HiCrypt: A Specialized Translator for Symmetric Block Cipher and GPGPU

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SUMMARY Many-core computer systems with GPUs are coming into mainstream use from high-end computing, including supercomputers, to embedded processors. Consequently, the implementation of cryptographic methods on GPGPU is also becoming popular because of such systems' performance. However, many factors affect the performance of GPUs. To cope with this problem, we developed a new translator, HiCrypt, which can generate an optimized GPGPU program written in both of CUDA and OpenCL from a cipher program written in standard C language with directives. Users must annotate only variables and an encoding/decoding function, which are characteristics of cipher programs, with directives. To evaluate the translator, five representative cipher programs are translated into CUDA and OpenCL programs by the translator. Generated programs perform high throughput almost identical to hand optimized programs for all five cipher programs. HiCrypt will contribute to development and evaluation of new and various symmetric block ciphers using GPGPU.

key words: translator, CUDA, OpenCL, symmetric block ciphers, GPGPU

1. Introduction

Small and inexpensive portable devices such as smartphones and tablet PCs have become adopted explosively into widespread use. The necessity for high-speed cryptographic technology for use with such devices has also increased. However, demand for high-performance encryption at high-end fields such as data centers holding enormous data, so-called "Big-data", continues growing too. These facts indicate that the field of security countermeasures is widely necessary. In fact, Intel and AMD have presented an AES-NI [1] instruction set that is implemented on a processor with an embedded cryptographic engine as a solution for high-speed encryption for a standard symmetric block cipher called Advanced Encryption Standard (AES) [2]. It drastically improves the speed of AES encryption by hardware acceleration. However, if AES is not used for a data encryption, then its high efficiency will not be valuable in the least, and the circuit area will have been wasted.

To date, heterogeneous many-core processors with a CPU-GPU (Graphics Processing Unit) integration architecture are becoming popular for their high-speed performance and low power consumption. A many-core architecture is scalable because the number of processor cores can be adjusted for use. Actually, computers embedding a GPGPU

are widely employed from mobile phones e.g. A5 processor of iPhone, to PC and servers e.g. Intel Ivy and Sandy bridge. And also the needs to process cryptography on these devices exist. For this reason, accelerating cryptographic processing while using a many-core processor with scalable architecture is expected to constitute one solution for high-speed and scalable cryptographic processing [3]–[5]. High-speed cryptographic processing accelerated by a many-core architecture such as that of GPGPUs will resolve problems that cannot be solved by AES-NI because those GPGPU accelerations based on a software implementation can accept any cryptographic algorithm. Moreover, such accelerators entail no extra hardware costs such as those associated with specialized circuits for cryptography because GPGPUs are embedded as a general purpose accelerator.

However another problem remains: difficulty of the program for GPGPU. Many factors are useful to exploit the performance of GPGPU for cipher applications. Particularly, problems such as optimizing the way of using various kinds of memory of GPGPU and considering computation granularity trouble many programmers. To address these problems, we suggest a special-purpose translator for symmetric block ciphers: HIGH-performance CRYptographic Program Translator (HiCrypt). HiCrypt generates optimized GPGPU programs written in CUDA [6] or OpenCL [7] from cipher programs written in a standard C language with directives. HiCrypt constitutes of a simple method to produce optimized cipher programs for GPGPU, because the translator requires annotations only of elements that are characteristic for cipher programs. In fact, HiCrypt requires no knowledge about a special feature nor an architecture of GPGPU. By supporting both of OpenCL and CUDA, HiCrypt provides the way to use various many-core accelerators to process cipher programs.

Moreover, HiCrypt targets not only users who need to process cryptography in high-speed but also developers and evaluators of cryptography. Although cipher algorithms are evaluated by its robustness, performance of which is also an important element for evaluation. Evaluators of cryptography such as National Institute of Standards and Technology (NIST), New European Schemes for Signatures, Integrity and Encryption (NESSIE) and Cryptography Research and Evaluation Committees (CRYPTREC) test processing speed of cryptography to select a standard and recommendation cryptography in fact. Processing speed on a general purpose processor and an embedded processor is evaluated for these purpose widely, however, performance accelerated by

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GPGPU is not adopted currently. HiCrypt will contribute for this situation by generating GPGPU's program from source code for evaluation of a general purpose CPU. And also HiCrypt will contribute to build a library for cryptography accelerated by GPGPUs. Some libraries for cipher program accelerated by GPGPU are now developed, however, these libraries are not employable condition because there are many platforms and many cipher algorithms.

The remainder of this paper is organized as follows. In the next section, we briefly introduce programming environments for GPGPU, CUDA and OpenCL. In Sect. 3, techniques for symmetric block ciphers on GPGPU are shown. In Sect. 4, details of HiCrypt directives are presented. In Sect. 5, design of the translator is shown. Implementation of the translator and its evaluation using five representative 128-bit symmetric block cipher programs, AES, Camellia [8], SC2000 [9], CIPHERUNICORN-A [10], and CLEFIA [11] are described in Sect. 6. Finally we explain our conclusion in Sect. 7.

2. Programming Environment for GPGPU: CUDA and OpenCL

To date, two industrial standard programming languages to make GPU programs are developed, CUDA and OpenCL. Each one provides both of a programming language and an abstract model for GPGPU. CUDA and OpenCL have many conceptual similarities but their terminologies are different. In this section, overview and important elements for cipher programs in each environment are shown.

