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(54) **SYSTEM, METHOD, AND COMPUTER PROGRAM PRODUCT FOR SHADING USING A DYNAMIC OBJECT-SPACE GRID**

(71) Applicant: **NVIDIA Corporation**, Santa Clara, CA (US)

(72) Inventors: **Anjul Patney**, Kirkland, WA (US); **Eric B. Enderton**, Berkeley, CA (US); **Eric B. Lum**, San Jose, CA (US); **Marco Salvi**, Kirkland, WA (US); **Christopher Ryan Wyman**, Redmond, WA (US); **Yubo Zhang**, Santa Clara, CA (US); **Yong He**, Pittsburgh, PA (US); **G. Evan Hart, Jr.**, Bristow, VA (US); **Kayvon Fatahalian**, Pittsburgh, PA (US); **Yury Uralsky**, Santa Clara, CA (US); **Henry Packard Moreton**, Woodside, CA (US); **Aaron Eliot Lefohn**, Kirkland, WA (US)

(73) Assignee: **NVIDIA Corporation**, Santa Clara, CA (US)

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G06T 15/80 (2011.01)
(Continued)

(52) **U.S. Cl.**
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(56) **References Cited**

U.S. PATENT DOCUMENTS

6,940,505	B1	9/2005	Savine et al.	
2004/0174376	A1*	9/2004	Deering	G06T 15/503 345/592
2014/0139512	A1	5/2014	Piazza et al.	
2015/0070355	A1	3/2015	Clarberg et al.	
2015/0170345	A1	6/2015	Vaidyanathan et al.	
2016/0049000	A1	2/2016	Patney et al.	

OTHER PUBLICATIONS

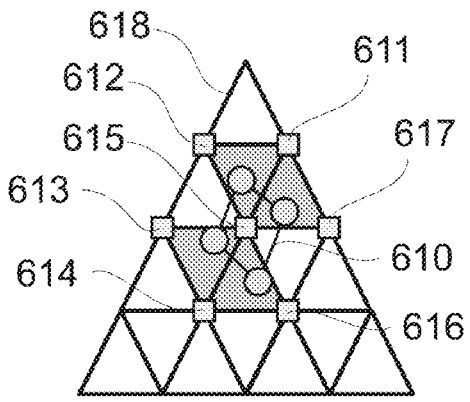
Hüttner, Tobias. "High resolution textures", Visualization '98-Late Breaking Hot Topics Papers (1998): pp. 13-17.*
(Continued)

Primary Examiner — Xiao Wu
Assistant Examiner — Sarah Lhymn
(74) *Attorney, Agent, or Firm* — Zilka-Kotab, PC

(57) **ABSTRACT**

A system, method, and computer program product are provided for shading using a dynamic object-space grid. An object defined by triangle primitives in a three-dimensional (3D) space that is specific to the object is received and an object-space shading grid is defined for a first triangle primitive of the triangle primitives based on coordinates of the first triangle primitive in the 3D space. A shader program is executed by a processing pipeline to compute a shaded value at a point on the object-space shading grid for the first triangle primitive.

20 Claims, 11 Drawing Sheets



(51) **Int. Cl.**
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G06T 17/20 (2006.01)

(52) **U.S. Cl.**
CPC *G06T 2200/04* (2013.01); *G06T 2210/36* (2013.01)

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USPC 345/418, 419, 420, 421, 422, 423, 426, 345/427, 501, 581, 582, 583, 584, 587, 345/589, 619
See application file for complete search history.

