Intel® oneAPI DPC++ Library (oneDPL)

Reduce Cross-platform Programming Efforts & Write Performant Parallel Code with oneDPL

Alexey Kukanov

Principal Engineer, Intel Corporation

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Agenda

- Parallel Algorithms API
  - Overview
  - Support for Data Parallel C++ (DPC++)
- C++ Standard APIs for Device Programming
- Custom Iterators
- Outlook: Experimental Features
  - Ranges API
  - Async API
- Summary

oneAPI

One Programming Model for Multiple Architectures and Vendors

Freedom to Make Your Best Choice

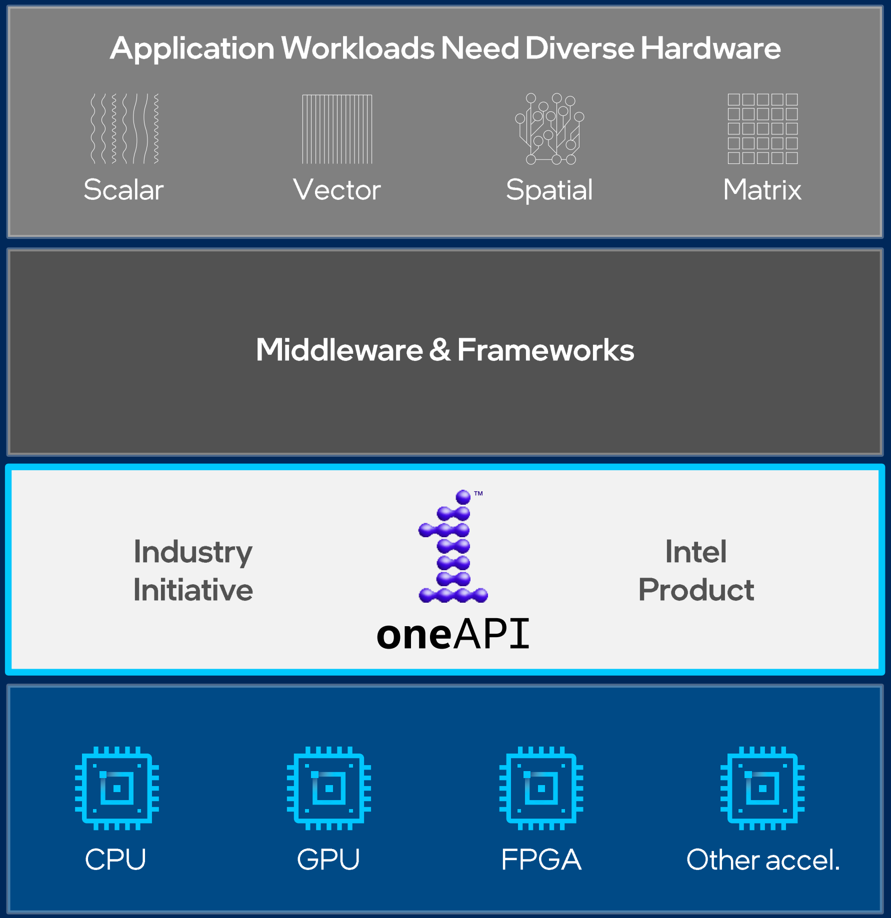
- Choose the best accelerated technology; the software doesn't decide for you