CUDA is a programming tool for GPGPU computing provided by Nvidia Corp. CUDA provides an extended C language with type qualifier extensions for indicating data locality and a special function-call syntax for kernel invocation with specifying the parallelism. APIs for synchronization, initializing GPU and communication between GPU and CPU are also provided. In CUDA, a GPU of the graphics processor is hidden as a parallel computing architecture. CUDA architecture provides a structured hierarchical memory space and multiprocessor which consists of processors named streaming processors. Memory space consists of global memory, shared memory, constant memory, local memory, and registers. Multi-processor structure is hidden by thread execution model which provides single instruction multi-thread (SIMT) model. Each multi-processor executes 32 threads in parallel. CUDA exclusively supports NVIDIA GPUs and it can provide high-performance computing. On the other hand, OpenCL has published as a hardware independence programming framework for many-core environment including GPU. OpenCL is also published as an open standard specification. This standard defines an abstract device model which maps well to contemporary GPU architectures and a GPU programming model. It has a set of C language extensions called as "OpenCL C language" in the same manner as CUDA including APIs. In contrast to CUDA, OpenCL supports many devices provided by plural vendors, Apple, ARM, AMD, Nvidia, Intel and

Table 1 Comparison of terms of CUDA and OpenCL.

Category	CUDA term	OpenCL term
Hardware	GPU Streaming processor Streaming multiprocessor	OpenCL Device Processing element Compute unit
Execution	Grid Block Thread Kernel Stream	NDRange Work-group Work-item Kernel Command Queue
Memory	Global memory Constant memory Shared memory Registers & Local memory	Global memory Constant memory Local memory Private memory

more. OpenCL architecture abstract consists of host computer and attached one or more compute devices. Each of which is comprised of one or more compute units with one or more processing elements. The OpenCL memory model describes a similar hierarchy to that of CUDA. Each compute device has global memory to which all work-items in work-groups, analogous with CUDA's threads and blocks, can read/write, local memory which is shared in a work-group, private memory is private to each work-item and constant memory is same as CUDA's. Program written in each environment can be translated to each other. Some previous works compared CUDA with OpenCL and they also showed a comparison of terms used in each environment [12], [13]. Table 1 shows corresponding terms in both environments. Note that, CUDA terminology will be used in the rest of this paper, therefore readers can replace them with adequate OpenCL's word depending on their needs.

3. Typical Implementation of High-Speed Symmetric Block Ciphers

AES is adopted as an example of symmetric block cipher in this paper, although HiCrypt tries to translate many symmetric block ciphers. Moreover, some conditions are fixed to simplify the description herein. For example, the secret key size is fixed to 128-bit. The calculation time of an extended key, hereinafter referred to as "key", which is calculated from the secret key is not discussed because it is much smaller than the encryption time. Moreover, an encoding algorithm of AES is only discussed because decoding will apply the same technique as that shown in the encoding.

3.1 AES

AES is a symmetric block cipher introduced in 2001 by NIST [2]. Although 128-bit, 192-bit, and 256-bit key size can be selected, we discuss only 128-bit in this paper. Its algorithm of the 128-bit key defines 10-round processes. Each round includes four transformations: SubBytes, ShiftRows, MixColumns, and AddRoundKey. The final round differs slightly from the other rounds: it does not include MixColumns. In AES, a round process can be combined into a transformation simply using a look-up table called T-box

and XOR operation [14]. Letting a be the round input, which is divided into four inputs a_0, a_1, a_2, a_3 , each of which consists of 32 bits, the round output e is represented as

$$e_j = T_0[a_{0,j}] \oplus T_1[a_{1,j+1}] \oplus T_2[a_{2,j+2}] \oplus T_3[a_{3,j+3}] \oplus k_j$$

where T_0, T_1, T_2 , and T_3 are look-up tables and k_j is the j -th column of a round key. This algorithm requires only four look-up table transformations and four XOR operations. Using a pre-computed look-up table such as T-box is valid for other symmetric block ciphers, but the look-up table requires more memory space. In fact, almost all software implementations of the block cipher use the look-up table.

Block ciphers have some modes - Electric Code Book (ECB), Cipher Block Chaining (CBC), CounTeR (CTR) and so on. Electronic Code Book (ECB), CountTeR (CTR), or Xor-encrypt-xor Tweakable code book mode with ciphertext Stealing (XTS) [15] are known as parallelizable modes in block cipher. ECB uses a single key applied to all plaintexts. CTR uses a key stream generated from a secret key and combined with plaintexts. In the CTR mode, the generation of the key stream is conducted in the same manner as ECB. In the XTS mode, plaintexts are encrypted using two ECB modes. Therefore, we discussed only ECB mode to evaluate the parallel processing of symmetric block ciphers.

3.2 Optimization for Cipher Programs on GPGPU

Some previous works had clarified which techniques are valid for the AES program with CUDA. Biagio et al. [16] described a study of the relations between the parallelizing granularity and its performance. The effect of the number of threads and file size are also shown. Iwai et al. [17] further discussed granularity and the variety of memory allocations for variables of cipher programs. It showed that efficient CUDA programs made a difference of more than 50 times in performance. Nishikawa et al. [18], [19] applied the technique shown in [17] to other ciphers to validate the effectiveness of it. The result showed that implemented ciphers, Camellia, CIPHERUNICORN-A, Misty, and SC2000 also exhibit high-performance. This section explains the optimization technique which is used by HiCrypt introduced in previous works.

3.2.1 Granularity

In 128-bit symmetric block ciphers, the input data are separated specifically to 128-bit block size and are then encrypted. Each 128-bit block can be processed by each thread in parallel. There is greater computation granularity such as 64-bit, 32-bit and 16-bit per thread. Even greater 128-bit per thread granularity has the benefit of no synchronization instruction during parallel processing by multiple threads compared with the other granularity. For this reason, a HiCrypt translator set the computation granularity to 128-bit per threads in parallel encryption processing on GPUs.

3.2.2 Memory Allocation

Generally in optimized software implementation of symmetric block ciphers, the same look-up tables are referred multiple times. Their contents are not modified. Therefore, tables stored in shared memory with low access latency engender higher performance than those stored in global memory. If the cache mechanism works well, then constant memory will provide the same low latency as local memory. However, the look-up table operation of block cipher requires random access [17]. Therefore, constant memory should be a wrong selection to store for such look-up tables.