(56) **References Cited**

OTHER PUBLICATIONS

U.S. Appl. No. 14/645,340, filed Mar. 11, 2015.
Burns, C. A. et al., "A Lazy Object-Space Shading Architecture With Decoupled Sampling," High-Performance Graphics, 2010, pp. 1-10.
Hill, S. and Baker, D., "Rock-Solid Shading," SIGGRAPH 2012, pp. 1-96.
Liktor, G. et al., "Decoupled Deferred Shading for Hardware Rasterization," ACM, 2012, pp. 1-8.
Clarberg, P. et al., "A Sort-based Deferred Shading Architecture for Decoupled Sampling," ACM Transactions on Graphics, vol. 32, No. 4, Article 141, Jul. 2013, pp. 141:1-141:10.
Ragan-Kelley, J., "Decoupled Sampling for Graphics Pipelines," ACM Transactions on Graphics 30(3), 2011, pp. 1-17.
Clarberg, P. et al., "AMFS: Adaptive Multi-Frequency Shading for Future Graphics Processors," 2014, pp. 1-12.
Vaidyanathan, K. et al., "Coarse Pixel Shading," High-Performance Graphics, 2014, pp. 1-10.
Andersson, M. et al., "Adaptive Texture Space Shading for Stochastic Rendering," Eurographics, 2014, pp. 1-10.
He, Y. et al., "Extending the Graphics Pipeline with Adaptive, Multi-Rate Shading," ACM Transactions on Graphics, vol. 33, No. 4, 2014, pp. 1-12.
Triangle textures, Sep. 2013, retrieved from http://ptex.us/tritex.html.
Yuksel, C. et al., "Mesh Colors," ACM Transactions on Graphics, vol. 29, No. 2, Article 15, Apr. 2010, pp. 1-11.
Non-Final Ofice Action from U.S. Appl. No. 14/645,340, dated Jun. 17, 2016.

