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A Digital Rights Enabled Graphics Processing System

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Abstract

With the emergence of 3D graphics/arts assets commerce on the Internet, to protect their intellectual property and to restrict their usage have become a new design challenge. This paper presents a novel protection model for commercial graphics data by integrating digital rights management into the graphics processing unit and creating a digital rights enabled graphics processing system to defend against piracy of entertainment software and copyrighted graphics arts. In accordance with the presented model, graphics content providers distribute encrypted 3D graphics data along with their certified licenses. During rendering, when encrypted graphics data, e.g. geometry or textures, are fetched by a digital rights enabled graphics processing system, it will be decrypted. The graphics processing system also ensures that graphics data such as geometry, textures or shaders are bound only in accordance with the binding constraints designated in the licenses. Special API extensions for media/software developers are also proposed to enable our protection model. We evaluated the proposed hardware system based on cycle-based GPU simulator with configuration in line with realistic implementation and open source video game Quake 3D.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Digital Rights, Graphics Processor

1. Introduction

The industry of real time graphics applications such as video games, interactive avatars, 3D online games, handheld mobile gaming, etc., grows rapidly with the advancement of new graphics hardware technology. However, it remains a great technological and legal challenge to enforce digital rights protection for graphics applications. The problem becomes even more prominent with the emergence of 3D graphics/arts commerce on the Internet. In the virtual space, these trademarked and proprietary 3D models or textures in the forms of digitized sculptures [LPC*00], characters, avatars, vehicles, weapons, outfits, wallpapers, etc., possess real monetary values to online gamers, collectors and artists. According to International Intellectual Property Alliance, the loss of revenue due to piracy of entertainment software is measured in billions of dollars every year globally [IIP]. In the past, digital rights enabled silicon chips have made significant contribution to fight against piracy of music and video contents [BCK*99, HDC, SVP]. Today digital rights management (DRM) IC is widely used for protecting digital content in set-top boxes, satellite video/audio receivers, video players, mobile devices, etc. However, little research has been performed in the area of protecting digital rights of graphics data and 3D objects for the consumer market. In this paper, we explore the technologies of digital rights enabled graphics processing unit (GPU) for countering piracy of real time graphics entertainment software and graphics assets.

Different from digital rights protection of media data (audio/video) that can use specially tailored hardware and protocol to enforce an end-to-end digital rights solution [HDC, SVP], enforcing the protection of graphics data with a tamper-proof silicon chip was almost impossible. In a conventional computing platform, CPU is heavily involved in pre-processing graphics data before the data are sent to the specialized graphics accelerator or GPU for accelerated rendering. Such tightly-coupled dependency and involvement of CPU in graphics processing pipeline leave many security holes to the hackers for duplicating and reverse-engineering digital contents guarded by a digital rights protection system that runs the protection software on CPU.

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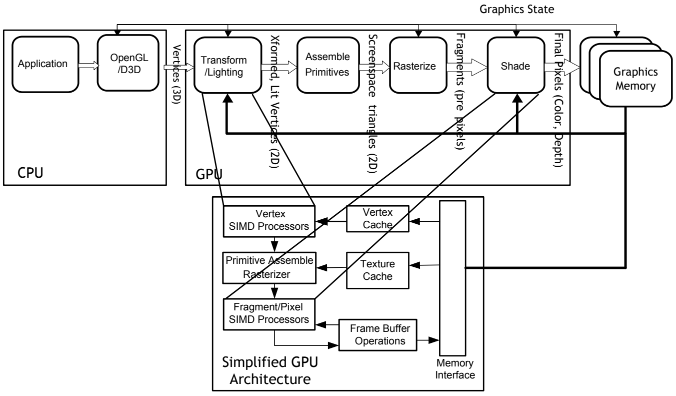

Figure 1: *3D Graphics Pipeline*

There were techniques proposed for tracing illegal users of 3D meshes by embedding watermarks into 3D models under protection [Ben99, DGM02, PHF99]. However, watermarking does not prevent unauthorized users from duplicating, sharing or using watermarked graphics data. In addition, watermarks are often fragile and could be easily destroyed via data transformations. In general, a pure software based digital rights protection solution, as shown by history, offers very weak content protection because software components can be easily bypassed, circumvented, subverted, or reverse engineered.

The main objective of this work is to provide a tamper-proof digital rights management scheme for real time graphics data through an innovative combination of digital rights protection functionalities with GPU. The result is a *digital rights enabled graphics processing system* that provides tamper-proof processing for graphics data. Since it directly integrates digital rights protection into GPU, it leaves no loophole for the hackers to launch software exploits or simple hardware based tampering. A hacker cannot defeat the protection offered by the presented model by simple reverse-engineering, patching, altering, modifying software and data accessible by the CPU.

This paper represents the first thrust to forge a common ground for digital rights community, GPU designers, and computer graphics researchers for studying digital rights issues of graphics data. The rest of the paper is organized as follows. In Section 2, we briefly discuss the background information for modern day graphics processing pipeline and GPU architecture. Section 3 presents the design of the digital rights enabled graphics processing unit. In Section 4, we discuss design challenges and graphics API extension. Finally, Section 6 concludes the paper.

2. 3D Graphics Pipeline

3D graphics processing involves projecting and rendering 3D geometry models onto a 2D display with surface detail enhancement such as texture mapping, bump mapping to create realism [FvDFH95, WDS99]. The rapid growth of 3D graphics industry to a great extent ascribes to the advancement of high performance and low cost graphics hardware and real-time graphics applications such as video games.