By contrast, the key can be stored in the shared memory or the constant memory because it is referred as common data by all threads and accessed in a regular pattern.

3.2.3 Thread Management

The following two solutions should exist to parallelize the encryption process of 128-bit block ciphers. One is to generate the same number of threads as the number of 128-bit blocks that construct a plaintext. Another one is to process several 128-bit blocks in a repetitive fashion by each thread. This technique shows 3–5% improvement over the first because look-up tables on the shared memory can be reused.

4. Design of the Directives

4.1 Design Concept

HiCrypt requires annotations for only characteristics of the cipher program, because HiCrypt is tailored to translating cipher programs. It means that HiCrypt requires neither parallelization nor optimization annotations. This is a major difference from other parallelization compiler/translators. Users can use HiCrypt easily, because all of “must directives” required by HiCrypt are essential elements for cipher programs such as variables of a plaintext and a ciphertext.

4.2 Directives

Directives of HiCrypt are specified with the `#pragma` mechanism. The syntax of directive is displayed as described below.

```
#pragma cryptcuda directive-name [clause] new-line
```

Each directive starts with `#pragma cryptcuda`. The remainder of the directive follows the C conventions for program. The format of this directive is similar to OpenACC [20] and so on. All of directives defined by HiCrypt are shown in Table 2 with their brief descriptions.

Directives of HiCrypt consist of directive groups of two kinds. The first one includes must directives, which annotate elements for characteristics of cipher programs. Another group consists of parameters for optimization and hints for a translator such as the size of the plaintext.

Table 2 Brief descriptions of the directives.

Annotate variables		For optimization	
<u>plaintext</u>	plaintext, pointer	<u>arch</u> [†]	CUDA architecture version
<u>ciphertext</u>	ciphertext, pointer	<u>threadNum</u> [†]	Number of threads
<u>key</u>	key, pointer	<u>blockNum</u> [†]	Number of blocks
<u>table</u>	look-up table		
For functions		Others	
<u>kernelCall</u>	Earmark of kernel call	<u>filesize</u> [†]	Filesize of plaintext
<u>kernelFunc</u>	Kernel function definition	<u>blocksizeOfCipher</u> [†]	Blocksize of cipher
<u>device</u>	Definition of function called from kernel		

Underlined directives are must directives.

[†]Directives operated by themselves with a clause.

Must directives, `plaintext`, `ciphertext`, `key`, `table`, `kernelCall`, and `kernelFunc`, are introduced here. Directives `plaintext`, `ciphertext`, `key`, and `table` annotate variables. They apply to an immediately following statement that is a variable declaration. The remaining two must directives, `kernelCall` and `kernelFunc`, annotate an encoding function call and its definition. `kernelCall` applies to an immediately following single statement that encodes function call so that the function can be offloaded to GPGPU. `kernelFunc` applies to an immediately following structured function definition block that is definition of function annotated `kernelCall`. The structured function definition block will be parallelized and translated to the OpenCL or CUDA program. The optional directive `device` provides a solution to call functions from an inner function, which is annotated as `kernelFunc`.

Other directives for optimization are `arch`, `threadNum` and `blockNum`. `threadNum` and `blockNum` provide a solution when users would like to optimize the number of thread and block manually, although HiCrypt has default numbers of them. Furthermore, `arch` defines an architecture of GPU such as CUDA's `sm_20` and `sm_13`. It provides a hint for optimization to the translator.

Directives `filesize` and `blocksizeOfCipher` provide a hint of a targeted cipher algorithm to the translator. If `filesize` and `blocksizeOfCipher` are defined, then the translator will work reliably, but the translator will seek the file size of a plaintext and the block size of a cipher algorithm.

4.3 Restrictions

To use HiCrypt directives, some restrictions must be made on a program format. This section shows all restrictions required by the translator.

At the first brush, variables, which represent plaintext, ciphertext, and key, must be declared as a single-dimension array. Look-up tables annotated by `table` must be declared as single-dimension arrays too, although look-up tables for symmetric block cipher are sometimes declared as multi-dimension arrays. These restrictions are presented in Table 3. These pointer variables must have no aliases because the translator uses their names directly to generate a CUDA and OpenCL program.

Table 3 Restrictions: declaration of variables.

Variable type	Format
Plaintext	<i>type *varname; or type varname[size];</i>
Ciphertext	<i>type *varname; or type varname[size];</i>
Key	<i>type *varname or type varname[size];</i>
Tables	<i>type varname[size] = { /* statically initialize */ }</i>

There are two additional restrictions. The first is a restriction on order and members of argument of the function definition, shown as below:

```
void function-name(integertype *plaintextpointer,
integertype *ciphertextpointer, integertype *key,
integertype numberofblocks);
```

Types of the dummy arguments except *numberofblocks* accept any integer pointer type, such as `unsigned char*`, `int*` and `long*`. The type of the *plaintextpointer* and *ciphertextpointer* must be the same. Moreover, dummy arguments *plaintextpointer*, *ciphertextpointer* and *key* must have no aliases. Another restriction is format of the “for” loop, which encodes a cipher block repetitively in an encoding function annotated by the directive. The loop must be written according to the format shown below:

```
for (counter=0; counter < numberofblock;
counter++, plaintextpointer += blocksize,
ciphertextpointer += blocksize).
```

The parameter *numberofblock* represents the number of plaintext blocks and *blocksize* represents the block size of the block cipher. For example, the block size of AES is described as “16” in byte size or “4” in word (32-bit) size. HiCrypt accepts any type of variables and there is no need to care for it, because HiCrypt can parallelize a formatted for loop shown above by the simple dividing. However it is better to use these variables’ unit in coherent for safe programming. Also HiCrypt applies simple type-checking for these variables as an assistance for users.