* cited by examiner

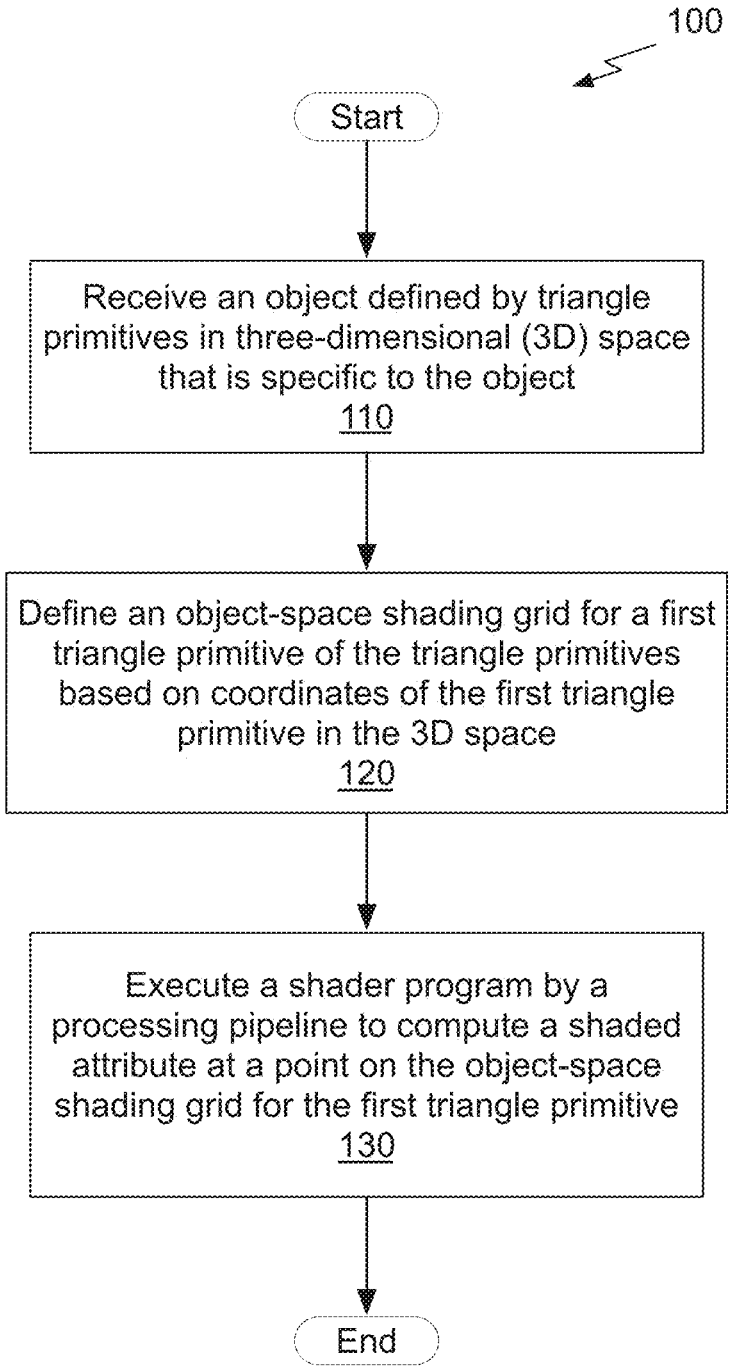

100
Start
Receive an object defined by triangle primitives in three-dimensional (3D) space that is specific to the object
110
Define an object-space shading grid for a first triangle primitive of the triangle primitives based on coordinates of the first triangle primitive in the 3D space
120
Execute a shader program by a processing pipeline to compute a shaded attribute at a point on the object-space shading grid for the first triangle primitive
130
End