Figure 1 illustrates a graphics pipeline for polygon-based rendering that converts graphics input data from 3D geometry vertices into 2D image frames. It also shows the functional partitioning of CPU and GPU for state-of-the-art computing platforms. The graphics input consists of a list of geometry data, denoted by triangle vertices in world coordinates. The first stage of the processing, the geometry stage, transforms each vertex from the world space into the viewer's space, culls backfaced vertices, performs perspective correction, and calculates lighting intensity for each vertex. This process is generally called geometry pipeline (transformation and lighting) and is floating-point intensive. The output from the geometry pipeline is comprised of triangles in the viewer's space. In the rasterization stage, a rasterizer determines the plane equation of each triangle surface and its corresponding coordinates on the screen. Then for each screen pixel, it computes a set of graphics parameters by interpolating vertex parameters of the triangle computed in the previous stage. The result of the rasterization stage is a set of fragments (or pixels) enclosed by each triangle. The next stage, the fragment or pixel processing stage computes the color of each pixel. When surface details enhancement is applied, each fragment takes the color values provided by texture maps into account. For each fragment, there is a set of corresponding texels. The fragment stage computes texture access addresses based on the texel coordinates and fetch the associated texture values from the textures stored in the system memory or GPU's memory. Then the fragment stage combines the fetched texture color with the interpolated lighting color to generate the fragment's final color. Finally, fragments are assembled into the frame buffer as a 2D image of color values. The graphics processing selects the final color of each pixel based on the depth (z value) if several fragments overlap to the same location.

Figure 1 also shows the functional decoupling of 3D graphics processing between today's 3D GPU and CPU. Over the last few years, GPU architectures became increasingly powerful. It gradually engulfed most of the graphics processing stages originally completed by CPU, starting from rasterization to floating-point intensive geometry processing into hardware. In addition to absorbing more graphics processing stages into silicon, the GPU architecture itself also evolved by converting some of the fixed functional stages into more flexible programmable stages. These high performance GPU architectures employ programmable pipelined SIMD engines known as vertex processor and fragment processor (or pixel processor) to process graphics data. Those engines use specially designed SIMD instructions internal to the GPU and run special *shader programs* for vertex and pixel processing.

With the continuing advancement of GPU hardware, the software driver on CPU became very thin layer in standard 3D pipeline. The primary task of CPU reduces to controlling of the GPU hardware, setting up, and moving graphics com-

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mands and data around, leaving extra computing power for artificial intelligence, simulations, and game logics.

3. DRM for Graphics

The industry of real time graphics entertainment applications has been mauled by wide-spread piracy since the very beginning. Theft or piracy of graphics arts assets or even the applications themselves is relatively easy when graphics rendering relies primarily on CPU. Hackers can easily reverse-engineer a graphics application, circumvent any software based digital rights protection, recover its art assets, or make illegal copies. [KL05] discusses several potential exploits hackers can launch for violating digital rights of graphics data including attacks such as 3D model file reverse-engineering, 3D application tampering, or graphics driver tampering, etc.

The advancement of graphics hardware brings looming opportunities to enforce digital rights protection of graphics assets at silicon level because the role of CPU in a traditional graphics pipeline withers while the complexity of GPU increases over different generations. Integration of digital rights protection within GPU has the following advantages:

- **Strong digital rights protection**. Integrating digital rights protection with GPU results in a very secure content protection system. It is extremely difficult to break such a system using software based attacks or physical hardware tampering, e.g. using a logical analyzer to probe and dump signal traces at chip interconnects.
- **Sufficient protection**. Integrating digital rights protection with GPU also provides sufficient protection to graphics based entertainment software such as video games. Assume that a hacker can freely duplicate the software and violate its copyrights. Since copyrights of graphics data are enforced by the digital rights enabled GPU, the pirated software will become useless to the offenders because graphics data will not be rendered properly.
- **High performance**. Digital rights protection of graphics data requires real-time decryption of protected data. Implementing it directly on the silicon reduces its potential negative impact on graphics processing performance.

Note that a hacker may still be able to launch sophisticated hardware attacks such as micro-probing directly on the die or other side-channel exploits e.g. differential power analysis [Wit02]. These attacks can be addressed by security countermeasures at packaging level or circuits level [Wit02]. Such studies are general to all the approaches that use silicon hardware to build a security system, thus orthogonal to the study of this work. It is also worth pointing out that different from music or video content protection, graphics protection as proposed in this paper does not significantly suffer from analog attack such as dumping display output. Reconstructing 3D models from 2D images is considered a great challenge, remaining a major research topic in computer vision. There exists no handy and reliable method for hackers to launch such sophisticated attacks to reconstruct 3D models from rendered images.

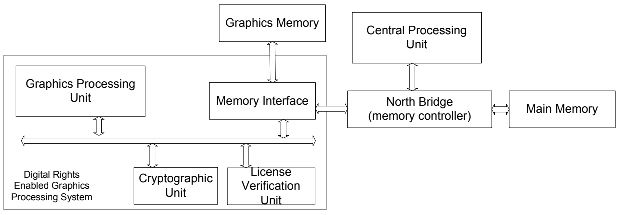

Figure 2: *Digital Rights Enabled GPU*

However, the nature of the research does require a cross-disciplinary collaboration in digital rights management (DRM) community, graphics researchers, and GPU architects.

