OpenCL™ Basic Tutorial for Android* OS

User's Guide

Compute Code Builder - Samples

Document Number: 330185-002US

Contents

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Introduction

OpenCL™ Basic Tutorial for Android* OS provides guidelines on using OpenCL in Android applications. The tutorial is an interactive image processing Android application.

The main focus for the tutorial is to show how to use OpenCL in an Android application, how to start writing OpenCL code, and how to link to OpenCL runtime. The tutorial shows a typical sequence of OpenCL API calls and general workflow to get a simple image processing kernel running with an animation on an OpenCL device. Advanced topics like efficient data sharing or Android OpenCL performance BKMs are out of the scope of this tutorial.

The tutorial is a minimalistic GUI activity that displays the computation results and statistics, and implements a simple full-screen image processing algorithm, with which you can interact through screen touches. After launching the tutorial application, a built-in image is displayed, and no post-processing happens until user interaction begins.

When you touch the screen, an animated growing circle, centered at coordinates of the touch, appears, and all pixels that are inside the circle become black and white. The circle continues to grow each frame until the complete picture becomes black and white.

Look into `README.TXT` for more details on the tutorial file structure and build/run steps.

What Is OpenCL™?

OpenCL™ (Open Computing Language) is an open standard for general-purpose parallel programming for a diverse mix of multi-core CPUs, graphics processors, coprocessors, and other parallel processors. OpenCL provides a flexible execution model and uniform programming environment for software developers to write portable code for systems running on CPU, GPU, and/or other devices.

OpenCL is used to accelerate compute operations in various domains, including image and video processing, computer vision, game engine acceleration, and so on. OpenCL can also be effective for reducing power consumption. It achieves this by allowing the programmer to schedule compute work on the best suitable device where it may be executed faster and/or with lower power consumption.

An OpenCL device is an abstraction for hardware which can perform compute operations. Typical examples of OpenCL devices include CPUs, GPUs, and specialized hardware modules like DSPs.

OpenCL programs consist of two parts: a host side and a device side. The host side is written in C/C++ language and includes a sequence of OpenCL API function calls to select/create OpenCL objects like devices, contexts, queues, buffers, and so on. The host code is responsible for initiating and controlling kernel execution on the device side.

The device side is a program written in OpenCL C language, which is C with extensions. The program consists of one or more kernels. Each kernel is intended to run on an OpenCL device. OpenCL program is loaded in a textual form and compiled at run-time or loaded in pre-built binary format by the running host program. In this tutorial, the program is loaded from source.

Roughly speaking, each kernel invocation runs several work-items – one work-item for each point in the iteration space for the kernel. The iteration space is a 1-, 2-, or 3-dimensional grid, which is called NDRange in OpenCL. You may look at each work-item as being on a thread that executes OpenCL C code. For example, each work-item may process a single pixel in a 2D NDRange which is mapped to all pixels in a given image. So all work-items in one kernel invocation process a complete image.

Data processed in the OpenCL kernels are placed in OpenCL buffers. Each buffer can be read and/or written in a kernel on the device. The results then can be retrieved on the host side by means of calling one of the OpenCL API calls.

Running and Controlling the Tutorial

If you compile the tutorial using the Eclipse IDE, you should be able to run the tutorial on the device directly from the IDE. Refer to Building the Tutorial section and Android documentation for details on building and running from Eclipse with ADT. Alternatively, you can use the ADB utility from the Android SDK platform-tools to install the pre-built executable yourself from `bin/AndroidBasicOpenCL.apk`.

