMP_SCHEDULE决定

样例代码

```
for (int i = 0; i < N; i++) {
  for (int j = i; j < N; j++) {
    double sum = 0;
    for (int k = 0; k < N; k++) {
      sum += A[i * N + k] * A[j * N + k];
    }
    B[i * N + j] = sum;
    B[j * N + i] = sum;
  }
}

#pragma omp parallel for schedule(runtime)
for (int i = 0; i < N; i++) {
  for (int j = i; j < N; j++) {
    double sum = 0;
    for (int k = 0; k < N; k++) {
      sum += A[i * N + k] * A[j * N + k];
    }
    B[i * N + j] = sum;
    B[j * N + i] = sum;
  }
}
```

```
# export
OMP_SCHEDULE="dynamic"
size: 1024
sequence time: 1.46233
omp time: 0.133192

# export
OMP_SCHEDULE="static"
size: 1024
sequence time: 1.47874
omp time: 0.219114
```

Reduction

特殊的数据从句

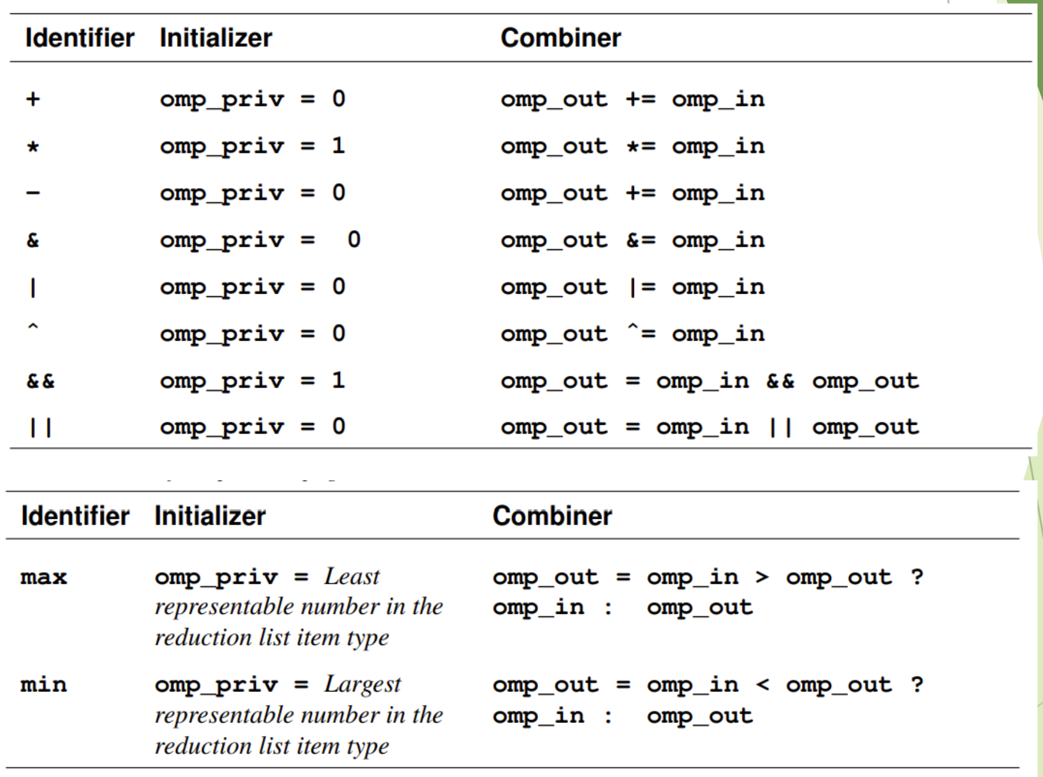
样例代码

```
for (int i = 0; i < N; i++) {
  ans_seq += b[i] * b[i];
}
ans_seq = sqrt(ans_seq);

#pragma omp parallel for reduction(+ : ans_omp)
for (int i = 0; i < N; i++) {
  ans_omp += b[i] * b[i];
}
ans_omp = sqrt(ans_omp);

#pragma omp parallel for
for (int i = 0; i < N; i++) {
#pragma omp atomic
  // #pragma omp critical
  ans_omp_sync += b[i] * b[i];
}
ans_omp_sync = sqrt(ans_omp_sync);
```

```
# atomic
size: 33554432
sequence result: 3344.05
omp result: 3344.05
omp sync result: 3344.05
sequence time: 0.0928805
omp time: 0.0180116
omp sync time: 5.17156

# critical
size: 33554432
sequence result: 3344.2
omp result: 3344.2
omp sync result: 3344.2
sequence time: 0.0929021
omp time: 0.0179938
omp sync time: 7.74378
```

reduction执行过程

- fork线程并分配任务
- 每一个线程定义一个私有变量omp_priv
  - 同private
- 各个线程执行计算
- 所有omp_priv和omp_in一起顺序进行reduction，写回原变量