4. Digital Rights Aware Graphics Processing System

In this section, we outline the architecture of our digital rights enabled graphics processing system. It comprises three aspects: (1) digital rights enabled GPU architecture; (2) digital rights enabled graphics API; and (3) content distribution.

4.1. Digital Rights Enabled GPU

Compared to a traditional GPU architecture, a digital rights enabled GPU contains two more components, a *cryptographic unit* to decrypt protected graphics input data, and a *license verification unit* to process the licenses of graphics data. Figure 2 illustrates a digital rights enabled GPU. Similar to digital rights licenses used in other content protection cases, the graphics digital rights licenses released by their content providers specify and designate the desired usage of the graphical data. A digital rights enabled GPU features the necessary means to authenticate the licenses. During actual graphics rendering, it is guaranteed that graphics data be used strictly in compliance with the license agreement.

As discussed in Section 2, an advanced graphics processing system performs both geometric and fragment (as programmable shaders) processing in GPU. A GPU generally allows arbitrary binding of geometry data with any texture and arbitrary binding of shader programs with any geometry input. Such freedom creates potential security loopholes for hackers to reverse-engineer protected graphics data. For example, customized malicious shader programs can output raw, unprocessed geometry data or in a format friendly for reverse-engineering to a result buffer that a hacker can read. To reverse-engineer protected textures, a hacker can draw a textured square into the frame buffer and dump the original texture data. To prevent these exploits, bindings among geometry input, textures, and shaders must be restricted. As shown in Figure 3, such restrictions can be incorporated into the licenses of the protected graphics data.

A license of a geometry object may look like what is shown in the left-hand side of Figure 3. It comprises a name, decryption key context, digests of the encrypted geometry data, a geometry data ID, the binding constraints as

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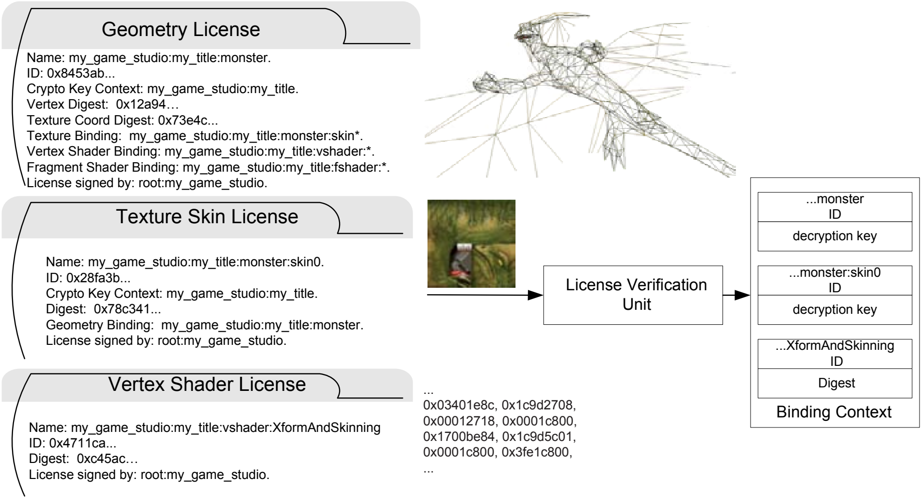

Geometry License
Name: my_game_studio:my_title:monster.
ID: 0x8453ab...
Crypto Key Context: my_game_studio:my_title.
Vertex Digest: 0x12a94…
Texture Coord Digest: 0x73e4c...
Texture Binding: my_game_studio:my_title:monster:skin*.
Vertex Shader Binding: my_game_studio:my_title:vshader:*.
Fragment Shader Binding: my_game_studio:my_title:fshader:*.
License signed by: root:my_game_studio.

Texture Skin License
Name: my_game_studio:my_title:monster:skin0.
ID: 0x28fa3b...
Crypto Key Context: my_game_studio:my_title.
Digest: 0x78c341...
Geometry Binding: my_game_studio:my_title:monster.
License signed by: root:my_game_studio.

Vertex Shader License
Name: my_game_studio:my_title:vshader:XformAndSkinning
ID: 0x4711ca...
Digest: 0xc45ac…
License signed by: root:my_game_studio.

```
...
0x03401e8c, 0x1c9d2708,
0x00012718, 0x0001c800,
0x1700be84, 0x1c9d5c01,
0x0001c800, 0x3fe1c800,
...
```

Figure 3: *Graphics Asset Licenses and Binding Context*

to which textures or shaders can be applied to this object, and the digest of its license signed by a certified content provider. Note that the binding permission can be inherited by all the sub-classes of this object. In the example of *Geometry License* for a monster 3D object in Figure 3, the geometry object is released by a certified content provider my_game_studio for a game titled my_title. The name of the geometry object is monster which belongs to a root class: my_game_studio:my_title that includes all the graphics sub-class objects released for my_title. According to the license, monster geometry model should be decrypted using decryption key associated with the root class my_game_studio:my_title. The monster geometry model is allowed to bind with any texture whose name is prefixed by my_game_studio:my_title:monster:skin. In addition, the license specifies the shader programs allowed to bind with the geometry object.

Similarly, a license for a texture map comprises similar fields. According to the license specified for monster skin texture in Figure 3, the monster skin can be decrypted using the decryption key of the root class my_game_studio:my_title, and is allowed to bind with the geometry object: my_game_studio:my_title:monster. It should be understood that the binding is not a one-to-one mapping. The same texture can be bound to several graphics objects and vice versa.