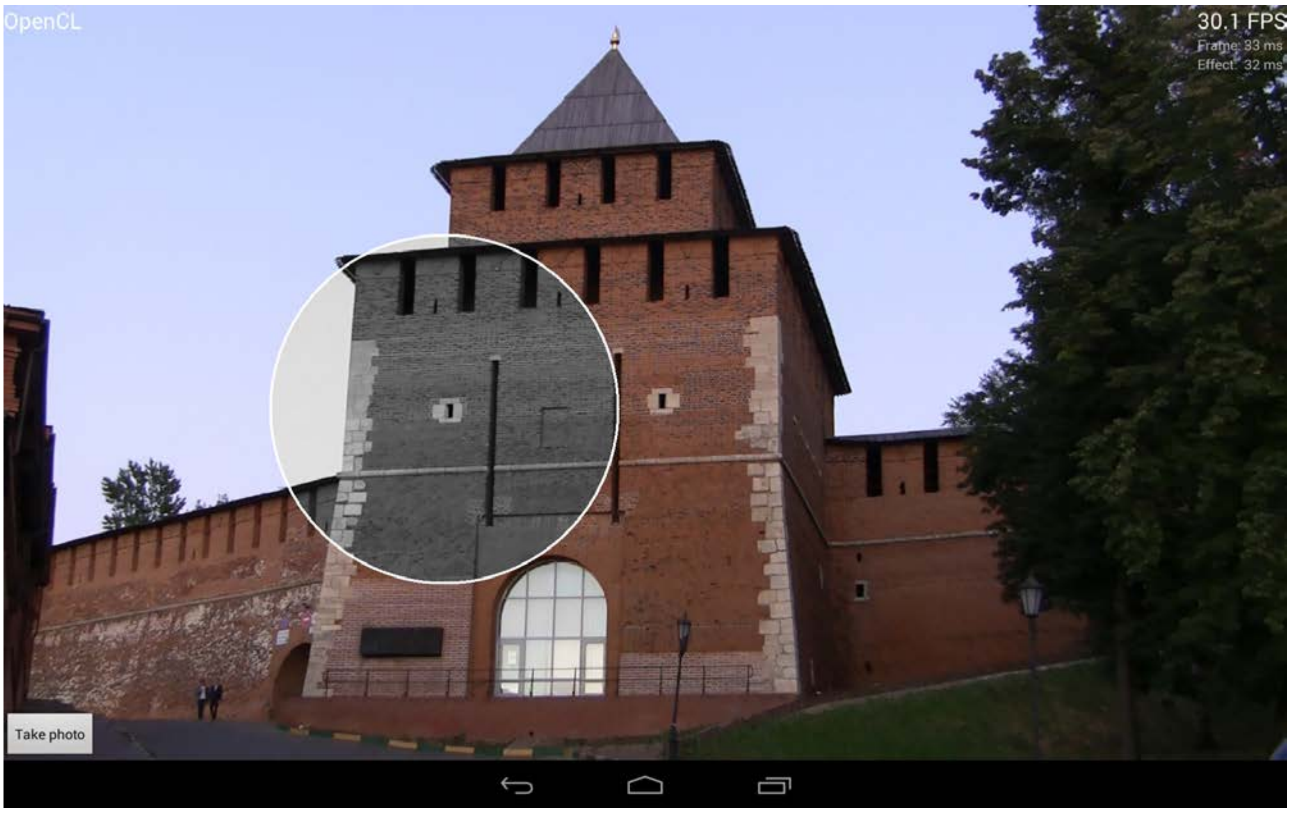
Finally, if you have neither IDE nor even Android SDK (and thus no ADB) you may still copy the pre-built APK to the device over regular USB and install it directly on the device using any file manager for Android OS.

After successful installation, the tutorial application becomes available on the device with the following icon:

Upon launching, the tutorial starts in the full-screen mode and displays an image, which is being updated with the results of applying the OpenCL kernel to each frame. On the right-top corner you can find the current FPS and corresponding frame time (tagged “Frame”) and the time taken by the OpenCL kernel itself (tagged “Effect”). The compute API itself is also shown at the left topmost corner (“OpenCL”).

NOTE: The sample requires OpenCL runtime installed on the device or the emulator. If your device/emulator doesn’t have OpenCL runtime you will see an error message upon application start and then the application will be terminated. To install OpenCL runtime, refer to dedicated chapter in the Intel® SDK for OpenCL™ Applications – User’s Guide.

The effect or processing that applies to the input image originally loaded from the application resources is computing the “circle of black-and-white” with the dedicated OpenCL kernel. The effect becomes apparently visible upon a screen touch. Specifically, the origin of the circle is the point of touch, so when you touch the screen the new circle appears and expands over time. For each input pixel, the OpenCL kernel determines if the pixel is inside or outside the circle. It then outputs the outer pixels untouched, while converting the inner pixels to the black-and-white for the output and also draws a thin circle border.