Identifier	Initializer	Combiner
`+`	`omp_priv = 0`	`omp_out += omp_in`
`*`	`omp_priv = 1`	`omp_out *= omp_in`
`-`	`omp_priv = 0`	`omp_out += omp_in`
`&`	`omp_priv =  0`	`omp_out &= omp_in`
`|`	`omp_priv = 0`	`omp_out |= omp_in`
`^`	`omp_priv = 0`	`omp_out ^= omp_in`
`&&`	`omp_priv = 1`	`omp_out = omp_in && omp_out`
`||`	`omp_priv = 0`	`omp_out = omp_in || omp_out`

Identifier	Initializer	Combiner
`max`	`omp_priv =` *Least representable number in the reduction list item type*	`omp_out = omp_in > omp_out ? omp_in : omp_out`
`min`	`omp_priv =` *Largest representable number in the reduction list item type*	`omp_out = omp_in < omp_out ? omp_in : omp_out`

同步构造

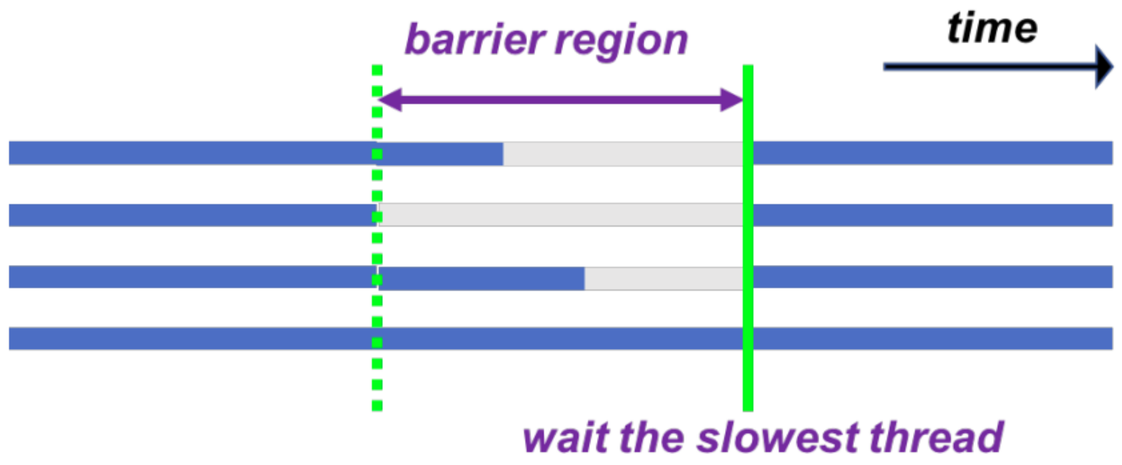
sections构造

- 将并行区内的代码块划分为多个section分配执行
- 可以搭配parallel合成为parallel sections构造
- 每个section由一个线程执行
  - 线程数大于section数目：部分线程空闲
  - 线程数小于section数目：部分线程分配多个section

```
#pragma omp sections
{
#pragma omp section
  code1();
#pragma omp section
  code2();
}
```