These restrictions must be accepted to use HiCrypt. However these restrictions are reasonable for users because many optimized programs for symmetric ciphers are written similarly. To explain details of these directives and the behavior of the translator, a base code for AES with HiCrypt’s directives is shown in Fig. 1 as an example. This code shows only important statements and structures of the program.

```

// <abbreviate program header>
// Compute capability
// for CUDA (optional)
#pragma cryptcuda arch sm_20
// look-up tables
#pragma cryptcuda table
const char Sbox1[256]={...};
#pragma cryptcuda table
const char Sbox2[256]={...};
// <and more tables...>
//prototype
void AESEncode(char*, char*,
               char*, int);
..
main(){
#pragma cryptcuda plaintext
    char *pt;
#pragma cryptcuda ciphertext
    char *ct;
#pragma cryptcuda key
    char key[64];
    ..
    // pt, ct and key initialize
    pt = (char *)malloc(pt,
        sizeof(char)*FILESIZE);
    ..
    // AES Encoding call
#pragma cryptcuda kernelCall
    AESEncode(pt, ct, key, numblocks);
    ..
}

#pragma cryptcuda kernelFunc
void AESEncode(char* pt, char* ct,
               char* key, unsigned int size)
{
    // <local variables>
    u32 s0, s1, s2, s3, t0, t1, t2, t3;
    ..
    // loop to encode plaintext blocks
    for(i=0; i < size; i++){
        ct+=blocksize, pt+=blocksize){
            // <rounds for encoding>
            ... = in[.
            ... = Sbox1[] ...^key[]..
            out[] =..
        }
    }
}

```

Fig.1 Base code of AES.

5. Design of the Translator

5.1 Translation Overview

Two groups of programs, host program and kernel program are generated by HiCrypt in both of OpenCL and CUDA environment. Additional statements, which consist of qualifiers, new variables for GPGPU, data transfer and allocation APIs, GPGPU initialization, and kernel call are generated into the host program. Also generating statements, which are qualifiers, new variables and initialization to use the shared memory, and restructuring of encoding loop for parallelizing are applied for kernel program.

5.2 The flow of Translation

An implemented translator described in Sect.6 scans a source program twice as shown in Fig. 2. On the first pass, it finds all directives and annotated elements in the source program. Then it stores them in its working memory, called a directive table. A symbol table which stores all symbols in source program is also built simultaneously. Contents of the directive table for AES are shown in Table 4 for example.

On the second pass, it translates statements of the source program annotated by the directives to an optimized CUDA/OpenCL program. The transformation technique for the host program consists of primary four parts, “Creating new variables”, “Generating code for device initialization”,

Fig.2 The flow of translation.

Table 4 Directive table for AES base code.

Directive	ID	Type	Size	Line	Filename
plaintext	pt	char*	FILESIZE	593	AESCore.c
ciphertext	ct	char*	FILESIZE	595	AESCore.c
key	e_key	char*	64	591	AESCore.c
table	Sbox1	uint32 []	256	52	AESCore.c
table	Sbox2	uint32 []	256	187	AESCore.c
table	Sbox3	uint32 []	256	321	AESCore.c
table	Sbox4	uint32 []	256	454	AESCore.c
kernelCall	AESEncode	NA	NA	631	AESCore.c
kernelFunc	AESEncode	NA	NA	659	AESCore.c

“Generating code for allocation and transfer” and “Generating kernel function call”. Moreover, translation of kernel program consists of “shared memory management” and “Loop parallelization”. Finally, they are outputted as a single file in case of CUDA but as discrete files in case of

Table 5 Recommended combinations for variables and memory hierarchy.

Variable	Memory
plaintext and ciphertext	Global Memory
Key	Constant memory or Shared Memory
Table	Shared memory

Table 6 Qualifier for variables for CUDA and OpenCL.

Type	CUDA	OpenCL
pointer for global memory	-	cl_mem
pointer for constant memory	__constant__	__constant
pointer for shared memory	__shared__	__local
kernel function prototype	__global__	__kernel

OpenCL.

5.3 Translation of Host Program

5.3.1 Creating New Variables

HiCrypt creates new variables which contain data used on the GPU at the beginning. In cipher programs, they are plaintext, ciphertext, key and table. These elements are annotated by the HiCrypt directive. Figure 1 shows these annotated variables `pt`, `ct`, `key`, and `S_box`. HiCrypt makes these new variables with unique names which correspond with the memory on which each variable is stored. Each variable must be placed in a correct hierarchy of memory according to previous work. The best combination of variables and memory hierarchy which was shown in a previous work are summarized in Table 5. HiCrypt allocates these variables to adequate places according to the combination of variables and memory using memory hierarchy qualifiers. Qualifiers for each variable to allocate each memory are shown in Table 6. The translator creates new variables with added prefix “d_” to the basename to be unique[†], to allocate `pt` and `ct` shown in Fig. 1 on the global memory. Similarly, new variables to which are added prefix “c_” to the basename to allocate variables annotated by `key` and `table` in the constant memory are created[†]. Their declaration is also created in front of a `main()` function.

Tables must be allocated on the shared memory of the GPU. However, data cannot be sent from CPU directly to the shared memory. Tables need not always be allocated on constant memory. However, the current version of the translator allocates them on the constant memory first. Furthermore, allocating a variable for a key on the shared memory is valid. The key can be allocated on the shared memory or constant memory because each allocation does not make a difference for their performance [17].