Figure 3 also shows an exemplary license for vertex shader and a binding example. For a shader program, the license comprises the name of the shader, digest of its binary image, and digest of the license signed by the content provider. The described solution applies effortlessly when the shader programs are distributed in machine code binaries directly executable by the GPU. This is the case of content distribution on mobile platform. However, sometimes shader programs are distributed as source codes or in some intermediate formats that require additional compilation or translation at runtime before they are loaded to the GPU. If source code distribution is employed, the above license binding model may not be applicable. In this case, the content provider needs to pre-compile the shaders for different GPU targets to provide a list of shader digests compatible with different target GPUs and device drivers and distributes them along with the sources. During execution when a shader is compiled by a runtime compilation module in a host computing system, a digital rights enabled graphics processing system can verify its authenticity by computing the digest based on the given binary image and comparing it with the corresponding shader digest picked from the list of pre-computed digests targeted for the GPU.

An alternative yet elegant solution is to integrate a secure micro-controller into the proposed system for runtime shader optimization and translation. The micro-controller resides in a secure and protected domain. It authenticates shader sources before runtime optimization or translation and the object shader code is then protected with a digest generated by the micro-controller. The area cost of integrating a lean micro-controller into today's GPU is very small provided the vast number of transistor budget in the design of modern GPUs.

Given a set of licensed geometry input, textures and shaders, the digital rights enabled graphics processing system creates a binding context that comprises decryption keys that will be used during graphics processing for decrypting protected contents such as geometry models or textures. The right-hand side of Figure 3 illustrates this process. Furthermore, when the integrity of graphics data is a security concern, the binding context comprises digests of the protected graphics data that can be used by the digital rights enabled graphics processing system to verify the integrity of graphics data during rendering. The digital rights enabled graphics processing system securely preserves confidentiality of sensitive binding context information such as decryption keys.

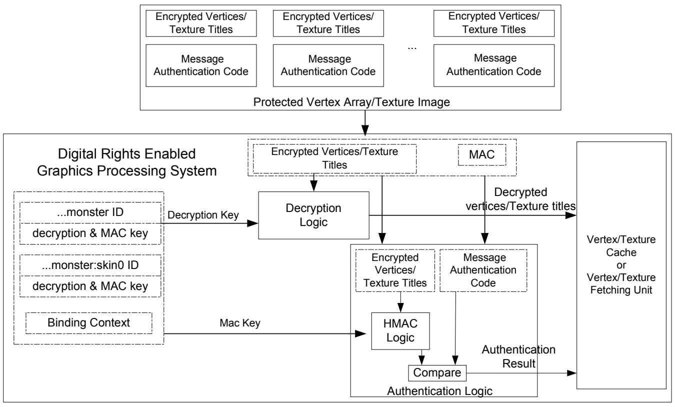
Encrypted Vertices/ Texture Titles
Message Authentication Code
Encrypted Vertices/ Texture Titles
Message Authentication Code
...
Encrypted Vertices/ Texture Titles
Message Authentication Code
Protected Vertex Array/Texture Image
Digital Rights Enabled Graphics Processing System
Encrypted Vertices/Texture Titles
MAC
...monster ID
decryption & MAC key
...monster:skin0 ID
decryption & MAC key
Binding Context
Decryption Key
Decryption Logic
Decrypted vertices/Texture titles
Vertex/Texture Cache or Vertex/Texture Fetching Unit
Encrypted Vertices/ Texture Titles
Message Authentication Code
Mac Key
HMAC Logic
Authentication Result
Compare
Authentication Logic

Figure 4: *Processing Encrypted Vertices*

There is a piece of enable information included as part of a binding context to indicate whether a piece of graphics data requires decryption or authentication. When graphics data are not protected, the binding context is disabled, and all the graphics data are processed in the usual manner.

Figure 4 shows the components and steps for decrypting or authenticating protected geometry data during graphics processing. Each individual vertex and its attributes or a collection of vertices and their attributes are separately encrypted. Optionally stored together with vertex attributes is a message authentication code (MAC). If not only privacy but also authentication and integrity of graphics content is needed then an authenticated encryption need to be used since encryption does not provide authenticity in general. A secure generic way to construct an authenticated encryption scheme from a secure encryption and a message authentication code (MAC) schemes is to “encrypt-then-MAC” [BN00]. More precisely, a sender encrypts the data, and append to the ciphertext its MAC. The receiver first verifies the MAC of the ciphertext and if it is correct decrypts the ciphertext to get the data. During graphics processing, the digital rights enabled graphics processing system fetches encrypted vertices (or a single vertex). Based on the binding context, the cryptographic unit decrypts these vertices. Furthermore, the authentication logic computes the corresponding MAC digest for the encrypted vertices. Then the result is compared with the MAC digest stored with the encrypted vertices. If they match, the integrity of these vertices is not compromised and verified.

Still, hackers could reconstruct a 3D model by dumping out the content of the Z-buffer that stores depth values. [KB00] presents a re-mesh technique that allows a user to reconstruct a mesh from the depth buffer. To tackle this issue in a digital rights enabled GPU, Z-buffer or other temporary result buffer should be encrypted in a way as shown in Figure 5. The key for encrypting depth buffer or other temporary results is generated by the digital rights enabled graphics system and considered as part of a binding context.