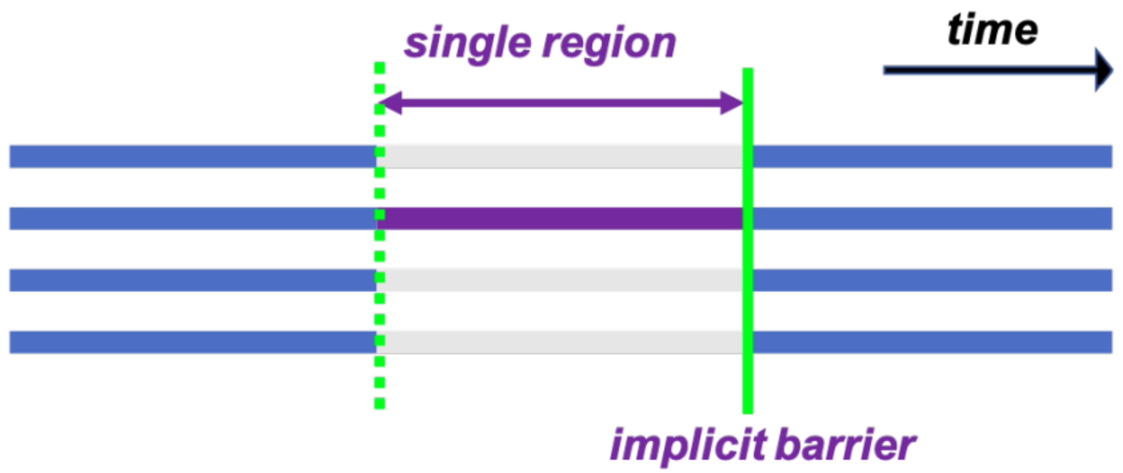
#pragma omp barrier

- 在特定位置进行栅栏同步



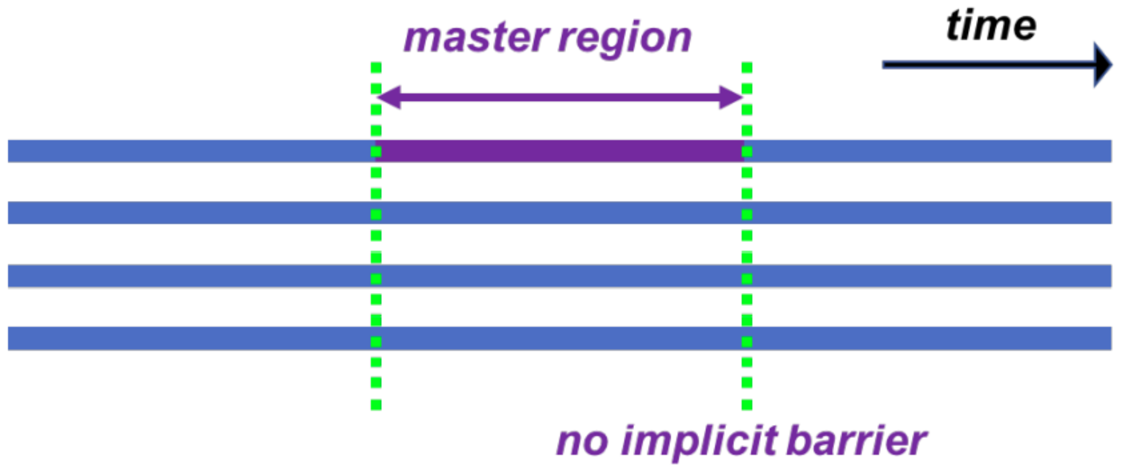
#pragma omp single

- 某段代码单线程执行，带隐式同步（使用nowait去掉）



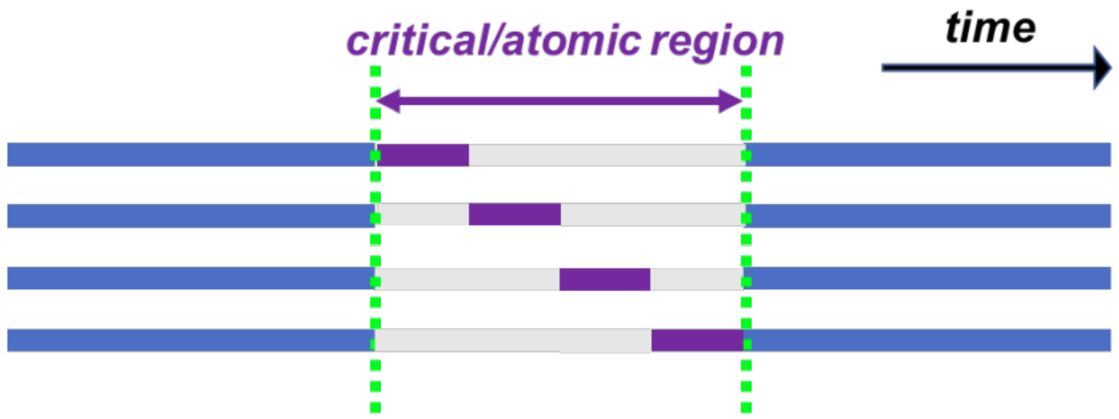
#pragma omp master

- 采用主线程执行，无隐式同步



#pragma omp critical

- 某段代码线程互斥执行



#pragma omp atomic

- 单个特定格式的语句或语句组中某个变量进行原子操作

False Sharing

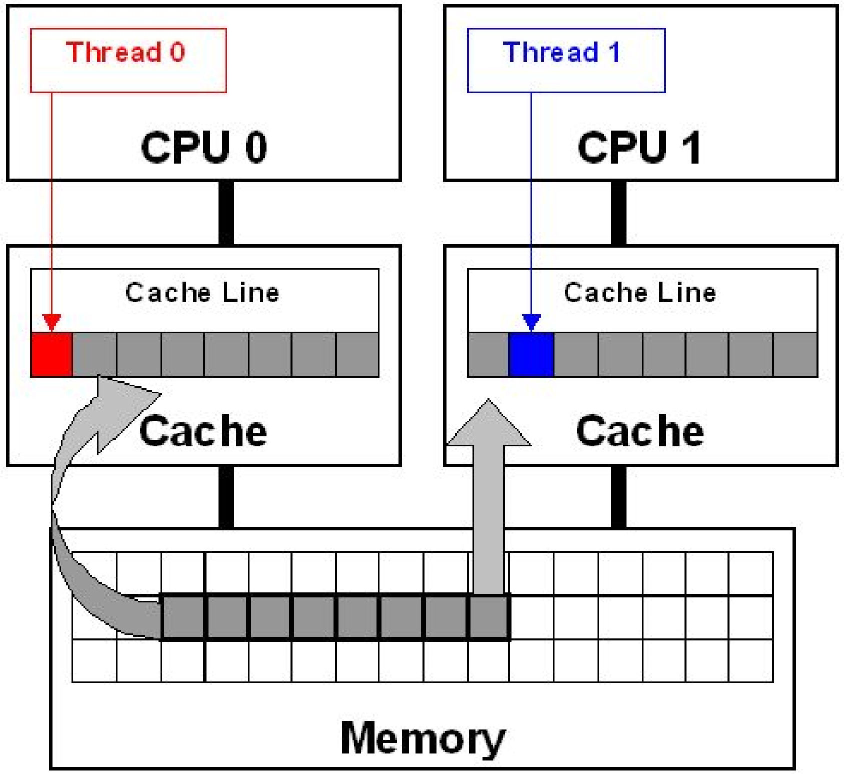
样例代码

```c
for (int i = 0; i < N; i++) {
  for (int j = 0; j < N; j++) {
    x_seq[i] += A[i * N + j] * b[j];
  }
}

#pragma omp parallel for
for (int i = 0; i < N; i++) {
  double tmp = 0;
  for (int j = 0; j < N; j++) {
    tmp += A[i * N + j] * b[j];
  }
  x_omp[i] = tmp;
}

#pragma omp parallel for
for (int i = 0; i < N; i++) {
  for (int j = 0; j < N; j++) {
    x_omp_fs[i] += A[i * N + j] * b[j];
  }
}
```

```
size: 16384
sequence time: 1.07896
simple omp time: 0.0938018
false sharing time: 0.110479

size: 16384
sequence time: 1.38333
simple omp time: 0.0958252
false sharing time: 0.115473

size: 16384
sequence time: 1.0359
simple omp time: 0.0973124
false sharing time: 0.129693
```