Some more variables to control OpenCL program are generated to keep information device id, kernel program and more, although CUDA program does not require them. These variables are generated as a simple constant of strings. Figure 3 portrays a generated program by the translator. Variables created by the translator are placed at lines 9–16 in Fig. 3.

```

1 //<abbreviate program header>
2 #define BLOCKNUM 56 //generated as the default
3 #define THREADNUM 256 //generated as the default
4
5 const uint32 Sbox0[256]={...};
6 const uint32 Sbox1[256]={...};
7 //<more tables and variables...>
8 //<generated OpenCL variables>
9 cl_platform_id cl_platform;
10 cl_command_queue command_queue;
11 cl_device_id d_id; cl_program program;
12 cl_kernel kernel; cl_context context;
13 // plain & ciphertext
14 cl_mem d_pt, d_ct;
15 // key & tables
16 cl_mem c_Sbox0, c_Sbox1; cl_mem c_Key;
17 // <some more autogenerated variables...>
18
19 int main(int argc, char** argv){
20     char *pt;
21     char *ct;
22     char key[64];
23     //get the information, create context and command queue
24     ret = clGetPlatformIDs(1, &cl_platform, &numPlatforms);
25     ret = clGetDeviceIDs(cl_platform, CL_DEVICE_TYPE_...);
26     context = clCreateContext(0, 1, &d_id, NULL, NULL, &ret);
27     command_queue = clCreateCommandQueue(context, d_id,...);
28     // <abbreviate some statements...>
29     // allocation & transfer
30     d_plaintext=clCreateBuffer(context,CL_MEM_READ_ONLY,...);
31     d_ciphertext=clCreateBuffer(context,CL_MEM_WRITE_ONLY,...);
32     c_Sbox0=clCreateBuffer(context,...);
33     c_Key=clCreateBuffer(context,...);
34     // <more allocation statements...>
35     //Kernel program load and compile
36     const char fileName[] = "aes_core_kernel.cl";
37     size_t source_size; char *source_str;
38     program = clCreateProgramWithSource(context, 1, ...);
39     ret = clBuildProgram(program, 1, &d_id, ...);
40     // create kernel, set args and data transfer
41     kernel =clCreateKernel(program,"AES_encrypt",&ret);
42     ret = clSetKernelArg(kernel,0,sizeof(cl_mem)*1,...);
43     ret |= clEnqueueWriteBuffer(command_queue,c_Sbox0,...);
44     // <more clEnqueueWriteBuffer()s...>
45     // Kernel call
46     ret=clEnqueueNDRangeKernel(command_queue,kernel,...);
47     // read back
48     ret |= clEnqueueReadBuffer(command_queue,d_ct,...);
49 }

```

Fig. 3 Generated OpenCL program including new variable declaration, allocation, transfer and kernel call except kernel function definition.

5.3.2 Generating Code for Device Initialization

When the translator finds a `kernelCall` directive in `main()` function, statements for initializing device are generated. Only `CUDA_Init()` is created in case of CUDA program. On the other hand, some procedures such as getting device information and making command queues to make

Table 8 Generated APIs for data allocation and transfer.

	CUDA	OpenCL	Allocated or transferred variables
Device memory allocation	cudaMalloc()	clCreateBuffer()	plaintext, ciphertext
Constant memory allocation	-	clCreateBuffer()	key, tables (only OpenCL)
Data transfer (constant memory)	cudaMemcpyToSymbol()	clEnqueueWriteBuffer()	key, tables
Data transfer (host to device)	cudaMemcpy()	clEnqueueWriteBuffer()	plaintext
Data transfer (device to host)	cudaMemcpy()	clEnqueueReadBuffer()	ciphertext

Table 7 Generated APIs for initialize.

Type	CUDA	OpenCL
Initialize	CUDA_Init()	-
Getting device information	-	clGetPlatformIDs() clGetDeviceIDs()
Making command queues	-	clCreateContext(), clCreateCommandQueue()

program are required by OpenCL. These initializing statements are simply created as a constant strings value. Example of created APIs in this stage is shown in Table 7, but some more APIs may be generated for initialization. Initialization created by the translator is placed at lines 24–27 in Fig. 3.

5.3.3 Generating Code for Allocation and Transfer

APIs for the device memory allocation and data transfer are generated after device initialization code. Generated APIs for an allocation and a transfer are shown in Table 8. Firstly to allocate a ciphertext and a plaintext on the global memory, two `cudaMalloc()` or `clCreateBuffer()` are generated. Also `clCreateBuffer()` is required for OpenCL to use constant memory for key and tables, although CUDA does not require. Then data transfer codes for all created variables are generated, `cudaMemcpy` and `cudaMemcpyToSymbol` for CUDA, and `clEnqueueWriteBuffer()` for OpenCL. Their parameters, variable name, its type, and size are generated by automatically based on information stored in the directive table. Then, to receive ciphertext processed on GPU, `cudaMemcpy()` or `clEnqueueReadBuffer` are generated after the encoding function call. These generated codes are shown in Fig. 3 at lines 30–34, 43–44, 48.

5.3.4 Generating Kernel Function Call

OpenCL requires more procedure to create kernel call compared with CUDA program. In case of OpenCL, one `clCreateKernel()` to create kernel object, same number of `clSetKernelArg()` as arguments of kernel function, and `clEnqueueNDRangeKernel()` to invoke kernel are generated. Moreover to compile kernel program (called on-line compile), `clCreateProgramWithSource()` and `clBuildProgram()` are created for OpenCL program. Meanwhile, simply two `dim3` type variables to set the threads and the blocks, and function call to invoke kernel in original format are generated for CUDA.

The number of threads and blocks are given by directives as `threadNum` and `blockNum`. If they are not specified,

Table 9 Elements attached in kernel function definition.