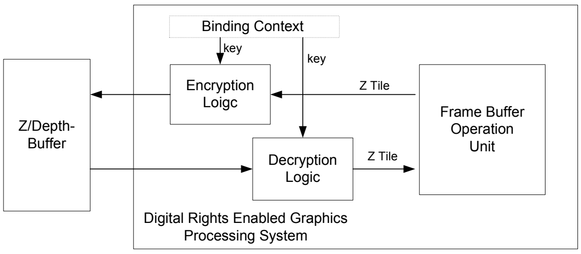

Figure 5: *Depth Buffer Protection*

4.2. Graphics API Extension

For a graphics application, it would be unnecessary and too restrictive to have all the graphics data protected. It is the content provider’s discretion to make the judgment as to what are vaaluable graphics data that require digital rights protection. For example, if a content provider charges a fee for advanced or customized ingame weapons and characters in virtual space, then it has enough justification to have them protected. Having all the graphics data protected indiscriminately will be an overkill on creativity because protected graphics data can only be understood and processed by the digital rights enabled graphics processing system.

Today’s GPU is able to perform most of the graphics processes such as transformation, lighting, clipping, texturing, skeleton based character animation, vertex morphing, simulation, using either fixed logic or programmable shader units. Nevertheless, processes such as collision detection or backface culling are mostly done by the CPU. Having geometry data encrypted and protected may have impact on how CPU carries out these tasks. To solve this issue, a content provider may prepare two levels of detail (LOD) for each protected geometry model using multi-resolution geometry representations [HDD*93, CVM*96, KL05], namely, one finer LOD model with digital rights protection and the other coarser LOD models without protection. The resolution of the coarse LOD data is substantially lower than that of its finer LOD counterpart to prevent proprietary models from being disclosed via the CPU. The CPU can use the coarse LOD data to perform coarser level collision detection or culling test and the finer LOD data can be used for actual rendering. Based on our study and evaluation, introducing digital rights enabled GPU should not cause any incompatibility.

glVertexAttribPointerPrivateARB()

Argument	Attribute
index	index of the generic vertex attribute
type	data type of each component in the array (must be Private{234}f)
normalized	Same as glVertexAttribPointerARB
stride	Same as glVertexAttribPointerARB
pointer	Same as glVertexAttribPointerARB

Table 1: *Defines an encrypted generic vertex attribute array*

We use OpenGL to demonstrate our API extension. There will be a new geometry data type to define protected vertex data. As an example, Private{234}f can be used to denote encrypted vertex attributes comprising 2 to 4 floats. Note that most standard ciphers conduct basic encryption operations on a data unit of at least 64 bits or 128 bits long. If a vertex attribute does not have enough number of bits, it has to be padded or the encryption has to be carried out over a collection of vertices. Also note that this new data type is platform independent and is not affected by the endianness of the host CPU. In accordance with this new data type, a user program can declare vertex buffers of Private{234}f and create a vertex attribute array of encrypted data. Figure 6 shows an example of declaring vertex buffers to store encrypted vertex data and setting up vertex array pointers using Private{234}f. The example uses OpenGL API with encrypted vertex format extension. It specifies monster vertex attribute arrays using **glVertexAttribPointerPrivateARB** that is an extension of **glVertexAttribPointerARB**. The new API shown in Table 1 allows users to specify vertex array format as encrypted floats.

A typical way to store the licenses of graphics data is to store them as arrays of data byte. Similar to the case of geometry data, a new encrypted texel format, Private_R8G8B8A8, is defined to represent the encrypted r8g8b8a8 texture format. Note that encrypted texture format may treat a tile of texels as one unit and encrypt them as a whole. One reason of using tiles is that in many cases, the size of one texel is much smaller than the required data size of an encryption cipher. Using tile is also compatible with how GPU fetches texture data from memory into its texture cache. Figure 6 also shows how to declare an encrypted texture as Private_R8G8B8A8 using extended OpenGL texture API. The program calls extended **glTexImage2D**. It specifies that the monster skin's data format is Private_R8G8B8A8 and the data type is Private_BYTE, which indicates the texture's data values are encrypted bytes.

In addition, a digital rights enabled graphics driver defines the following new API calls in Table 2 to support binding context for graphics application developers.

API
GenBindingContext(int size, int* ptr_to_handles)
ConfigBindingContext(int handle, enum type,
int data_handle, unsigned char* license)
type = PRIVATE_VERTEX_ATTR0..15
type = PRIVATE_TEXTURE0..7
type = VERTEX_SHADER
type = PIXEL_SHADER
type = GEOMETRY_SHADER
...
data_handle = handle to vertex buffer,
texture, or shader
license = license byte array
EnableBindingContext(int handle)
DisableBindingContext(int handle)
DeleteBindingContext(int handle)

Table 2: *Graphics API Extension Based on OpenGL*

The way a binding context is created, destroyed or used is similar to other OpenGL objects. As shown in Table 2, the user program can call **GenBindingContext** to create an array of binding contexts wherein size is the number of binding contexts and ptr_to_handles is a pointer to an array of binding context handles filled in by the underlying API implementation. To delete a binding context, the user program calls **DeleteBindingContext** using the binding context's handle as input. **EnableBindingContext(context_handle)** will set the bind context referenced by context_handle the current binding context. Graphics drawing commands such as commands of drawing a vertex array will consult the current binding context for digital rights information such as decryption keys for encrypted vertices and textures. **DisableBindingContext(context_handle)** will disable the binding context referenced by context_handle if it is the currently enabled context. The user program uses the **ConfigBindingContext** API call to configure the current binding context.

