Tutorial: Using Shared Virtual Memory

Intel® SDK for OpenCL™ Applications

OpenCL Sample Application Code

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Overview

This sample demonstrates the fundamentals of using Shared Virtual Memory (SVM) capabilities in OpenCL™ applications. The SVM Basic code sample uses the OpenCL 2.0 APIs to query SVM support and manage SVM allocations for the selected OpenCL 2.0 device.

The sample code implements an algorithm to demonstrate pointer sharing between host and device with OpenCL SVM features. Advanced topics like use of atomics within SVM allocations and associated performance considerations are out of the scope of this tutorial.

About This Tutorial

This tutorial demonstrates an end-to-end workflow you can ultimately apply to your own applications:
- Check SVM availability
- Allocate SVM memory. Access SVM memory in host code
- Pass pointers to SVM memory to OpenCL C device code

Estimated Duration

10-15 minutes.

Learning Objectives

After you complete this tutorial, you should be able to:
- Allocate SVM memory
- Use the SVM memory in host- and device code.

More Resources

Intel SDK for OpenCL Applications documentation:
- Optimization Guide
- User’s Guide
OpenCL Specification Version 2.0

About Shared Virtual Memory (SVM)

Intel’s Shared Virtual Memory capabilities can be programmed via OpenCL 2.0’s Shared Virtual Memory (SVM) APIs and OpenCL C language support. OpenCL SVM enables the host and device portions of OpenCL applications to seamlessly share pointers and complex data-structures. OpenCL 2.0 also defines memory model consistency guarantees for SVM.

OpenCL 2.0 defines three types of SVM:
- **Coarse-Grained buffer SVM:** Sharing occurs at the granularity of regions of OpenCL buffer memory objects.
- **Fine-Grained buffer SVM:** Sharing occurs at the granularity of *individual loads and stores* within OpenCL buffer memory objects.
- **Fine-Grained system SVM:** Sharing occurs at the granularity of *individual loads/stores occurring anywhere within the host memory*.

In Coarse-Grained buffer SVM, consistency is enforced at synchronization points and with map/unmap commands to drive updates between the host and the device. This form of SVM is similar to non-SVM use of memory; however, it lets host and device share a single region of virtual memory address space containing pointer-based data structures (such as linked-lists), which was not possible in OpenCL versions lower than 2.0.

Coarse-Grained buffer SVM is the minimum required by the core OpenCL 2.0 specification. So if there is an OpenCL 2.0 device in your OpenCL platform, it should support the necessary functionality to run the sample code. The other two (fine-grained) levels described above are optional OpenCL 2.0 features. Consider
coarse-grained buffer SVM as a compatibility option to be able to run on any OpenCL 2.0 device.

Even the basic coarse-grained buffer type of SVM lets applications avoid duplicating data structure representations between the host and each OpenCL device. Thus, SVM can save extra memory copying and eliminate the need for fragile data structure marshalling code and its overhead. Pointers initialized on the host can be used “as is” on the device side in OpenCL C kernels. This is the main benefit of the shared address space that SVM provides.

Fine-grained buffer SVM eliminates the need to call map/unmap OpenCL API functions on the host to access SVM allocations. This simplifies the programming experience in real applications compared to coarse-grained SVM.

Besides a shared virtual address space, fine-grained SVM gives the application the capability to seamlessly read and write *the same region* of memory from both the host and from the device *simultaneously*. That is true for any non-overlapping modifications with granularity of byte. To modify *the same bytes* of memory concurrently, applications should synchronize between device(s) and the host via OpenCL 2.0-defined atomic operations applied on variables in SVM allocations. This expands the programmability of OpenCL 2.0 platforms opening the door to true heterogeneous programming.

Those advanced topics are out of the scope for this basic tutorial, which focuses on the key API functions necessary for allocation and use of SVM buffers.

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**See Also**

OpenCL 2.0 Specification:

- SVM Introduction: 3.3.3 Memory Model: Shared Virtual Memory
- SVM Host API: 5.6 Shared Virtual Memory

**Prerequisites**

Before you start with the tutorial, make sure your system meets the following requirements.

To build and run the sample application, you need

- Microsoft Visual Studio® 2010 and higher.

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**Navigation Quick Start**

This tutorial includes sample code that you can compile using Microsoft Visual Studio 2010 and higher. Find the relevant solution file in the sample root directory > SVMBasic subfolder.