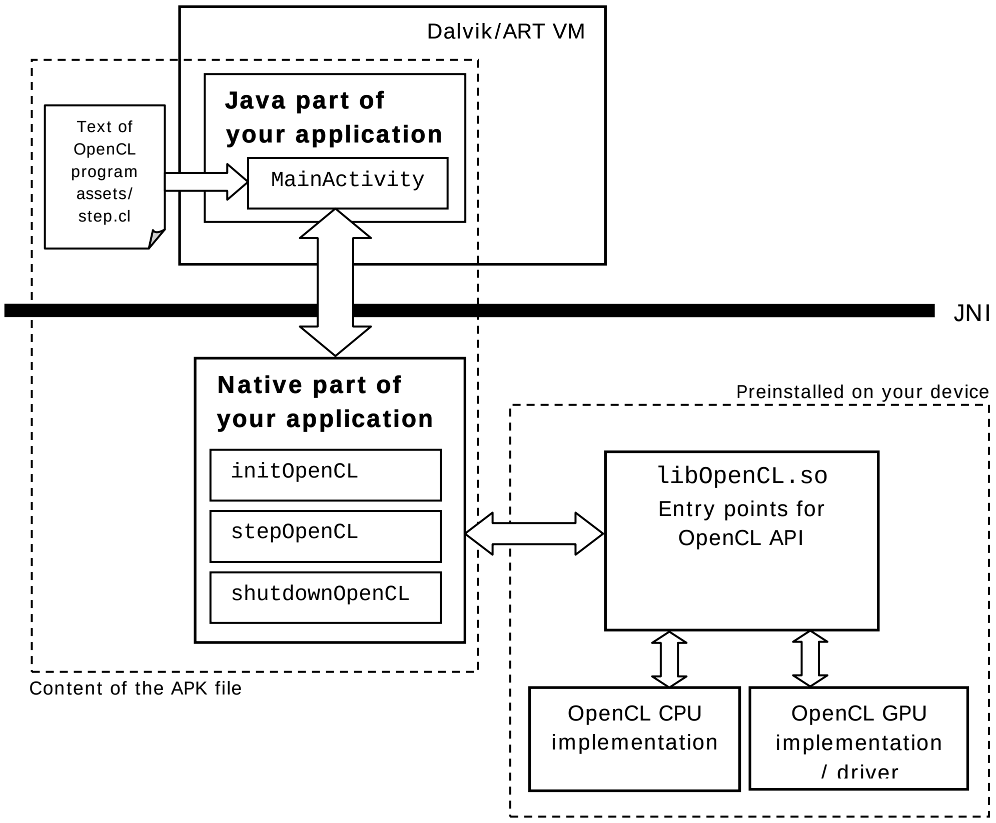
The **TakePhoto** button enables you to replace the default image for processing with the picture taken from the camera of your device. For details and the general machinery of this functionality, refer to the tutorial code. The code that handles the camera is intentionally simplified (for example it does not handle camera orientation) to keep focus on the core tutorial topic, which is OpenCL.

OpenCL in Android* Applications

Though it is possible to use other programming languages (Java* OpenCL bindings) for writing the host side, the tutorial uses true native OpenCL interface using C/C++. Therefore it is required that application use Java Native Interface (JNI) and is built with Android Native Development Kit (Android NDK).

The picture below shows a high-level architecture of the OpenCL Android application. It essentially consists of two parts: a Java part and a Native part. The Java part controls the UI, receives input from the user, loads the text of the OpenCL program from assets, and calls the native function from the native part to do actual image processing using OpenCL. Communication between the Java part and the native part is performed via JNI, which is typical for any Android application that includes native modules.