Figure 6 illustrates how to create a binding context and configure the binding context comprising monster vertices, monster texture coordinates and monster skin. For each **ConfigBindingContext**, the user program specifies the type of graphics data, handle to the graphics data, and pointer to the data's license. **ConfigBindingContext** will trigger a sequence of processing:

(a) Setup memory references to all the required information such as the pointer to encrypted vertex buffer/texture buffer/binary shader image and the pointers to the license and the like by the software driver;

(b) Inform the digital rights enabled graphics processing system to verify the configuration and licenses;

(c) Check the integrity of the referenced graphics data by the digital rights enabled graphics processing system and authenticate the involved licenses;

(d) Verify that the binding of graphics data is consistent with the license requirement;

(e) Fill out an internal data structure comprising decryption key and IDs of the graphics data bound by the binding context.

The digital rights enabled graphics system should protect the confidentiality of the binding context. The system may store current binding contexts in an on-chip SRAM and encrypt the binding contexts when they are stored in system or video memory. Furthermore, a digital rights enabled graphics processing system considers binding context as volatile data.

Global information such as content provider's certificate, certified root name and root decryption key for all graphics data of an application are considered as environment settings. As an example, user program calls **SetLicenseEnvironment(unsigned char* license)** with content provider's certificate as input. A digital rights enabled graphics processing system verifies the license's authenticity and extracts keys from the license.

```
// vertices and texture coordinates
unsigned char* geometry_license; // geometry license
unsigned char* private_monster_vertices; // vertex data
int monster_vertex_buffer; // vertex buffer handle
unsigned char* private_monster_tex_coords; // tex coords
int monster_tex_coord; // tex coord buffer handle

// texture
unsigned char* skin_license; // tex license
unsigned char* private_monster_skin; // tex data
int monster_skin; // tex handle

int binding_context;

// load encrypted geometry data
glGenBuffersARB(1, &monster_vertex_buffer);
glBindBufferARB(GL_ARRAY_BUFFER_ARB, monster_vertex_buffer);
glBufferDataARB(GL_ARRAY_BUFFER_ARB,
        SIZE_OF_MONSTER_VERTICES,
        private_monster_vertices, GL_STREAM_DRAW);
glVertexAttribPointerPrivateARB(0, PRIVATE4f,
        GL_FALSE, 0, 0); //encrypted 4f vertex coordinates
...

glGenBuffersARB(1, &monster_tex_coord);
glBindBufferARB(GL_ARRAY_BUFFER_ARB, monster_tex_coord);
glBufferDataARB(GL_ARRAY_BUFFER_ARB,
        SIZE_OF_MONSTER_TEX_COORDS,
        private_monster_tex_coords, GL_STREAM_DRAW);
glVertexAttribPointerPrivateARB(8, PRIVATE2f,
        GL_FALSE, 0, 0); //encrypted 2f texture coordinates
...

// load encrypted texture
glGenTextures(1, &monster_skin);
glBindTexture(GL_TEXTURE_2D, monster_skin);
glTexImage2D(GL_TEXTURE_2D, 0, PRIVATE_R8G8B8A8,
        WIDTH,HEIGHT,
        0, PRIVATE_R8G8B8A8, PRIVATE_BYTE,
        private_monster_skin);
...

// create binding contexts for monster
GenBindingContext(1, &binding_context);
ConfigBindingContext(binding_context, PRIVATE_VERTEX_ATTR0,
        monster_vertex_buffer, geometry_license); //vertex coordinates
ConfigBindingContext(binding_context, PRIVATE_VERTEX_ATTR1,
        monster_tex_coord, geometry_license); //tex coordinates
ConfigBindingContext(binding_context, PRIVATE_TEXTURE0,
        monster_skin, skin_license);

...

// rendering setup
glEnableVertexAttribArrayARB(0); //use monster vertex data
glEnableVertexAttribArrayARB(8); //use monster tex coords
glBindTexture(GL_TEXTURE_2D, monster_skin);
EnableBindingContext(binding_context);

// draw array command
glDrawArrays(GL_TRIANGLES, 0, VERTEX_COUNT);
```

Figure 6: *Example Program Using DRM Extended OpenGL API*

4.3. Content Distribution

The presented digital rights protection technique also comprises a distribution method of protected graphics data. Distributing protected graphics data along with their licenses through a communication network is straightforward. Similar to many digital rights systems, a content distribution server can authenticate the receiver's graphics processing system and generate required licenses specifically for the targeted graphics system. The protected graphics content along with the software can also be distributed through regular retail service and stored in a regular digital storage medium such as CD-ROM or DVD. The simplest solution is to ask users to register purchased graphics application online to a registration server. The server will generate root license for the user's digital rights enabled graphics system and return it to the user.

There are several more advanced and flexible ways to distribute decryption keys and licenses of protected digital content using tamper-proof IC such as smart card. It is not the main objective of this paper to give a thorough treatment of this issue because the problem is general to all types of digital content and has been heavily studied. [AG99] describes a secure and flexible way for distributing digital rights licenses using smart card. The techniques applies to both online based and retail service based license distribution. [UKKK04] also presents a solution for distributing protected digital content and usage licenses in a more user friendly way also using smart card. Those techniques can be applied directly or with little adaptation to the presented digital right model for graphics data. The smart card based solutions also allow a user to redistribute the digital content or upgrade their GPUs. Note that it is not possible for a user to replicate smart card and the key or licenses stored inside.