False Sharing

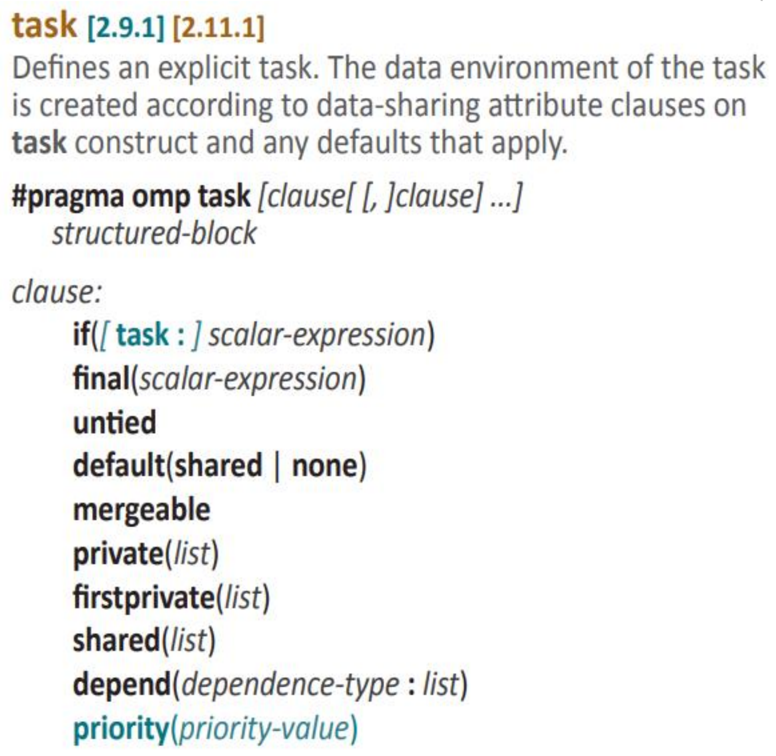
- 耗时增加24%
- 不同核心对同一cache line的同时读写会造成严重的冲突，导致该级缓存失效



更多特性

任务构造

- 前述的构造都遵循Fork-Join模式，对任务类型有限制
- 任务（task）构造允许定义任务以及依赖关系，动态调度执行
- 即动态管理线程池（thread pool）和任务池（task pool）



task [2.9.1] [2.11.1]

Defines an explicit task. The data environment of the task is created according to data-sharing attribute clauses on **task** construct and any defaults that apply.

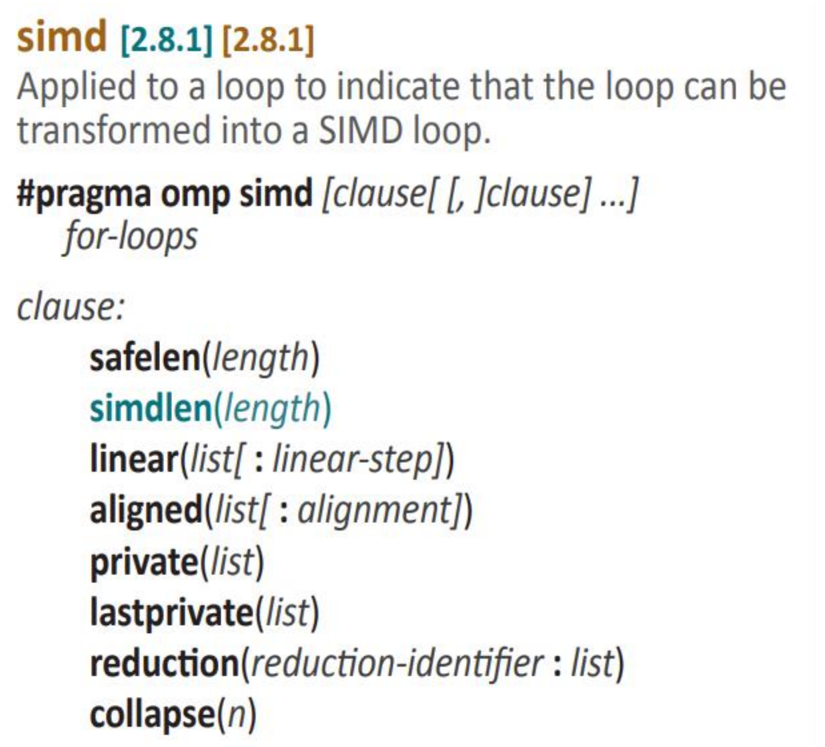
```
#pragma omp task [clause[ [, ]clause] ...]
    structured-block
```

clause:

- **if**(*[* **task :** *] scalar-expression*)
- **final**(*scalar-expression*)
- **untied**
- **default**(**shared** | **none**)
- **mergeable**
- **private**(*list*)
- **firstprivate**(*list*)
- **shared**(*list*)
- **depend**(*dependence-type* **:** *list*)
- **priority**(*priority-value*)

向量化

- 将循环转换为SIMD循环
- aligned用于列出内存对齐的指针
- safelen用于标记循环展开时的数据依赖



simd [2.8.1] [2.8.1]
Applied to a loop to indicate that the loop can be transformed into a SIMD loop.