Realize all the Hardware Value

- Performance across CPU, GPUs, FPGAs, and other accelerators

Develop & Deploy Software with Peace of Mind

- Open industry standards provide a safe, clear path to the future
- Compatible with existing languages and programming models including C++, Python*, SYCL*, OpenMP*, Fortran, and MPI



oneAPI Industry Initiative

Break the Chains of Proprietary Lock-in

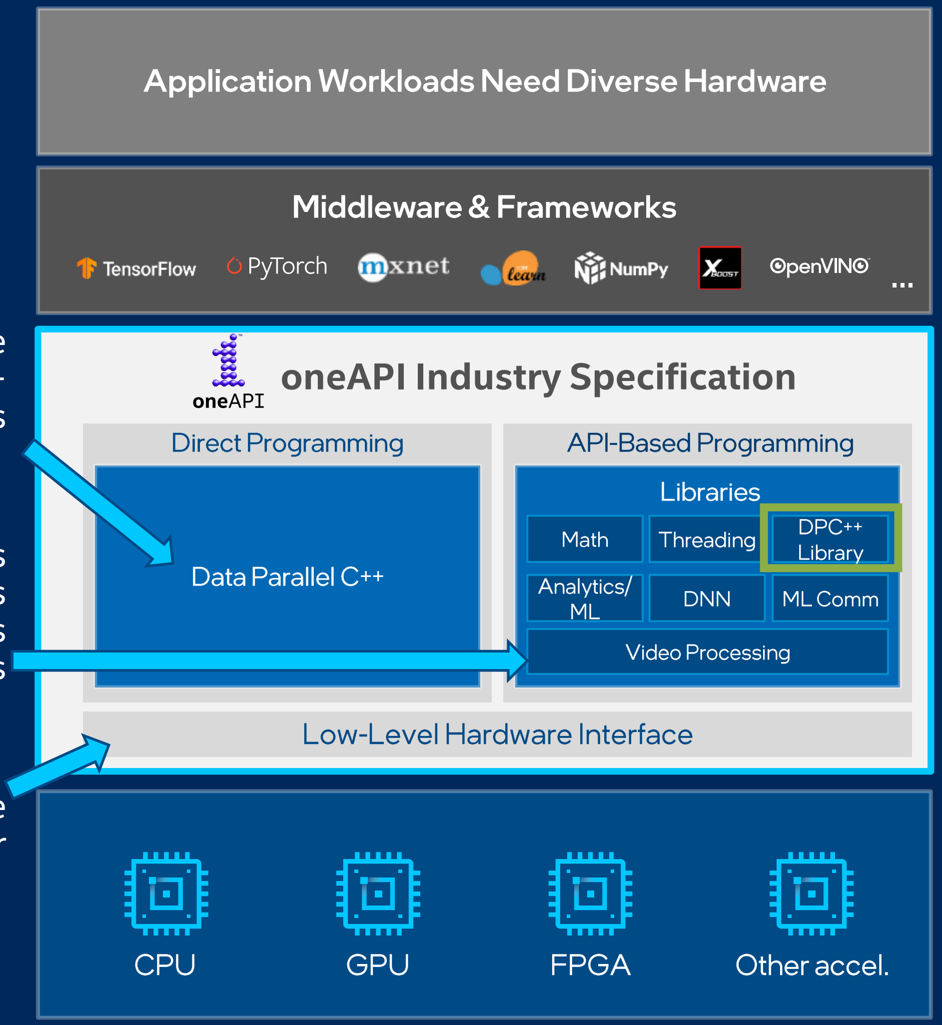
Open to promote community and industry collaboration

Enables code reuse across architectures and vendors

A cross-architecture language based on C++ and SYCL standards

Set of libraries minimizes programming efforts across different devices and domains

Low-level hardware abstraction layer



oneAPI

The productive, smart path to freedom for accelerated computing from the economic and technical burdens of proprietary programming models

Intel® oneAPI DPC++ Library (oneDPL)

- **High productivity and portable performance for heterogeneous computing** – CPUs, GPUs, and FPGAs
- **APIs based on standards and familiar extensions** – C++ STL, SYCL, Boost.Compute
- **Optimized C++ standard algorithms** implemented on top of SYCL, OpenMP, oneTBB
- **Interoperable with DPC++ and other oneAPI libraries**
- **Integrated with Intel® DPC++ Compatibility Tool** to simplify migration of CUDA* applications using Thrust* API to DPC++ code

oneDPL Specification & Reference Implementation

Spec: oneDPL section covers:

- Parallelized C++ algorithms
- Tested C++ standard APIs that work in DPC++ kernels
- Execution Policies
- Custom Utilities and Algorithms

oneAPI

https://spec.oneapi.io/versions/latest/elements/oneDPL/source/index.html#onedpl-section

oneDPL implementation

Source Code

- Available as part of the Intel® oneAPI Base Toolkit
- Supports multiple backends: oneTBB, OpenMP, DPC++
- Header-only library (relies on runtime libraries of the respective backends)

oneAPI

https://github.com/oneapi-src/oneDPL

Basic oneDPL Usage Guidelines

- C++17 is the minimal supported version of the C++ standard
- Header names start with oneapi/dpl:
  `#include <oneapi/dpl/algorithm>`
- All functionality is provided in `namespace oneapi::dpl`
  - short alias: `namespace dpl = oneapi::dpl;`

Parallel Algorithms API

Parallel Algorithms API: Brief Overview

- C++ parallel algorithms
- Execution policies define how to run an algorithm

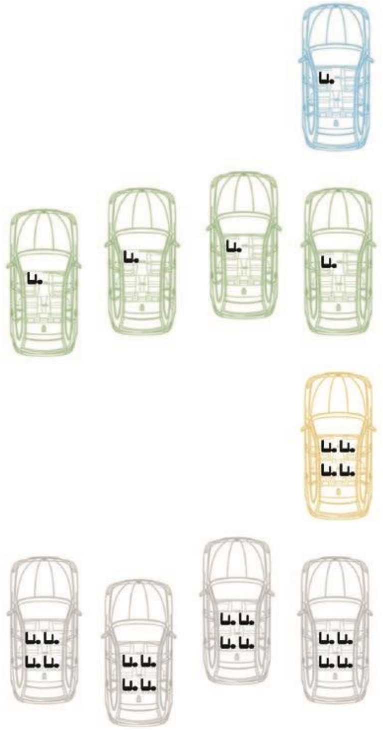
Expressing Parallelism in C++17/20

```
/* a serial range-based for loop */
for(auto &i : v) {i++;}

------------
#include <algorithm>
/* a serial for-each algorithm w/o execution policy  */
std::for_each(v.begin(), v.end(), [](auto &i){i++;});

------------
#include <algorithm>
#include <execution>
/* a for-each algorithm with parallel execution policy */
std::for_each(std::execution::par, v.begin(), v.end(), [](auto &i){i++;});
```

Semantics of Standard Execution Policies

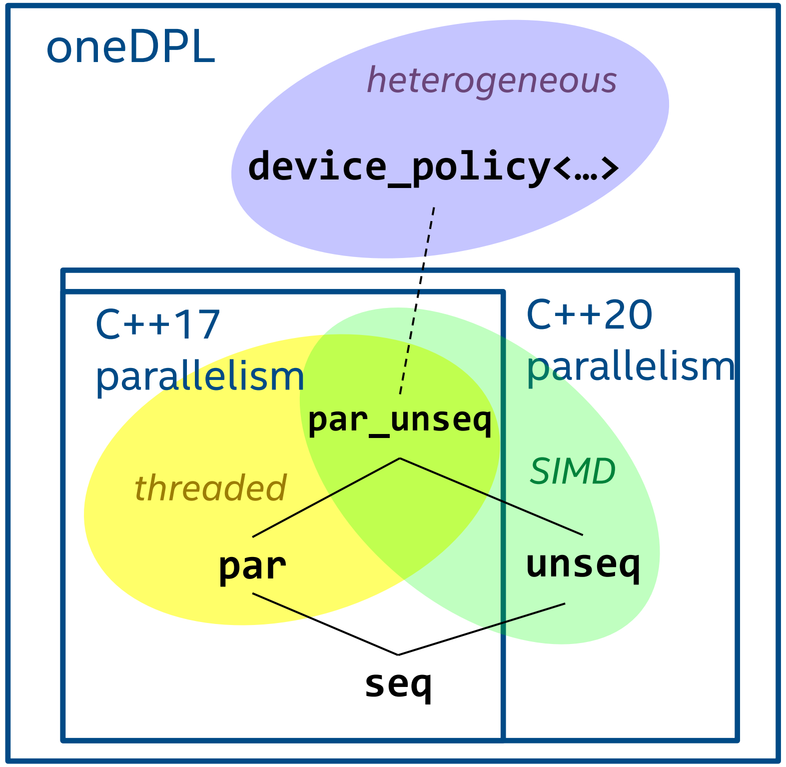
- **standard sequential** sort
  `std::sort(v.begin(), v.end());`
- **explicitly sequential** sort
  `std::sort(std::`**`execution::seq`**`, v.begin(), v.end());`
- permitting **parallel execution**
  `std::sort(std::`**`execution::par`**`, v.begin(), v.end());`
- permitting **vectorization only (no parallel execution)**
  `std::sort(std::`**`execution::unseq`**`, v.begin(), v.end());`
- permitting **parallel execution** and **vectorization**
  `std::sort(std::`**`execution::par_unseq`**`, v.begin(), v.end());`