The native part contains all of the OpenCL calls. The native part is linked against the `libOpenCL.so` library, where all OpenCL entry points reside. The `libOpenCL.so` library is a dispatcher, which passes OpenCL API calls to a specific implementation of OpenCL dedicated to a particular device, for example CPU or GPU. The `libOpenCL.so` library should already be installed on the target device before an application can be deployed. In case you don't have the OpenCL runtime installed on your Android device, refer to the Compute Code Builder or Intel® SDK for OpenCL Applications 2014 Beta at http://software.intel.com/en-us/vcsource/tools/opencl-sdk.


Dalvik/ART VM
Java part of your application
MainActivity
Text of OpenCL program assets/step.cl
JNI
Native part of your application
initOpenCL
stepOpenCL
shutdownOpenCL
Content of the APK file
Preinstalled on your device
libOpenCL.so
Entry points for OpenCL API
OpenCL CPU implementation
OpenCL GPU implementation / driver

OpenCL Implementation

The OpenCL implementation consists of the following parts:

- `initOpenCL` - where all the OpenCL objects are created and initialized
- `stepOpenCL` - where the host to device communication and the actual OpenCL image processing happens
- `shutdownOpenCL` - where cleanup of the OpenCL objects happens

Each of the above parts has a dedicated native function implemented in `jni/step.cpp` file. The first function, `initOpenCL` is called from `MainActivity.onCreate` method. Then, in the background thread, `stepOpenCL` function is called to perform image processing each frame in a loop.

InitOpenCL

The `initOpenCL` performs the following steps:

1. Pick the OpenCL platform. Your mobile device may support more than one platform, and the code by default looks for Intel OpenCL platform.

```
    clGetPlatformIDs(0, 0, &num_of_platforms);
    clGetPlatformIDs(num_of_platforms, &platforms, 0);
    // then go across all platform and search for Intel platform
    // . . .
```

2. Create an OpenCL context from a particular device type. All other objects are created in this context.

```
context = clCreateContextFromType(context_props, primary_device_type, …);
```

Where primary_device_type is a supported OpenCL device type on your Android device, typically CL_DEVICE_TYPE_CPU or CL_DEVICE_TYPE_GPU. Please see **Choosing OpenCL Device Type** section for basic guidelines about how to choose between CPU and GPU.

NOTE: The code in the sample attempts to create OpenCL context with primary_device_type first. If it is not available (for example, in the emulator), secondary_device_type is used. This is a part of flexibility implemented in the code, which shows you how to avoid crashes in case of using diverse types of hardware (or the emulator).

3. Obtain the OpenCL device ID, which was selected during context creation in the previous step. The device ID is needed for building the OpenCL program (in one of the following steps). This is achieved by calling the `clGetContextInfo` function.

4. Create an OpenCL program from the source text. The source text is obtained as an argument of `initOpenCL` and passed from Java part of application. First, it is converted from a Java string to a native string and then passed to `clCreateProgramWithSource`.

5. Build the OpenCL program. In case of build errors, the build log is printed to `LogCat`:

```
    cl_int err = clBuildProgram(program, . . .);
    if(err == CL_BUILD_PROGRAM_FAILURE)
    {
        clGetProgramBuildInfo(
            program, device, CL_PROGRAM_BUILD_LOG,
            log_length, &log, …);
    }
```

6. Extract (create) an OpenCL kernel from the program specifying the name of the kernel:

```
    kernel = clCreateKernel(program, "stepKernel", …);
```

7. Create an OpenCL command queue, which is used to enqueue the OpenCL kernel to target OpenCL device.

```
    queue = clCreateCommandQueue(context, device);
```

After completing the steps above, you are ready to enqueue the kernel to perform the image processing. This happens for each frame in `stepOpenCL` native function.

stepOpenCL

Two buffers are created in this function: one is for input image and the second is for output image. Images are stored as OpenCL buffers, not as OpenCL images, because they are obtained from the Java part of the application as arrays of pixels.