Fig. 1A

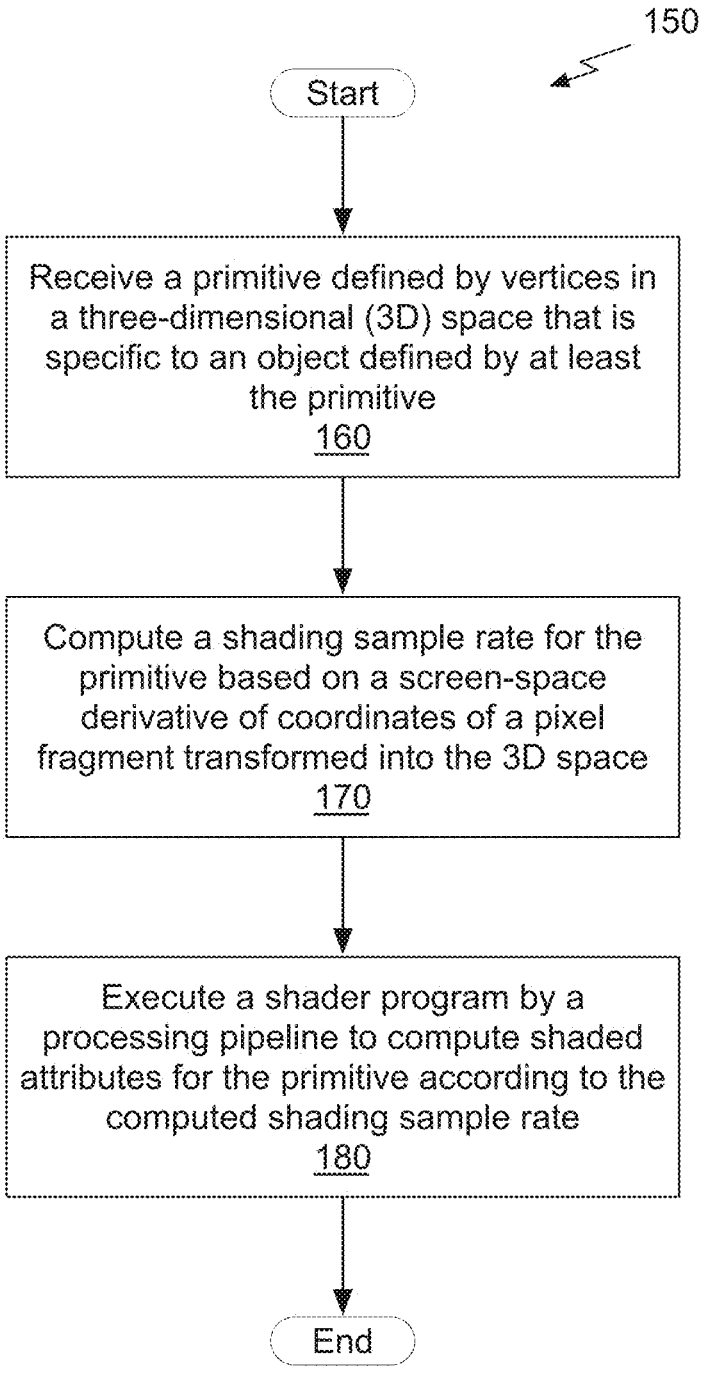
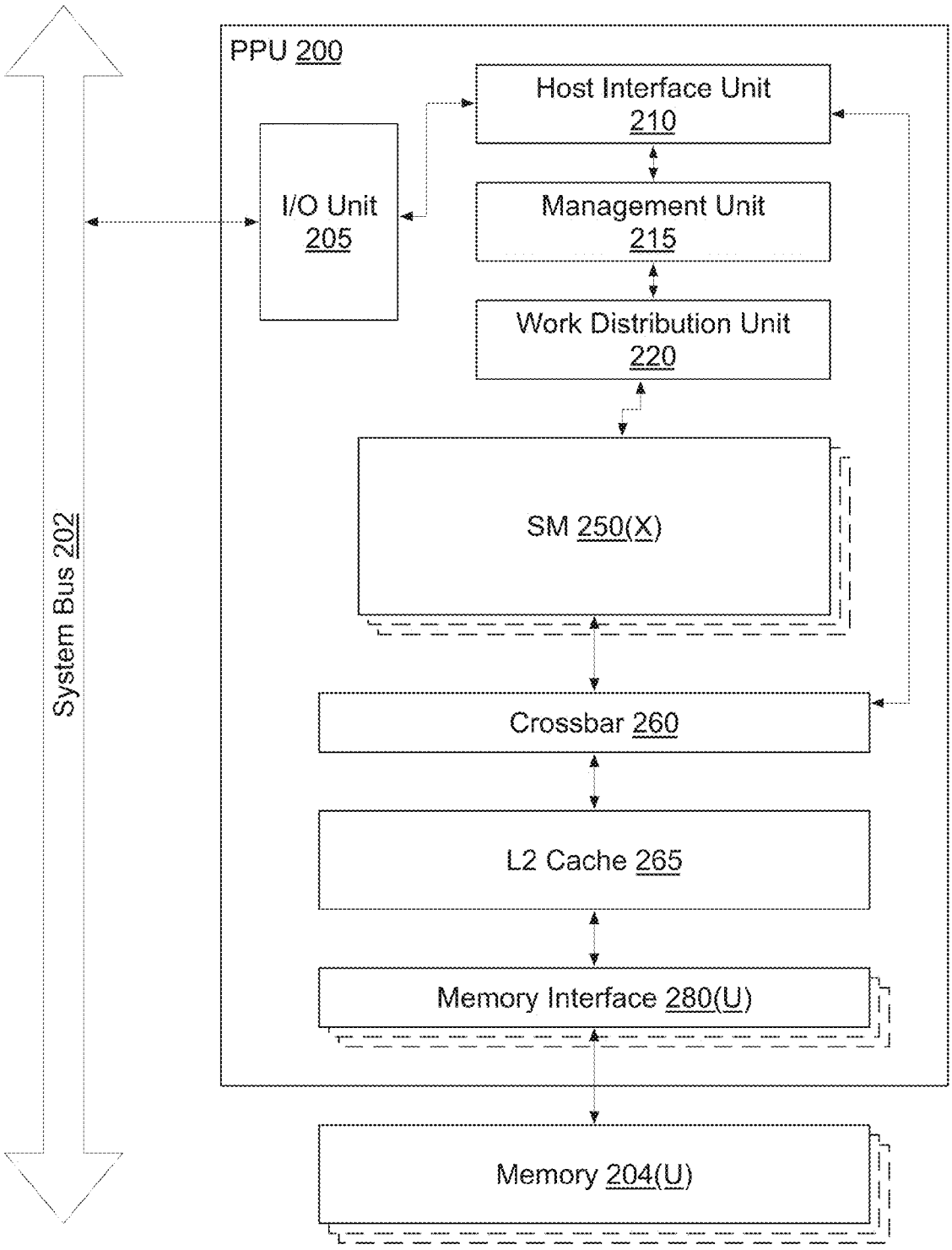