multilane highway analogy from ProTBB book, M. Voss et al.



Parallel Algorithms API: Brief Overview (cont.)

- C++ parallel algorithms
- oneDPL extension algorithms
  - Segmented reduction & scan, binary search of multiple values
- Execution policies define how/**where** to run an algorithm
  - CPU: oneTBB or OpenMP for threading (par), OpenMP for SIMD (unseq)
  - GPU & accelerators: DPC++ supported devices



DPC++ Support in Parallel API

DPC++ Execution Policies

- `oneapi::dpl::execution::device_policy<…>` class template
  - The policy type selects the SYCL-based implementation of an algorithm
  - A policy object encapsulates a SYCL queue that defines the device to run on
  - Implicitly convertible to `sycl::queue` for better interoperability
- Policy usage:
  - Construct a policy object using a SYCL queue, device, device selector, or an existing policy object
  - Pass the created policy object to a oneDPL algorithm
- `oneapi::dpl::execution::dpcpp_default`
  - Predefined object of the device_policy class, uses the default SYCL queue

How to Target a Device:

First simple example (to be continued …)

```
#include <oneapi/dpl/execution>
#include <oneapi/dpl/algorithm>
int main()
{
      std::vector<int> vec(1000);
      dpl::fill(dpl::execution::dpcpp_default,
                vec.begin(), vec.end(), 42);
      return 0;
}

// To build: dpcpp <example_name>.cpp -o test
```

Buffer Wrappers

`oneapi::dpl::begin` and `oneapi::dpl::end` are helper functions for passing SYCL buffers to oneDPL algorithms

Applied to a SYCL buffer, these functions return an object of an unspecified type with some properties of a random access iterator:

- Can be copy-constructed and copy-assigned
- Can be compared for equality (== and !=)
- Can be used in expressions a + n, a – n, a – b, where **a** and **b** are objects of the type and **n** is an integer value

But most importantly, it can be passed to oneDPL algorithms

Simple Example using SYCL Buffer

Keeping data on the device with consecutive usage

```
#include <oneapi/dpl/execution>
#include <oneapi/dpl/algorithm>
#include <oneapi/dpl/iterator>
#include <sycl/sycl.hpp> // or <CL/sycl.hpp>
int main()
{
    sycl::buffer<int> buf{ 1000 };
    dpl::fill(dpl::execution::dpcpp_default, dpl::begin(buf),
              dpl::end(buf), 42);
    auto result = dpl::find(dpl::execution::dpcpp_default,
                            dpl::begin(buf), dpl::end(buf), 42);
    return 0;
}
```

Advanced Techniques:

Passing access modes to the backend

```
auto buf_begin = dpl::begin(buf);
dpl::fill(my_policy, buf_begin, buf_begin + 1000, 42);
```

```
auto buf_begin = dpl::begin(buf, sycl::write_only, sycl::noinit);
dpl::fill(my_policy, buf_begin, buf_begin + 1000, 42);
```

Example with SYCL Unified Shared Memory (USM)

Directly pass USM pointers to parallel algorithms

```
#include <oneapi/dpl/execution>
#include <oneapi/dpl/algorithm>
#include <sycl/sycl.hpp>
int main()
{
        using oneapi::dpl::execution::make_device_policy;
        sycl::queue q;
        const int n = 1000;
        int* data = sycl::malloc_shared<int>(n, q);

        auto pol = make_device_policy<class Fill>(q);
        dpl::fill(pol, data, data + n, 42);
        auto result = dpl::find(make_device_policy<class Find>(q),
                                data, data + n, 42);
        // q.wait();

        sycl::free(data, q);
        return 0;
}
```

C++ for Device Programming

Using the C++ Standard Library in DPC++

- Host
  - Code running on the host CPU can use everything
- Device
  - Some std classes/functions cannot work in device kernel code due to SYCL/DPC++ restrictions
    - Functions/methods that use exception
    - Dynamic memory allocation
    - Virtual functions

Tested Standard C++ APIs

- 120 standard C++ APIs have been tested
  - Usage in DPC++ kernels
  - Data transfer between host and device (only for specific C++ types)
- Across 3 major implementations:
  - libstdc++(GNU): deployed in most Linux* distributions
  - libc++(LLVM): macOS* and FreeBSD*
  - Microsoft STL*: Windows*; shipped with Microsoft Visual Studio*
- Available in both `namespace std` and `namespace oneapi::dpl`

Visit Intel® oneAPI DPC++ Library Guide for a detailed list

Example: Complex Numbers

use of std components on the device

```
#include <oneapi/dpl/execution>
#include <oneapi/dpl/algorithm>
#include <oneapi/dpl/iterator>
#include <sycl/sycl.hpp>
#include <complex>

int main() {
    const size_t n = 100;
    sycl::buffer<std::complex<double>> c_buf{n};
    auto idx = dpl::counting_iterator<int>(0);

    dpl::transform(dpl::execution::dpcpp_default, idx, idx+n, dpl::begin(c_buf),
    [=](auto i) {
        const double v = fabs(static_cast<double>(n)/2.0 - static_cast<double>(i));
        return std::complex<double>{v, v};
    });
    return 0;
}
```

Custom Iterators

Expanding Applicability of Parallel Algorithms with Custom Iterators

Custom Iterators:

- counting_iterator
- zip_iterator
- transform_iterator
- permutation_iterator
- discard_iterator

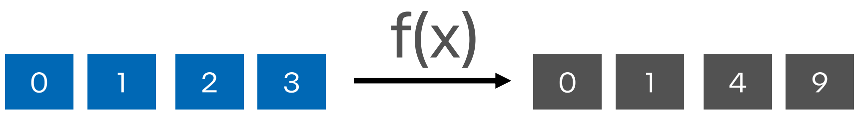
Counting Iterator

[0,4) → 0 | 1 | 2 | 3

- Represents a linear, increasing sequence of integer values
- Commonly used as an index: `[](auto i){a[i] = b[i];}`
- Advantage: Not in memory

Increase Adaptability with Custom Iterators

Transform Iterator

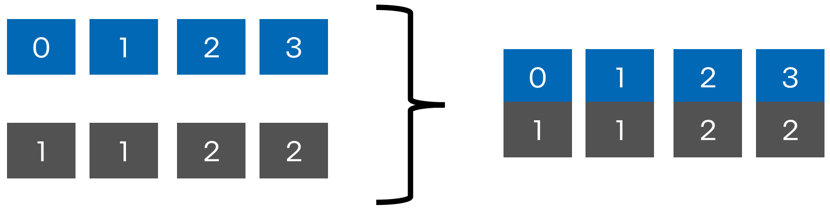


- Applies transformation to dereferenced values of another iterator
- Example: Square numbers
  - Input iterator