Input buffer is created only once since it doesn’t change every frame. In the code the input buffer is conditionally created in case when Java part updates its content.

```
    if(!isInputBufferInitialized || updateInputBitmap)
    {
        . . .

        /* You receive input buffer as a Java bitmap object.
         * To use it in the native part, lock it and obtain a native pointer
         * to the area with pixels.
         */
        void* inputPixels = 0;
        AndroidBitmap_lockPixels(env, inputBitmap, &inputPixels);

        inputBuffer =
           clCreateBuffer
           (
               context,
               CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
                bufferSize,    // Buffer size in bytes.
                inputPixels,   // Bytes for initialization.
                &err
            );
        . . .

        AndroidBitmap_unlockPixels(env, inputBitmap);

    }
```

AndroidBitmap_lockPixels and AndroidBitmap_unlockPixels are standard native Android functions which enable accessing bitmaps passed from the Java side of the application directly in the native part of the application. These functions can be used by including <android/bitmap.h> header file.

The output buffer, on the other hand, is created each frame, because it is created on top of pixels that need to be drawn on the screen.

The output buffer is created using CL_MEM_USE_HOST_PTR, which means that the application enables OpenCL implementation to use the output array of pixels in the bitmap as the storage bits for the OpenCL memory object:

```
    void* outputPixels = 0;
    AndroidBitmap_lockPixels(env, outputBitmap, &outputPixels);

    cl_mem outputBuffer =
        clCreateBuffer
        (
            context,
            CL_MEM_WRITE_ONLY | CL_MEM_USE_HOST_PTR,
            bufferSize,    // Buffer size in bytes, the same as input buffer.
            outputPixels,  // Area on top of which buffer is created.
            &err
        );

    . . .

    /* Set the arguments for kernel, execute it, and retrieve data back. */

    . . .

    clReleaseMemObject(outputBuffer);

    // Now make output content visible at Java side by unlocking
    // pixels in output bitmap.
    AndroidBitmap_unlockPixels(env, outputBitmap);
```

NOTE: According to the OpenCL specification section "Creating buffer objects", OpenCL implementations are allowed to cache the buffer contents pointed to by outputPixels in device memory even if CL_MEM_USE_HOST_PTR parameter is used. This cached copy can be used when kernels are executed on a device.

In order to execute the OpenCL kernel all the required arguments need to be passed to it. Specifically for this tutorial, inputBuffer and outputBuffer need to be passed together with other necessary arguments (see complete source code for details):

```

    clSetKernelArg(kernel, 0, sizeof(inputBuffer), &inputBuffer);
    clSetKernelArg(kernel, 1, sizeof(outputBuffer), &outputBuffer);
    . . . // Setting the rest of arguments.
```

These arguments directly correspond to OpenCL kernel arguments defined in assets/step.cl file:

```
kernel void stepKernel
(
    global const int* inputPixels,
    global int* outputPixels,
    . . . // The rest of arguments.
)
{
    // Source code of OpenCL kernel.
    . . .
}
```

After setting the appropriate arguments, the application is finally ready to enqueue kernel to the device queue:

```
    // Define global iteration space for clEnqueueNDRangeKernel.
    // Every work-item running the kernel will process a single pixel in the
image.
    size_t globalSize[2] = { /* Image width */, /* Image height */ };

    clEnqueueNDRangeKernel
    (
        queue,
        kernel,
        2,    // Dimension of iteration space: 2D.
        0,
        globalSize, // Dimenstions of iteration space: picture dimensions.
        0,
        . . .
    );
```

The above command only enqueues the kernel but doesn’t guarantee the execution on the device immediately. To immediately start execution and block until kernel is completely executed, the following call is used:

```
    clFinish(queue);
```

The last remaining step is to retrieve the processed data back and populate `outputPixels`. Recall that `CL_MEM_USE_HOST_PTR` was used, the best method to retrieve the data from such a buffer is using the map/unmap idiom:

```
    clEnqueueMapBuffer(queue, outputBuffer, …, CL_MAP_READ, …);
    clEnqueueUnmapMemObject(queue, outputBuffer, outputPixels, …);

    // And call clFinish to guarantee that output region is updated.
    clFinish(queue);
```

After releasing `outputBuffer` and unlocking `outputPixels` the code returns to the Java part and publishes the processed image content on the display.

NOTE: Two `clFinish` calls are used in the code. The first one is not needed for correct program execution, but it is used for correct measurement of time spent in the kernel execution. Refer to source code for details.

shutdownOpenCL

The last function, `shutdownOpenCL` implements a regular sequence of calls to deallocate all of the OpenCL resources created in `initOpenCL`.