150
Start
Receive a primitive defined by vertices in a three-dimensional (3D) space that is specific to an object defined by at least the primitive
160
Compute a shading sample rate for the primitive based on a screen-space derivative of coordinates of a pixel fragment transformed into the 3D space
170
Execute a shader program by a processing pipeline to compute shaded attributes for the primitive according to the computed shading sample rate
180
End

Fig. 1B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Host Interface Unit 210
I/O Unit 205
Management Unit 215
Work Distribution Unit 220
SM 250(X)
System Bus 202
Crossbar 260
L2 Cache 265
Memory Interface 280(U)
Memory 204(U)

Fig. 2

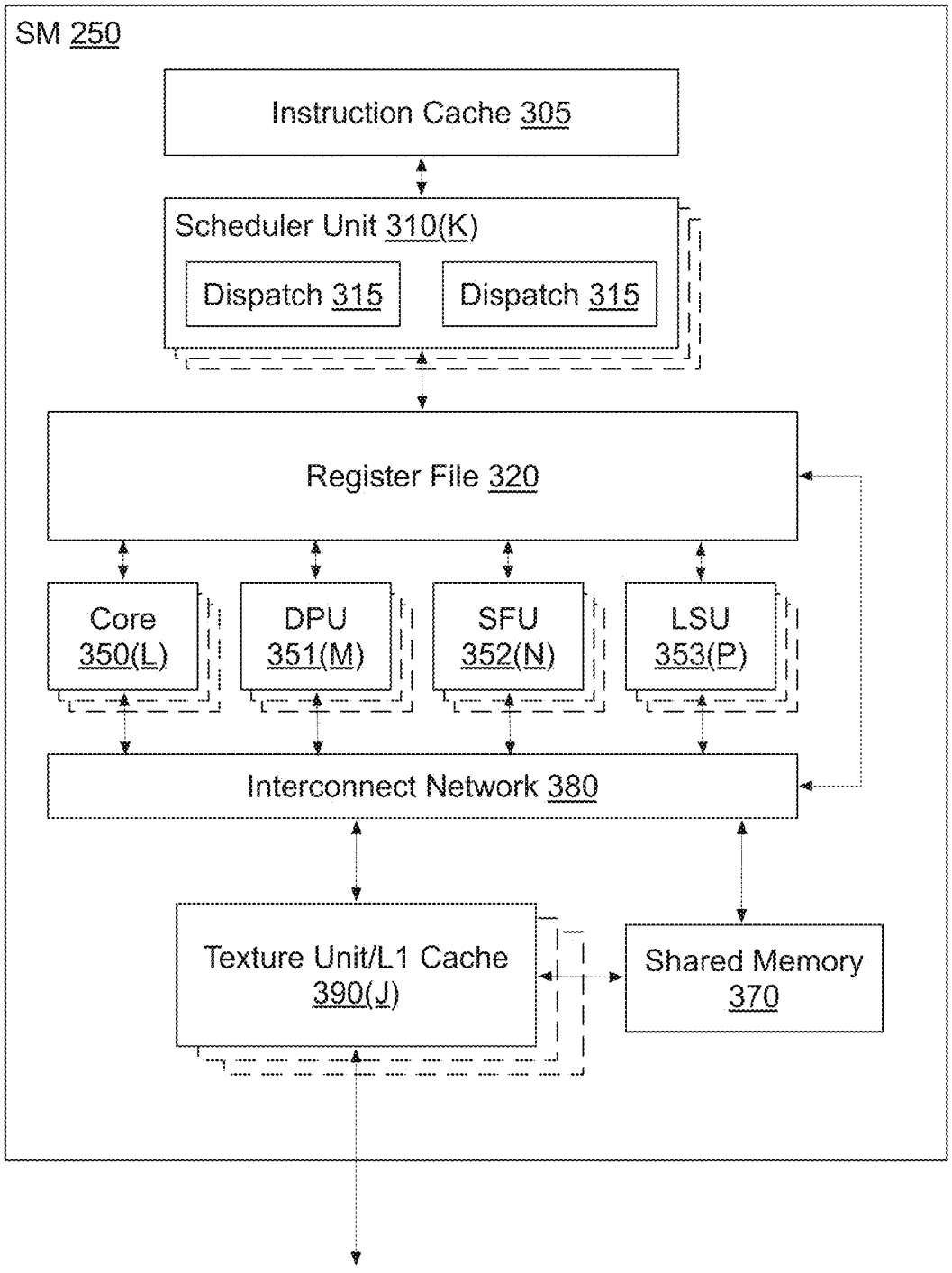
SM 250
Instruction Cache 305
Scheduler Unit 310(K)
Dispatch 315
Dispatch 315
Register File 320
Core 350(L)
DPU 351(M)
SFU 352(N)
LSU 353(P)
Interconnect Network 380
Texture Unit/L1 Cache 390(J)
Shared Memory 370