5. Implementation and Performance Assessment

5.1. Implementation

The latency and throughput of decryption logic vary substantially depending on many factors such as encryption mode, cipher, authentication scheme, process technology, architecture design, etc. To best justify our performance conclusions, we use reference RTL implementations. In simulation study, we conduct sensitivity studies to capture different variations and design scenarios.

5.1.1. Cipher and Crypto Unit

The AES (Advanced Encryption Standard)cipher can process data blocks of 128 bits by using key lengths of 128, 196 and 256 bits. It is based on a round function, which is iterated 10 times for a 128-bit length key, 12 times for a 192-bit key, and 14 times for a 256-bit key. However, AES is often unrolled with each round pipelined into multiple pipeline stages (4-7) to achieve high decryption/encryption throughput [MM01, HV]. The total area of unrolled and pipelined AES is about 100K - 400K gates to achieve 15-50Gbit/sec throughput [MM01, HV]. Based on verilog RTL implementation and synthesis results, each decryption round of pipelined AES takes around 2.5nsec using 0.18 μ standard cell library. The design can operate at 400MHz with

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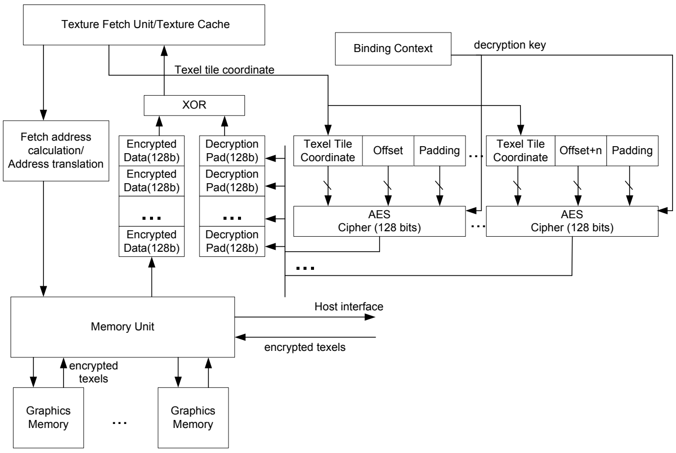

Figure 7: *Content Decryption Block Diagram*

area cost of around 400K gates and over 40Gbis/sec throughput. The simulated GPU comprises four independent memory partitions, each with its own crypto unit. Each crypto unit contains two AES blocks. This allows peak decryption throughput of 40GB/sec. The total area cost is 3200K gates, which is negligible compared to the size of the state-of-the art GPU , which typically has transistor count of hundreds of millions.

5.1.2. Integrity Verification

Integrity verification based on MAC is often a standard operation. But variation of different MAC approaches can have significant impact on verification latency. In the reference implementation, we use standard HMAC [BCK96] for protecting integrity of graphics data blocks and shader programs. The default size of MAC is 96 bits. The reference HMAC uses standard SHA-256 algorithm [NISa] with MAC truncated to 96 bits (HMAC-SHA256-96 [FK]). Simulation study is based on Verilog implementation of SHA-256, synthesized using Synopsys. This design is totally asynchronous and has a gate count of 19,000 gates. The latency for this design is 74ns for 512 bits of padded input (padding with the required padding in SHA-256).

5.1.3. Content Decryption

There are multiple possible implementations of content decryption logic depending on the design choices of cipher, encryption mode, content protection algorithm, etc. Here we illustrate two choices of content protection design. One is based on straight forward application of standard encryption modes such as CBC encryption mode (cipher block chaining) and CMAC [NISb] as recommened by NIST for integrity protection. During decryption, an AES decryption key will be set as part of the binding context. When CBC is employed, encryption is conducted on n 128-bit data chunks (n>=1). Each CBC encryption unit may comprise multiple vertices or texels. One main advantage of using standard encryption mode is its simplicity. However, many standard encryption modes such as CBC increase the overall memory fetch latency by adding decryption latency to the memory fetch latency.

Anther design choice is to use counter mode [DH79] for graphics data encryption and decryption. One of the advantages of using counter mode is significantly reduced latency overhead as it allows pre-computation of decryption pads or overlapping of some of decryption processing with communication latency or data fetch latency. To encrypt with the counter mode, one starts with a plaintext *P*, a counter *cnt*, a block cipher E, and a key. An encryption bitstream of the form E(key, cnt) || E(key, cnt+1) || E(key, cnt+2) ...|| E(key, cnt+n-1) is generated. This bitstream is XORed with the plaintext bit string P, producing the encrypted string ciphertext C. To decrypt, the receiver computes the same pad used for encryption based on the same counter and key, XORs the pad with C, then restores the plaintext P. Security holds under the assumptions that the underlying block cipher is a pseudo-random function family (this is conjectured to be true for AES) and that a new unique counter value is used for each chunk of encrypted data. For graphics data, texel coordinates or vertex indices are all valid choices as counters.