Element	CUDA	OpenCL
Kernel function qualifier	<code>__global__</code>	<code>__kernel</code>
shared memory qualifier for vars.	<code>__shared__</code>	<code>__local</code>
shared memory vars.	prefix “s.” added to variables annotated with <code>table</code>	
API to get the block id	<code>blockIdx.x</code>	<code>get_global_id()</code>
API to get the thread id	<code>threadIdx.x</code>	<code>get_local_id()</code>
thread synchronization	<code>syncthreads()</code>	<code>barrier()</code>

then the translator will attempt to calculate the best numbers according to an architecture of GPU. Default value of the `blockNum` is 28 or its multiples for Tesla C2050 currently. Default value of the `threadNum` is 256 or its multiples. To minimize a loss of performance attributable to padding in case of odd size of plaintext, it is better to set the number of threads and blocks as not too numerous. In contrast, to obtain higher performance, a certain number of blocks and threads are necessary. The kernel call including relevant API is shown in Fig. 3 at lines 36–42, 46.

5.4 Translation of Kernel Program

Kernel program is generated through translating encoding function. It is another important task for the translator. This task consists of two parts: shared memory management and loop parallelization.

5.4.1 Shared Memory Management

When the translator meets up with the directive `kernelFunc`, the translator adds qualifier `__global__` or `__global` to the line before the kernel function definition. In case of OpenCL, dummy arguments which consist of pointer for tables on the constant memory and tables on the shared memory are also added to original function. Then, new shared variables to store data of tables with a prefix “s.” added to variables annotated with `table` are created[†]. Declarations of new variables are placed at the beginning of the body of the kernel function definition with keyword `__shared__` or `__local`. Qualifiers used by the kernel program translation in CUDA and OpenCL are shown in Table 9. A variable annotated with `table` is called “table” hereinafter and a new variable allocated on the shared memory is hereinafter called an “s_table”. A table variable allocated on the constant memory is called a “c_table”.

To fill up each s_table with the content of each table that

[†]If created variable name was not unique, HiCrypt renames it to be unique.

is declared on the base code, initialization codes for each `s_table` are created. Three kinds of code are used to initialize `s_tables`. An initialization code is generated according to Algorithm 1. The algorithm shows three cases, the case of the number of threads is equal to, greater than, or less than

Algorithm 1 Initializing code generation for an `s_table`.

Parameters: TID, thread ID; SIZE & size, size of table; THNUM, the number of threads in the block

Output: Part of the OpenCL and CUDA program

```

if number of threads = size of table then
    print 's_table[TID] = c_table[TID];'
else if number of threads > size of table then
    print 'if(TID < SIZE) s_table[TID] =
        c_table[TID];'
else if number of threads < size of table then
    s ← size, i ← 0
    while s/number of threads > 0 do
        print 's_table[TID+THNUM*i] =
            c_table[TID+THNUM*i];'
        i ← i + 1, s ← s - number of threads
    end while
    if s > 0 then
        print 'if(TID < s, s)'
        s_table[TID+THNUM*i] =
            c_table[TID+THNUM*i];'
    end if
end if

```

```

1 __kernel void AES_encrypt(__global u32 *in,
2     __global u32 *out, __constant u32* c_Te0, ...
3     __constant u32* c_Key, __local u32* s_Te0,...,
4     u32 length){
5     // get thread ID
6     int tid=get_global_id(0);
7     int threadIdx=get_local_id(0);
8     // shared memory initialize
9     if(threadIdx <256)
10         s_Te0[threadIdx]=c_Te0[threadIdx];
11     if(threadIdx <256)
12         s_Te1[threadIdx]=c_Te1[threadIdx];
13     // <more tables...>
14     // synchronize
15     barrier(CLK_LOCAL_MEM_FENCE);
16     // initialize pointers in (input) and out (output)
17     in+=(tid*4);
18     out+=(tid*4);
19     // these variables are defined by the base code
20     u32 s0, s1, s2, s3, t0, t1, t2, t3;
21     // main loop
22     // TNT: total num of threads, SCB: Size of Cipher Block
23     for(i=0; i < (length/TNT);
24         in+=TNT*SCB, out+=TNT*SCB, i++){
25         // rounds for AES
26         .... = in[];
27         .... = s_Sbox1[...] ...^c_key[]..
28         out[] = ..
29     }
30 }

```

Fig. 4 Generated OpenCL code for a kernel function definition.

the table size. After generating an initialization code for all tables, API `syncthreads()` or `barrier()` will be inserted to synchronize the threads. Finally, all table references must be replaced to the `s_table`. Figure 4 at lines 1–15 shows this translation.

5.4.2 Loop Parallelization

The translator finds a loop that encodes the plain-text blocks by searching a keyword `for` and analyzes its parameters. The translator replaces an original `for` structure to a new loop divided by the fixed number of threads as shown in Sect.3.2.3. Therefore, each thread has a loop for encryption cipher blocks, so that the number of iterations is represented as $(\text{number of cipher blocks})/(\text{total number of threads})$. When the number of cipher blocks is broken, the translator uses a padding technique. Moreover, to exploit further performance, each thread must access the global memory in sequence. It provides a coalesced access to the global memory. A translated loop header is shown in Fig. 4 at lines 23–24, 27.

6. Implementation and Evaluation

6.1 Implementation of the Translator

The HiCrypt translator is implemented to confirm its effectiveness through performance evaluation of generated codes which are both of CUDA and OpenCL. According to the design of the translator shown before, it requires no syntax analysis. For this reason, this has been implemented using the Ruby programming language. It has achieved almost all functions of HiCrypt by pattern matching and replacing. A description for PC, OS, CUDA, OpenCL and GPU used for this evaluation is shown in Table 10.

6.2 Cipher Algorithms

For this evaluation, we have selected four more cipher algorithms, which are Camellia, SC2000, CIPHERUNICORN-A, and CLEFIA, aside from the AES. These ciphers have different data randomization structure. AES has a SPN, Camellia, CIPHERUNICORN-A and CLEFIA have a Feistel, and SC2000 has a hybrid of SPN and Feistel. In addition, four ciphers are listed on e-government recommended ciphers by CRYPTREC except CLEFIA. AES and Camellia are also recommended by NESSIE [21]. Moreover, SC2000

Table 10 Specification of environments.