Fig. 3

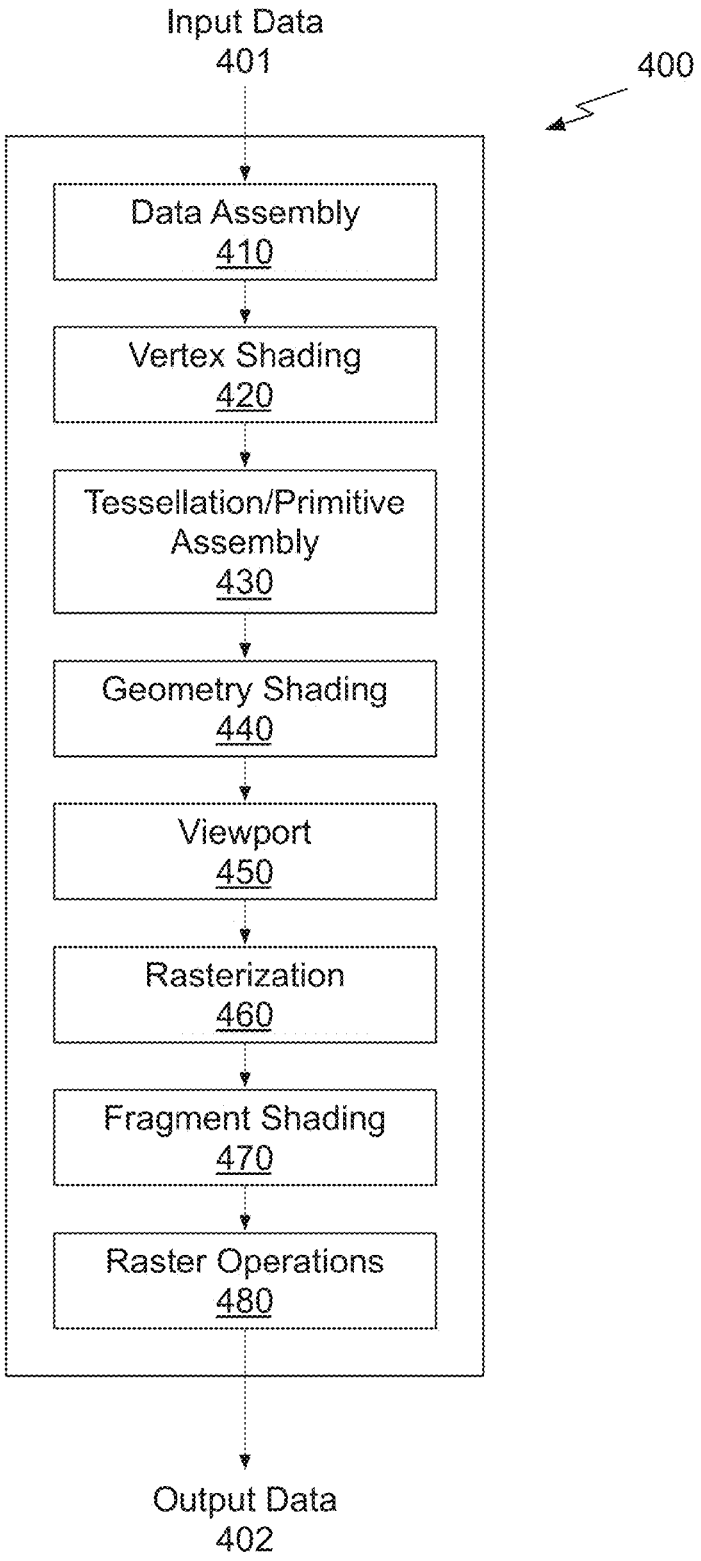
Input Data
401
400
Data Assembly
410
Vertex Shading
420
Tessellation/Primitive Assembly
430
Geometry Shading
440
Viewport
450
Rasterization
460
Fragment Shading
470
Raster Operations
480
Output Data
402