#pragma omp simd *[clause[[,]clause] ...]*
    for-loops

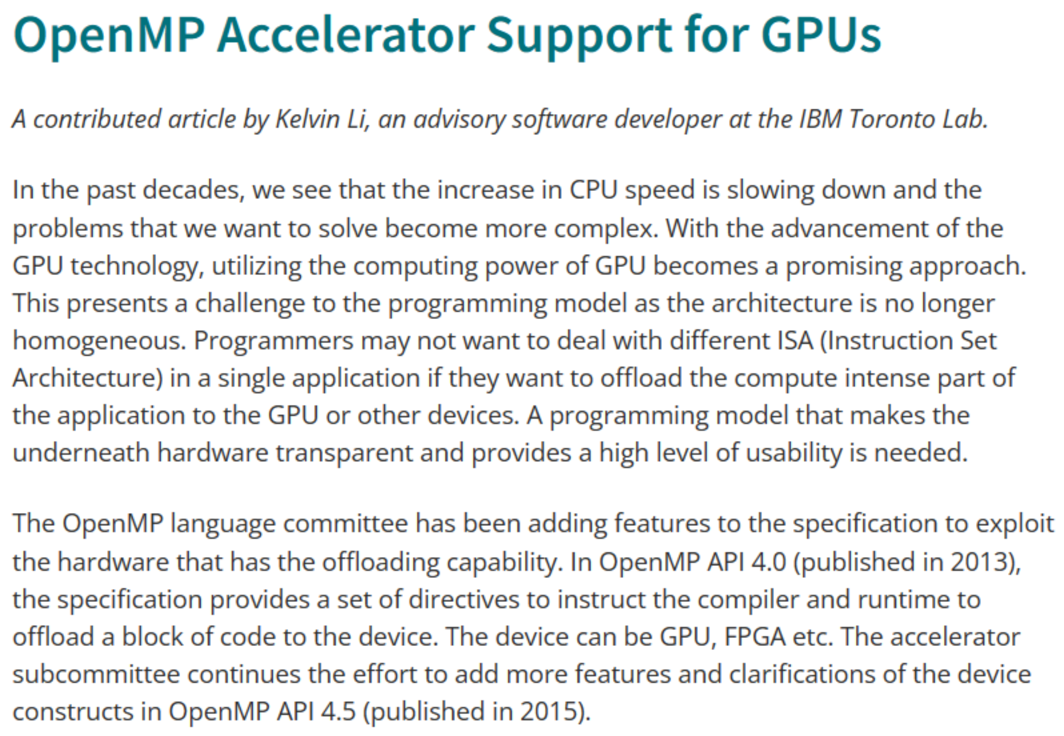
clause:
- **safelen**(*length*)
- **simdlen**(*length*)
- **linear**(*list[* **:** *linear-step]*)
- **aligned**(*list[* **:** *alignment]*)
- **private**(*list*)
- **lastprivate**(*list*)
- **reduction**(*reduction-identifier* **:** *list*)
- **collapse**(*n*)

向量化

- 编译器也自带向量化功能，例如gcc
  - -O3
  - -ffast-math
  - -fivopts
  - -march=native
  - -fopt-info-vec
  - -fopt-info-vec-missed

GPU支持

- 参考网页
- 从OpenMP API 4.0开始支持



OpenMP Accelerator Support for GPUs

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In the past decades, we see that the increase in CPU speed is slowing down and the problems that we want to solve become more complex. With the advancement of the GPU technology, utilizing the computing power of GPU becomes a promising approach. This presents a challenge to the programming model as the architecture is no longer homogeneous. Programmers may not want to deal with different ISA (Instruction Set Architecture) in a single application if they want to offload the compute intense part of the application to the GPU or other devices. A programming model that makes the underneath hardware transparent and provides a high level of usability is needed.

The OpenMP language committee has been adding features to the specification to exploit the hardware that has the offloading capability. In OpenMP API 4.0 (published in 2013), the specification provides a set of directives to instruct the compiler and runtime to offload a block of code to the device. The device can be GPU, FPGA etc. The accelerator subcommittee continues the effort to add more features and clarifications of the device constructs in OpenMP API 4.5 (published in 2015).

参考资料

参考资料

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- Schmidt B, Gonzalez-Dominguez J, Hundt C, et al. Parallel programming: concepts and practice[M]. Morgan Kaufmann, 2017.
- API reference
- C/C++ Reference Guide

Thanks