CPU	Intel Core i7 920 2.67 GHz
Memory	32 GB
OS	CentOS release 6.3
Compiler	gcc ver4.4.4 (option -O3)
GPU	Nvidia Tesla C2050
CUDA driver	Nvidia CUDA toolkit 4.0
OpenCL driver	Same as above (Nvidia's CUDA includes OpenCL)

Table 11 Summary of the cipher specifications.

Cipher	Structure	# of tables	Size of tables	# of rounds*
AES	SPN	4	1 Kbyte/table	10
Camellia	Feistel	4	1 Kbyte/table	18
SC2000	Hybrid	3**	8 Kbyte/table**	7
CIPHERU.	Feistel	1	1 Kbyte/table	16
CLEFIA	Feistel	8	1 Kbyte/table	18

*in case of 128-bit key length.

**Optimized as speed. # of tables and table size are selectable in SC2000.

have achieved the best throughput in the symmetric block ciphers currently. [19]. CLEFIA is adopted as a ISO/IEC 29192 light weight cryptography which is a new category of cryptography. In this evaluation, the length of the key is fixed at 128-bit length for all cipher programs. Number of round and table are different each other. Table 11 presents a summary of the specification of five ciphers.

6.3 Creating a Source Program with Directives

Source codes of AES and Camellia are made from OpenSSL/TLS source code. Particularly, primary encoding codes are almost a direct quote from it. By contrast, SC2000, CIPHERUNICORN-A, and CLEFIA are implemented based on the specification [9]–[11] by one author of this paper. All programs are implemented with a restricted format shown as before. The directives, `plaintext`, `ciphertext`, `key`, `table`, `kernelCall` and `kernelFunc` are used. Therefore, the format of these programs is the same as a base code of AES shown in Fig. 1. The directive `device` is annotated to call the function in the kernel function in case of SC2000. All programs are implemented using look-up tables to speed up encryption, although some of ciphers have a quite different structure. Implementations without look-up table, which provide 10 times or more performance degradation compared with the look-up table based implementation, are not discussed because the purpose of HiCrypt is to achieve high performance cipher processing. The bitslice implementation, one of the high-performance implementation, is not employed by this paper because a bitslice implementation is not always true that it exerts better performance than look-up table based implementation [22]. Moreover, there is need to make up a difficult program design such as SIMD-like programming using general programming language such as the C in case of bitslice implementation. However all programs have different data randomize code in the source code, directives are easily inserted to all five ciphers. Because annotated variables are distinguished for all symmetric block cipher programs, making a program with HiCrypt directives is easy for programmers.

6.4 Performance Result

The translator could successfully generate OpenCL and CUDA programs for all five ciphers. Performances of generated programs and hand optimized programs are presented in Table 12. The hand optimized program is same as the

Table 12 Throughputs of AES, Camellia, SC2000, CIPHERUNICORN-A, and CLEFIA. HiCrypt: generated program by HiCrypt. Hand: hand optimized program.

Algorithm	Platform	Program	Gb/sec	Cycles/byte
AES	CUDA	HiCrypt	53.2	0.17
		Hand	53.3	0.17
	OpenCL	HiCrypt	50.6	0.18
		Hand	50.6	0.18
	CPU	-	1.3	16.58
Camellia	CUDA	HiCrypt	54.9	0.17
		Hand	54.9	0.17
	OpenCL	HiCrypt	52.6	0.17
		Hand	52.6	0.17
	CPU	-	1.0	22.1
SC2000	CUDA	HiCrypt	83.0	0.11
		Hand	83.0	0.11
	OpenCL	HiCrypt	71.4	0.13
		Hand	71.4	0.13
	CPU	-	1.1	19.89
CIPHERU.	CUDA	HiCrypt	25.0	0.37
		Hand	25.0	0.37
	OpenCL	HiCrypt	25.0	0.37
		Hand	25.0	0.37
	CPU	-	0.2	99.47
CLEFIA	CUDA	HiCrypt	53.7	0.17
		Hand	53.7	0.17
	OpenCL	HiCrypt	51.3	0.18
		Hand	51.3	0.18
	CPU	-	1.3	17.09

program which is shown in our previous work [19] except OpenCL's. OpenCL programs are manually written according to CUDA's. HiCrypt is designed to generate similar programs with our previous work, therefore, performance results of hand optimized programs and programs generated by HiCrypt shown in Table 12 are almost identical. In case of CLEFIA, it is implemented for hand optimized program in the same manner as other cipher programs. To evaluate their performance in cases near peak performance, each parameter is determined: the number of threads in a thread block is 512, the number of thread blocks is 56 and the size of plaintext is 10 MBytes. OpenCL programs exhibit around 0%-15% performance reduction. That is a well known fact, a current version of OpenCL program sometimes shows performance reduction compared with the CUDA program because of OpenCL compiler's immaturity [12]. As a result, HiCrypt succeed to generate optimized parallelized code for cipher programs in the both of environments, CUDA and OpenCL. Table 12 does not show a comparison of performance of CPU and GPU, although each performance is shown. CPU's throughput shows a validity of the base codes. To compare performance of GPU and CPU, there is a need to consider about a device cost, power consumption, CPU's programming environment, and more. Next, a performance comparison with several previous works for AES and Camellia is shown in Table 13. Performance of hand optimized AES and Camellia program by GTX285 from our previous work [19] is also shown. No related work for CIPHERUNICORN-A, Hierocrypt-3, SC2000, nor CLEFIA using GPGPU is described in the literature without our previous work.

Table 13 Performance results of previous works.