Figure 7 is a block diagram showing our content decryption design.In our design, protected graphics data such as texture tiles, depth buffer tiles, or collection of geometry attributes are encrypted with pseudo-random bits via bit-wise XOR operation. Decryption comprises simple XORing of the encrypted content with the same pseudo-random bits. The pseudo-random bits can be computed using standard ciphers such as AES by taking texture tile coordinate or depth buffer tile coordinate as input. This will generate unique pseudo-random bits for each texture tile or depth buffer tile. AES cipher takes 128-bit input and outputs a 128-bit pseudo-random bit string. When a tile of graphics data contains multiple of 128-bit blocks, inputs to the AES will comprise sub-tile coordinates or sub-tile offsets as shown in Figure 7. Furthermore, when the size of inputs is less than 128-bit, they will be padded. During decryption, the pseudo-random bit strings or pads used for decryption can be pre-computed in parallel with memory fetch when the texture tile coordinate or depth buffer tile is ready. This significantly reduces the decryption latency overhead. In addition, the design supports integrity protection using HMAC over the encrypted graphics data. When HMAC is applied, it uses a different MAC key from the AES key used for decryption. Both keys are part of a binding context as shown in Figure 4.

Note that HMAC could also be combined with CBC based content protection. We did not explore this choice in our evaluation. It is worth pointing out that here we use texture as an example. The scenario and design for geometry and depth buffer are similar.

5.2. Simulation Environment

Our performance evaluation environment is based on Qsilver, a cycle-time model for state-of-the-art GPU architecture [SLS04]. Qsilver comprises a front-end based on modified Chromium [HHN*02] to capture OpenGL command and

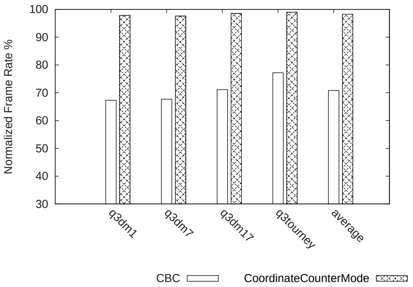

Figure 8: *Impact of Content Decryption on Quake 3D Frame Rate Under Different Decryption Schemes*

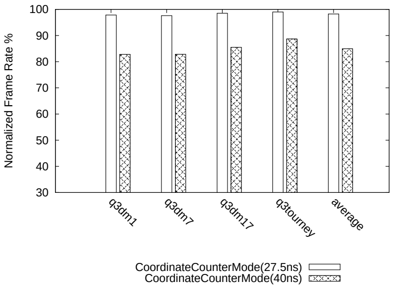

Figure 9: *Impact of Content Decryption on Quake 3D Frame Rate Under Different AES Latencies*

data traces, and a detailed cycle based architecture simulator back-end that models the flow of data and computation through each state of a GPU pipeline, which includes vertex processing, rasterization, fragment processing, frame buffer and depth buffer updates, etc. We modified and instrumented Qsilver with simulation of our digital rights protection mechanism in order to examine the potential impact of graphics data decryption on rendering performance. Simulation parameters are configured as close as possible to the commercial Geforce 4 GPU product line. Our Qsilver's memory model is based on GDDR3 standard. Memory parameters and latencies are set based on realistic GDDR3 performance data [Joh02].

We used open source Quake 3 Arena as evaluation workload. Protected and encrypted graphics data include static geometry data (skinned characters and mesh objects) and textures including mipmap textures. In the default protection setting, depth buffer is protected through encrypting of depth buffer tiles. We collected Quake traces under four different level maps. Each trace was collected after the user got into the representative part of the game.

5.3. Performance Results

First, we evaluated the impact of digital rights protection and graphics data decryption on frame rate. Figure 8 shows normalized frame rate results under two decryption designs. The frame rate is normalized to a baseline condition of no digital rights protection and data decryption. Figure 7 compares two different decryption schemes, one based on direct encryption of graphics data blocks using CBC mode and CMAC, the other one based on counter mode encryption with HMAC. As suggested by the figure, using counter mode decryption incurs only small performance overhead because it hides most of the additional decryption latency with graphics data fetch.

Decryption latency plays an important role in the overall rendering performance of protected graphics data. Though our default simulated decryption latency is based on realistic implementation, it is still necessary to perform sensitivity studies to show the impact of content decryption under different decryption latencies. Figure 9 shows normalized frame rate under the default 27.5ns decryption latency and a hypothetical 40ns decryption latency setting. It is clear that with the increase of decryption latency, the rendering performance decreases.

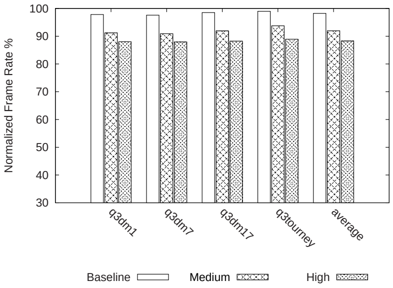

Figure 10: *Content Decryption on Quake 3D Frame Rate*

Another factor that might affect graphics rendering performance under content protection is memory throughput requirement. With the increase of the amount of graphics data fetched by a GPU, so is the pressure on content decryption. We studied how sensitive the rendering performance is to the increase of memory fetch workload by varying the texture cache and depth buffer miss rate. Figure 10 shows the normalized frame rate results. Texture cache and depth buffer miss rate are about 10% in the medium memory pressure setting and around 20% in the high memory pressure setting. Results in Figure 10 indicate that as memory fetch throughput demand and content decryption workload increases, rendering performance decreases.

6. Conclusion

This paper presents a hardware-based digital rights solution for protecting real time graphics assets and graphics application. It integrates digital rights functionalities with GPU to provide a strong content protection mechanism. The paper addresses hardware design issues, API extensions, and other details from the aspects of GPU design, graphics processing, and content protection and distribution.

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