    Here: counting iterator
  - Unary function

    Here: `[](auto& x){return x*x;}`

Zip Iterator



- Combines multiple iterators into a single iteration space
  - Combinations of custom iterators are possible (permutation, counting, …)
- Make function accepts an argument pack

How to Use a Zip Iterator

TriAdd example with oneDPL

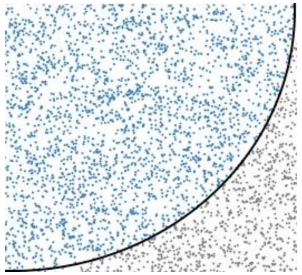
Adding two vectors **B** and **C** multiplied by a scalar **s** to vector **A**:

A += B + s * C

```
/* ... */
double *d_A = sycl::malloc_device<double>(length, q);
double *d_B = sycl::malloc_device<double>(length, q);
double *d_C = sycl::malloc_device<double>(length, q);
/* ... */
double scalar(3);
  {
    for (int iter = 0; iter <= iterations; iter++) {
        auto begin = dpl::make_zip_iterator(d_A, d_B, d_C);
        dpl::transform(dpl::execution::make_device_policy<class TriAdd>(q),
                       begin, begin + length, d_A, [=](const auto &t) {
                           auto [a, b, c] = t;
                           return a + b + scalar * c;
                       });
    }
  }
/* ... */
```

https://github.com/ParRes/Kernels/blob/default/Cxx11/nstream-onedpl.cc

Random sampling example: Monte Carlo Pi



Making full use of oneDPL

```
int main() {
    sycl::queue q(sycl::gpu_selector{});
    auto my_policy = dpl::execution::make_device_policy(q);
    auto sum = dpl::transform_reduce( my_policy, dpl::counting_iterator<int>(0),
                                      dpl::counting_iterator<int>(N), 0, std::plus<float>{},
                                      [=](auto n){
                                          float local_sum = 0.0f;
                                          // Get random coords
                                          dpl::minstd_rand engine(SEED, 2*n*LOCAL_N);
                                          dpl::uniform_real_distribution<float> distr(-1.0f,1.0f);
                                          for(int i = 0; i < LOCAL_N; ++i) {
                                            float x = distr(engine), y = distr(engine);
                                            if (x*x + y*y <= 1.0)
                                              local_sum += 1.0;
                                          }
                                          return local_sum / (float)LOCAL_N;
                                      });
    estimated_pi = 4.0*(float)sum / N;
    return 0;
}
```

Experimental Features: Ranges API

Range-based API for Algorithms

- C++20 adds Ranges into the C++ standard library
  - Very powerful and expressive functional API
  - But does not yet support execution policies
- oneDPL provides Range support as an experimental feature
  - A subset (~40) of the standard algorithms with execution policies
  - A dozen custom range views
  - Not fully standard-compliant (not based on concepts, no projections, …)
  - Only for DPC++ execution policies
  - sycl::buffer can be passed to algorithms as a range
- Available since Intel® oneAPI DPC++ Library (oneDPL) version 2021.1
  - As of today: not a part of oneAPI spec

SYCL buffer as a range

Pass a buffer to a parallel algorithm

```
#include <oneapi/dpl/execution>
#include <oneapi/dpl/algorithm>
#include <oneapi/dpl/ranges>
#include <sycl/sycl.hpp>
int main()
{
    using namespace oneapi::dpl;
    sycl::buffer<int> buf{ 1000 };
    experimental::ranges::for_each(execution::dpcpp_default,
                                   buf, [](auto& i){ i=42; });
    auto result = experimental::ranges::find(execution::dpcpp_default,
                                             buf, 42);

    return 0;
}
```