Reference	Framework	Algorithm	Device	Gb/sec
Nishikawa et al. [19]	CUDA	AES	GTX285	37.8
Nishikawa et al. [19]	CUDA	Camellia	GTX285	38.0
Osvik et al. [25]	CUDA	AES	GTX295 ^{*3}	30.9 ^{*4}
Li et al. [23]	CUDA	AES	C2050	60
Gilger et al. [26]	CUDA	AES	GTX295 ^{*3}	29.6
Gilger et al. [26]	OpenCL	AES	GTX295 ^{*3}	25.4
Gilger et al. [26]	CUDA	Camellia	GTX295 ^{*3}	26.3
Gilger et al. [26]	OpenCL	Camellia	GTX295 ^{*3}	26.3

^{*3} They use only 1 of 2 chips of GPU (240 cores)

^{*4} Including data transfer time

Qinjian Li et al. [23] implemented AES on Nvidia C2050 using CUDA and achieved 60 Gb/sec throughput by reordering plaintext data. A quantitative cost of reordering was not shown. This implementation looks similar to our hand optimized implementation and it refers our previous work [24]. Therefore, generated AES program by HiCrypt will have the same quality as this work by considering to the cost of reordering.

Osvik et al. [25] and Gilger et al. [26] showed AES implementation on Nvidia GTX295 and both previous works achieved around 30 Gb/sec used half of GTX295. The half of GTX295 contains the same number of cores as GTX285 but GTX295's core clock (576MHz) is slower than GTX285's (648MHz). If these programs had processed by C2050, throughput would be estimated roughly 53.2 Gb/sec by calculating with the number of cores and the clock speed though, it is difficult to compare performance between different architectures. Anyway, a generated code by HiCrypt has good enough quality since the throughput of program generated by HiCrypt nears estimated throughput of previous works. Note that Osvik's throughput includes data transfer, so there are possibilities that the data transfer program was implemented in a skillful manner to hide the cost of the data transfer or AES processing was implemented faster.

Gilger et al. also showed the performance of Camellia on Nvidia GTX295 and achieved 26.3Gb/sec. Converting this throughput to C2050's, 45.5Gb/sec is led. This throughput is slower than the throughput of Camellia generated by HiCrypt.

6.5 Translation Result

As shown before, the programs generated by HiCrypt achieved almost identical performance as those of hand optimized programs. Therefore, the generated programs seem almost identical to the hand optimized program, except for the order of the API call and the places of declarations of variables.

The usage of OpenCL and CUDA is quite similar to one another, but the amount of the created statement for OpenCL is much greater than CUDA's. Total number of lines of each cipher program is shown in Table 14. Note that, these lines include an encoding program, directives, variable declarations, main function and more, except a definition

Table 14 Increase of amount of lines of generated program by HiCrypt without lines for a definition of table of S-boxes.

Algorithm	AES	Camellia	SC2000	CIPHERU	CLEFIA
# of lines (input)	307	215	213	341	230
# of lines (OpenCL)	504	414	441	521	455
Ratio	1.64	1.93	2.07	1.53	1.98
# of lines (CUDA)	377	285	282	396	319
Ratio	1.23	1.32	1.32	1.16	1.39

of look-up table. Increase of amount of lines of the programs is around 160% to 200% in case of OpenCL, around 116% to 140% in case of CUDA compared to the source code with the directives. The number of generated statements for OpenCL program is about three times more than CUDA's one. Only around six to ten extra lines are required for HiCrypt to translate with only must directives, because six must directives shown before consist of one table directive and the others. Same number of the table directive as the number of tables contained target cipher programs must be annotated. As a result, HiCrypt can reduce a burden to write considerable additional CUDA/OpenCL code by inserting only around ten directives. Furthermore, All five programs which are written in a standard C program with HiCrypt directives have been compiled using a standard C compiler that ignored directives of HiCrypt.

HiCrypt has two more features, allowing nested loops and device function that calls an inner kernel function. Symmetric cipher algorithms consist of rounds which are repeated in the encoding process. To repeat rounds, a loop structure such as a "for" or "while" is used in an encoding function. In other words, loops for encoding to cipher blocks have a nested loop structure. Moreover, some data-randomize operations in rounds are defined as function calls to make a readable program. HiCrypt provides the directive device to support such a function. Results show that HiCrypt can translate such nested loops and device function calls. In contrast, general purpose automatic parallelization compilers for accelerator including GPGPU have been appearing recently, such as OpenACC [20], PGI Accelerator [27], and CAPS HMPP [28]. Moreover, academic suggestions to assist to make up OpenCL and CUDA programs have also been presented [29]–[31]. HiCrypt differs from them in their purpose, which is specialized for symmetric block ciphers. To make a small target, HiCrypt generated highly optimized CUDA programs from symmetric block cipher programs. As a future work, we would like to develop other features of HiCrypt such as automatic translation for public key cryptography. Furthermore, syntax analysis will be implemented to HiCrypt to relax its restriction.

7. Conclusion

This paper described a new translator, HiCrypt, for symmetric block ciphers. HiCrypt can generate optimized OpenCL and CUDA programs from symmetric block cipher programs written in a standard C language with HiCrypt directives. Usage of directives is simple for cipher pro-

grammers because directives require annotation of some elements that are characteristics of the cipher programs. To evaluate HiCrypt, we implemented the translator and evaluated its performance through translating of five symmetric block cipher programs, AES, Camellia, SC2000, CIPHERUNICORN-A and CLEFIA with directives. Results show that the translator could generate optimized OpenCL and CUDA programs that exhibit almost identical performance as hand optimized programs for all five cipher programs. Moreover, the translator accepts a nested loops as a target loop and a calling function in the target loop.

Ciphers are evaluated by not only its strength but also its performance. Although the heterogeneous multiprocessors that embed a GPU have become widely used, they will be able to accelerate ciphers. Therefore, we are suggesting to evaluate cipher's performance by GPGPU. For this reason, HiCrypt will contribute to the development of new symmetric block ciphers and evaluating their performance.

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