The deallocation can be done anytime during application execution if the OpenCL processing/objects are no longer required by the application in order to free some memory or to recreate OpenCL objects with different parameters.

Calling this function before application termination may not be so useful since Android doesn't guarantee such notification of termination to the application, rendering the call useless.

Choosing OpenCL Device Type

In OpenCL the device type, on which the kernel is executed, needs to be specified explicitly. Intel OpenCL implementation for Android devices supports CPU and GPU devices of the Intel® Atom™ processors (formerly codenamed Bay Trail).

NOTE: OpenCL is relatively low-level tool and it requires you to make this selection manually.

One may consider choosing the GPU device as a default device for image processing, computer vision algorithms, media and other similar tasks, since GPUs are optimized/designed for such tasks.

But most generally, the selection highly depends on the compute algorithm. The ultimate method to determine the right device for your compute kernel is experimentation. Run your application with kernel enqueued to CPU one time and to GPU another time. Compare the performance and power consumption, then select the best OpenCL device for your needs and code its type in the `clCreateContextFromType` call.

In case you want your application to run well on diverse hardware platforms like smartphones and tablets, you need to be careful and make sure that the application works on Android platforms with different combinations of OpenCL devices, or even Android platforms with no OpenCL devices. The right selection is dependent on target Android device hardware capabilities.

The *Intel SDK for OpenCL Applications - Optimization Guide* provides general guidelines that help in making the right choice during the OpenCL device selection.

Building the Tutorial

To be able to build the tutorial you need everything that is needed for development of a regular native application for Android OS. Refer to the Android standard documentation to see the complete list of required software.

You also need to install the Intel SDK for OpenCL Applications software with Android OS support. The latter is needed to build the native part because it includes OpenCL headers and links against `libOpenCL.so`.

NOTE: The native part of the application is built by means of a makefile: `jni/Android.mk`. Please consider looking into this file to learn how to write one. This is an essential part of the OpenCL application for Android OS.

NOTE: The makefile has a hardcoded path to the place where Intel SDK for OpenCL Applications software with Android support is installed. The path is assigned to `INTELOCLSDKROOT` variable. This path is used to locate the OpenCL header and library files. You need to check if the path matches the installation location of OpenCL on your system. If it doesn't match, you need to change `INTELOCLSDKROOT` variable in `jni/Android.mk` to set your custom path.

Several manual steps are required to build the native part of the tutorial, while Java part is built automatically inside your Eclipse IDE. The following are the steps to build a regular Android application with native part:

1. Go to the tutorial root directory in a terminal and issue the `ndk-build` command. This should build native part of your application. For details refer to the Android NDK documentation.

2. Then you are able to build the final APK file (or it is built automatically by Eclipse depending on your settings).

NOTE: Initial archive with tutorial project files already includes a pre-built APK file, which is ready to be installed on a device. Make sure that OpenCL is installed on this device before installing APK file.

Tutorial Application Structure

Generally, the structure of tutorial application is quite similar to any other Android application. So the tutorial comprises the single Activity (sub-classed in the `MainActivity.java`) that interacts with the user. The activity takes care of creating a (full-screen) window to place UI:

- `TextViews` to print performance statistics on the screen
- An `ImageView` to output the result of the computations that OpenCL produces

The visual structure of the GUI elements and the associated logic (like the relative layout) is declared in XML (refer to the `activity_main.xml` in the `res/layout` folder).

Separating OpenCL and UI Processing

One particularly important concept in the mobile domain is “Keeping Your Application Responsive”. Android applications typically run in a single thread, which is by default the "UI thread", which is the thread that handles the UI events. Any heavy calculations within this thread should be minimized, in order to keep the app (GUI) responsive.

Thus the first important tip is to utilize the rich set of task/threading primitives in the Android API to execute any potentially long running operations such as computationally intensive OpenCL kernels via some sort of asynchronous requests.

To express the producer-consumer relations between the UI and the OpenCL, a scheme with a dedicated “worker” thread is implemented. This thread computes the updated images and notifies the UI thread upon completion, so the UI thread updates the screen with the result. In this tutorial application the producer-consumer relations are presented by the UI thread displaying or “consuming” bitmaps that OpenCL kernel updates or “produces”.