Ranges: Programmability and Performance

- A pipeline of 3 algorithms (each using a DPC++ kernel)

```
using namespace oneapi::dpl;
reverse( policy, begin(data), end(data));
transform( policy, begin(data), end(data), begin(result), [](auto i){ return i*i; });
auto res = find_if( policy, begin(result), end(result), pred );
```

- With custom iterators (only 1 kernel)

```
using namespace oneapi::dpl;
auto iter =
    make_transform_iterator(make_reverse_iterator(end(data)), [](auto i){return i*i;});
auto res = find_if( policy, iter, iter + data.size(), pred );
```

- With ranges (only 1 kernel)

```
using namespace oneapi::dpl::experimental::ranges;
auto res = find_if( policy, views::all(data) | views::reverse |
                            views::transform([](auto i){return i*i;}), pred );
```

Experimental Features: Async API

Async API

- oneDPL algorithms with DPC++ execution policies are blocking
  - C++ standard compliant: return when execution completes (on the device)
  - In some cases, may transfer data back to the host
- Experimental explicitly asynchronous API
  - Algorithms never wait, instead returning a future-like object
  - Simultaneous use of multiple devices
  - Exploits DPC++ asynchronous capabilities (hiding latencies, etc.)
  - Composing oneDPL algorithms into static data flow graphs

Async Example

Avoids blocking between chained algorithms

```
#include <oneapi/dpl/execution>
#include <oneapi/dpl/iterator>
#include <oneapi/dpl/async>
#include <sycl/sycl.hpp>

int main() {
    sycl::buffer<int> buf { 1000 };
    auto policy = dpl::execution::dpcpp_default;
    auto first = dpl::begin(buf);
    auto last = dpl::end(buf);
    // returns a future-like object encapsulating a SYCL event
    auto future_1 = dpl::experimental::fill_async(policy, first, last, 42);
    auto future_2 = dpl::experimental::transform_async(
        policy, first, last, first, [](int x){ return x + 1; }, future_1);
    auto reduced_value = dpl::experimental::reduce_async( policy, first, last, future_2).get();
    // .get() method blocks and returns a value
    return 0;
}
```

Summary

And materials for further learning

Summary

oneDPL is a productivity library for heterogeneous computing

- Use C++ standard API in kernels
- Express higher-level parallel patterns with Parallel API
- Target compute devices with custom policies
- Improve expressiveness with custom iterators
- Combine programmability and optimizations with Ranges API
- Control non-blocking behavior with Async API

oneDPL resources

oneDPL specification

https://spec.oneapi.io/versions/latest/elements/oneDPL/source/index.html

oneDPL Library Guide

https://docs.oneapi.io/versions/latest/onedpl/index.html

oneDPL source code

https://github.com/oneapi-src/oneDPL

Build & optimize your code in the Intel® DevCloud for oneAPI

Intel® oneAPI preinstalled and ready to go: https://devcloud.intel.com/oneapi/

oneAPI Resources
software.intel.com/oneapi

Learn and Get Started

- software.intel.com/oneapi
- Training
- Documentation
- Code Samples

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Industry Initiative

- oneAPI.com
- oneAPI Industry Specification
- Open Source Implementations

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Ecosystem

- Community Forums
- Academic Program
- Intel® DevMesh Innovator Projects

oneAPI Available on

Intel® DevCloud

A development sandbox to develop, test and run workloads across a range of Intel CPUs, GPUs, and FPGAs using Intel's oneAPI software.

Get Up & Running In Seconds!

software.intel.com/devcloud/oneapi

intel. DevCloud

- 1 Minute to Code
- No Hardware Acquisition
- No Download, Install or Configuration
- Easy Access to Samples & Tutorials
- Support for Jupyter Notebooks, Visual Studio Code

Q & A session

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