**Building and Running Code Sample**

To build the SVM Basic code sample,

1. Double-click the solution file (*.sln) relevant to your Visual Studio version.
2. Select **Build > Build Solution**.
Then to run the application,
1. Select a project file in the Visual Studio Solution Explorer.
2. If the sample application is not set as a startup project, right-click the project and select Set as StartUp Project.
3. Press Ctrl+F5 to run the application.

To run the application in Debug mode, press F5.

You can also run the sample application using the command-line interface:
1. Run the command prompt.
2. Switch to the directory, where the solution file resides.
3. Go to the directory according to the platform configuration:
   - \Win32 - for Win32 configuration
   - \x64 - for x64 configuration
4. Open the appropriate project configuration (Debug or Release).
5. Run the sample by entering SVMBasic.exe.

**Controlling the Sample Application**

The sample executable is a console application. You can control OpenCL platform, device type, and array size with the dedicated command-line options. The sample uses default parameters if you run it without specifying any command-line options.

<table>
<thead>
<tr>
<th>Command-Line Options</th>
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<tbody>
<tr>
<td><strong>Short Form</strong></td>
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Sample Implementation

For illustrative purposes, the sample implements a traversal algorithm that handles a data structure populated with pointers. Core functionality is placed in the following files:

- svmbasic.cpp – OpenCL host code
- svmbasic.cl – OpenCL C kernel device code
- svmbasic.h – Definition of the structure type, arrays of which are used by both the device and the host code.

Code Execution Scenario

The sample code executes according to the following scenario:

1. Selects the OpenCL platform and device according to the specified command-line arguments.
2. Checks SVM availability for the selected OpenCL device. If SVM capabilities are not available the application exits immediately.
3. Allocate SVM memory by creating two arrays in two SVM buffers on the host side.
4. Access SVM memory on the host by mapping the newly-created arrays on the host and populating them via pointers in the host address space. The map/unmap pair is only required for coarse-grained buffer SVM.
5. Pass pointers to SVM memory to the device to enable the OpenCL C kernel to access SVM memory.
6. The OpenCL C kernel reads the shared memory and traverses the arrays using those shared pointers. With SVM, such pointers work seamlessly in OpenCL C kernels and point to the same data, just as they do in the host code.
7. The OpenCL C kernel performs arithmetic operations with values from the SVM buffers and writes to the dedicated output buffer.
8. The kernel-written data is read in the host code and validated against a CPU reference implementation to prove its correctness.

Steps 2-6 are specific for SVM, while the rest of the steps are common infrastructure. This tutorial document focuses on the SVM-specific steps only.

Using SVM in Your Application

The rest of the tutorial sections guide you through the process of using SVM in your application. The following steps correspond to the scenario described in the Code Execution Scenario section.

Check SVM Availability

You can check SVM availability using the checkSVMAvailability function, which queries CL_DEVICE_SVM_CAPABILITIES from clGetDeviceInfo. See svmbasic.cpp for details.

```cpp
bool checkSVMAvailability (cl_device_id device) {
    cl_device_svm_capabilities caps;
    cl_int err = clGetDeviceInfo(
        device,
        CL_DEVICE_SVM_CAPABILITIES,
    ...
This returns `true` if at least coarse-grained buffer SVM is available. `cl_device_svm_capabilities` is a bit-field that describes a combination of the following values:

- `CL_DEVICE_SVM_COARSE_GRAIN` is for coarse-grained buffer SVM
- `CL_DEVICE_SVM_FINE_GRAIN_BUFFER` is for fine-grained buffer SVM
- `CL_DEVICE_SVM_FINE_GRAIN_SYSTEM` is for fine-grained system SVM
- `CL_DEVICE_SVM_ATOMICS` is for atomics support

OpenCL 2.0 specification requires that `CL_DEVICE_SVM_COARSE_GRAIN_BUFFER` is supported by all OpenCL 2.0 devices.

For example, if your application requires fine-grained buffer support, the `return` statement should be replaced with:

```
return err == CL_SUCCESS && (caps & CL_DEVICE_SVM_FINE_GRAIN_BUFFER);
```

`false` might be returned in the case when the device is not an OpenCL 2.0 device (an OpenCL 1.2 device for example). In this case `clGetDeviceInfo` should respond with an error because `CL_DEVICE_SVM_CAPABILITIES` constant is an invalid value for OpenCL implementation version lower than OpenCL 2.0.

**Allocate SVM Memory**

Create two synthetic data structures - arrays to be allocated and filled:

- the first array should consist of `Element` structures (refer to `svmbasic.h` for the structure definition),
- the second one of `float` values.

Create the first array in the SVM memory with the `clSVMAlloc` function. This function returns a regular pointer in the host address space. At the same time, you can pass this pointer to the kernel to be used like a regular OpenCL buffer. Pointers to the memory in the SVM allocation are mapped to the same bytes on the host and on the device sides.

The arguments for `clSVMAlloc` are similar to `clCreateBuffer`. See the example below:

```
Element* inputElements = (Element*)clSVMAlloc(
    context,              // an OpenCL context where this buffer is
    CL_MEM_READ_ONLY,     // available
    size*sizeof(Element), // amount of memory to allocate (in bytes)
    0);                   // alignment in bytes (0 means default)
```

In case of fine-grained buffer SVM, while allocating SVM memory, you need to pass `CL_MEM_SVM_FINE_GRAIN_BUFFER` as an extra flag for `clSVMAlloc`, like in the following example:

```
Element* inputElements = (Element*)clSVMAlloc(
    context,              // an OpenCL context where this buffer is
    CL_MEM_SVM_FINE_GRAIN_BUFFER, // available
    size*sizeof(Element), // amount of memory to allocate (in bytes)
    0);                   // alignment in bytes (0 means default)
```
Do it for all allocations in case of using the fine-grained buffer SVM.

Each structure of the first array (struct Element) has two pointers:

- The first pointer (internal) points to the value field of another Element from the same array.
- The second pointer (external) points to a floating point value in the separate array.

You create the second array in a similar way:

```c
float* inputFloats = (float*)clSVMAlloc(
    context,              // context where this buffer is available
    CL_MEM_READ_ONLY,     // fine-grained: CL_MEM_SVM_FINE_GRAIN_BUFFER
    size*sizeof(float),   // amount of memory to allocate (in bytes)
    0                     // default alignment (0 means default)
);
```

Pointer values of the Element array entries are set randomly. The data structures do not reflect any real usage scenario, but are illustrative for a simple device-side traversal. After initialization the linked data structure appears as illustrated below:

```
<table>
<thead>
<tr>
<th>Array of Element Structures (inputElements)</th>
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<table>
<thead>
<tr>
<th>Array of floats (inputFloats)</th>
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</table>
```

The two arrays described above, are created separately to illustrate two different ways of passing pointers to SVM allocations to the kernel:

- The first array (inputElements) is passed to the kernel as one of the kernel arguments with the clSetKernelArgSVMPointer OpenCL 2.0 API function.
The second array (inputFloats) is used by the kernel indirectly and should be also made known to the kernel with the clSetKernelExecInfo OpenCL 2.0 new API (refer to Passing SVM Pointers to Kernel section below for details).

Access SVM Memory in Host Code

Much like new or delete operators, clSVMAlloc returns a conventional C/C++ pointer. Once allocated, OpenCL 2.0 platforms with fine-grained SVM support may just start using the pointer directly like any conventional C/C++ pointer.

In contrast to fine-grained SVM, coarse-grained-only enabled platforms should perform special steps to use allocated SVM memory on the host. In this case, although clSVMAlloc function returns a regular host pointer, according to the OpenCL 2.0 specification you cannot access this SVM memory in the host code without mapping it. To map the memory region, you should call clEnqueueSVMMap:

```c
clEnqueueSVMMap(
    queue,          // OpenCL queue
    CL_TRUE,        // block on this command until map is done
    CL_MAP_WRITE,   // map for writing on the host
    inputElements,  // pointer to the beginning of the SVM region to map
    sizeof(Element)*size,  // the size of the SVM region to map
    0, 0, 0
);
```

The code should map the SVM region for initialization, so you should use CL_MAP_WRITE. To be able to use the region in the OpenCL kernel, after initialization of inputElements, you need to unmap the region:

```c
clEnqueueSVMUnmap(
    queue,
    inputElements,
    0, 0, 0
);
```

By using map/unmap commands as synchronization points you coordinate the ownership over the SVM allocations between the host and OpenCL device(s), hence keeping the content of the allocations consistent. Refer to paragraph 5.6.2 “Memory consistency for SVM allocations” of the OpenCL 2.0 specification for details.

As it has been already said before, using clEnqueueSVMMap and clEnqueueSVMUnmap commands is necessary for coarse-grained buffer SVM only.

Pass SVM Pointers to a Kernel

Pointers to SVM memory may be passed to the OpenCL C kernel in two ways. The first one is to pass the SVM pointer as a kernel argument (such as inputElements below) with clSetKernelArgSVMPointer(). This is similar to passing a conventional OpenCL buffer cl_mem object as a regular argument to the kernel:

```c
clSetKernelArgSVMPointer(kernel, 0, inputElements);
```
This pointer will point to the first argument of the kernel (pointer to the array of Element, see the svmbasic.cl file for details):

```c
kernel void svmbasic (global Element* elements, global float *dst)
{
    . . .
}
```

The second method of passing SVM allocations is used when an SVM allocation is accessed implicitly by the OpenCL C Kernel (for example, when it is pointed to by pointers within another SVM allocation). This is the case for `inputFloats` usage in the kernel, as the sample does not pass `inputFloats` pointer directly as a kernel argument. Instead, `inputFloats elements` are used through pointers stored in `inputElements`:

```c
kernel void svmbasic (global Element* elements, global float *dst)
{
    int id = (int)get_global_id(0);
    float internalElement = *(elements[id].internal);
    float externalElement = *(elements[id].external);
    dst[id] = internalElement + externalElement;
}
```

In this case, according to OpenCL 2.0 specification (refer to section 5.9.2 'Setting Kernel Arguments') the SVM pointer must be specified using `clSetKernelExecInfo` function with parameter `CL_KERNEL_EXEC_INFO_SVM_PTRS`:

```c
clSetKernelExecInfo(
    kernel,
    CL_KERNEL_EXEC_INFO_SVM_PTRS,
    sizeof(inputFloats),
    &inputFloats
);
```

You need to do that for each non-argument SVM pointer in your program that is used in the kernel.

Note that using `clSetKernelExecInfo` is a necessary step for both coarse-grained and fine-grained buffer SVM allocations, but not for fine-grain system SVM allocations, which operates on the full range of the system virtual memory addresses.

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**Summary**

This tutorial demonstrated an end-to-end workflow you can apply to your own application.

<table>
<thead>
<tr>
<th>Step</th>
<th>Tutorial Recap</th>
<th>Key Tutorial Take-aways</th>
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</thead>
<tbody>
<tr>
<td>Check SVM availability</td>
<td>Use the <code>checkSVMAvailability</code> function to query OpenCL device capabilities.</td>
<td>Make sure your system contains OpenCL 2.0 devices, so that you are able to utilize the SVM feature.</td>
</tr>
<tr>
<td>Allocate SVM memory</td>
<td>Use the <code>clSVMAlloc</code> function to create two arrays: an array of <code>Element</code> structures and an</td>
<td>By allocating pointers to SVM memory, you create a pool of memory to be available for the host</td>
</tr>
</tbody>
</table>
| **Access SVM memory in host code** | In case of fine-grained SVM: use the pointers to SVM memory as you would use conventional C/C++ pointers.  
In case of coarse-grained SVM: use the `clEnqueueSVMMap` function to enable the host side of the application to use the allocated SVM memory. | In case of coarse-grained SVM only, to be able to access the allocated SVM memory on the host side of the application, you need to map the memory.  
Make sure you unmap the memory after using it in the host side, so that the device side of the application is also able to use the memory region.  
Fine-grained SVM doesn't require those steps. |
| **Pass SVM memory to the kernel** | Use the `clSetKernelArgSVMPointer` to pass the SVM pointer explicitly as a kernel argument, or use the `clSetKernelExecInfo` function with the `CL_KERNEL_EXEC_INFO_SVM_PTRS` parameter to pass the SVM pointers implicitly. | Even indirectly accessed (not through kernel arguments) SVM should be passed to the kernel via the `clSetKernelExecInfo`. |

**Exposed OpenCL APIs**

The sample application focuses on the following API functions:

- `clSVMAlloc`
- `clEnqueueSVMMap`
- `clEnqueueSVMUnmap`
- `clSetKernelArgSVMPointer`
- `clSetKernelExecInfo`
- `clSVMFree`