Unlike potential alternatives based on any notion of an “async task issued by the UI thread” which would essentially inverse the producer-consumer relations, the worker thread is not popping up each time the UI thread needs an updated image. Instead, it produces the images and waits for the UI thread to consume them. This is implemented through a couple of conditional variables, discussed in details below.

The lifetime of the worker thread spans the lifetime of the Activity itself, so this ensures no expensive thread creation/deletion happens behind the scene. Similarly, the double-buffering scheme prevents the intensive resource manipulation for the output Bitmaps.

Here is the loop the worker thread executes (simplified to the pseudo-code for brevity):

```
public void run()
{
    // Check if the application is exiting, so you don’t need frames anymore.
    while(!isShuttingDown)
    {
         // Conditional that allows the thread to sleep when
         // the application is not in focus.
         isGoing.block();

         // Conditional that prevents output to the bitmap the UI thread
         // displays now.
         isRendering.block();
         {
             // Check if you need to update the input image (after
             // photo).
                 . . .
```

```
                // Swap bitmaps used for processing and displaying.
                    . . .
                // Actual call to the kernel
                step();

                // Block the thread from computing next
                // frame to the same bitmap.
                isRendering.close();

                // issue the Bitmap/View update on behalf of
                // UI thread via post
                outputImageView.post
                (
                    outputImageView.setImageBitmap(outputBitmap);
                    outputImageView.invalidate();
                    // allow the worker thread to process the next frame
                    isRendering.open();
                );
            }
        }
}
```

Android Application Lifecycle Events

From the purposes of this tutorial, there are few important methods that your Activity needs to implement:

- `onCreate` - where the activity is initialized. Most importantly, beyond actually setting Views with the resources defining UI, the general OpenCL initialization (calling `initOpenCL` native function) is handled here.
- `onStart/onStop ()` - where the application becomes visible and invisible to the user. Most importantly this is the place where “worker” thread is paused and resumed.
- `OnWindowsFocusChanged(boolean)` which is called (with ‘true’) when all of the UI have been successfully loaded and created properly.
    - In this function it is safe to initialize corresponding bitmaps for double-buffering, because here you already know your widgets dimensions.
    - This is also a place where a dedicated “worker” thread is spawned, since the memory resources are already initialized at this point.
- `OnDestroy`, the final call to the application to release resources and enable the “worker” thread to exit.

Limitations

The main focus of this tutorial is OpenCL APIs and its place in an Android application. More advanced topics like Android application lifetime caveats, advanced efficiency are out of the scope of this tutorial. So for simplicity this tutorial uses screen orientation fixed to the ‘landscape’, so images taken with camera might be rotated.

Using bitmaps without efficient surface handling is also for simplicity. In real performance/power oriented application one may want to use OpenGL surfaces.

APIs Used

This tutorial uses the following OpenCL host functions:

- `clGetPlatformIDs`
- `clGetPlatformInfo`
- `clCreateContextFromType`
- `clGetContextInfo`
- `clCreateProgramWithSource`
- `clBuildProgram`
- `clGetProgramBuildInfo`
- `clCreateKernel`
- `clCreateCommandQueue`
- `clCreateBuffer`
- `clSetKernelArg`
- `clEnqueueNDRangeKernel`
- `clFinish`
- `clEnqueueMapBuffer`
- `clEnqueueUnmapMemObject`
- `clReleaseMemObject`
- `clReleaseKernel`
- `clReleaseProgram`
- `clReleaseCommandQueue`
- `clReleaseContext`

References

- Intel® SDK for OpenCL™ Applications – User's Guide
- Intel SDK for OpenCL Applications – Optimization Guide
- OpenCL 1.2 Specification at http://www.khronos.org/registry/cl/specs/opencl-1.2.pdf
- Android* Development Tools at http://developer.android.com/tools/sdk/eclipse-adt.html
- Android NDK at http://developer.android.com/tools/sdk/ndk/index.html
- Installing OpenCL* Runtime on Android* Emulator