Fig. 4

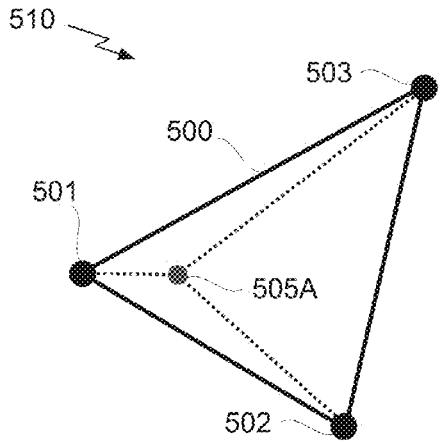

Fig. 5A

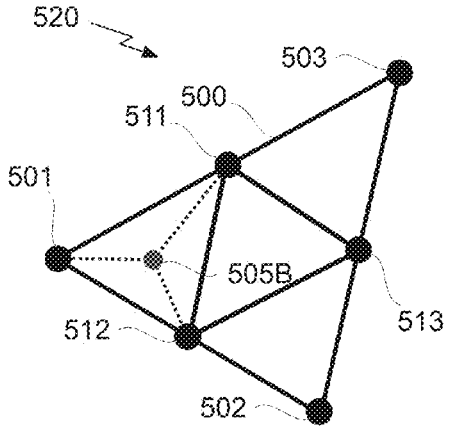

Fig. 5B

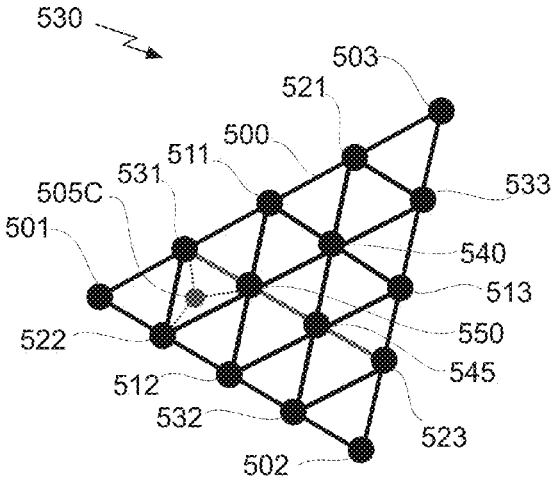

Fig. 5C

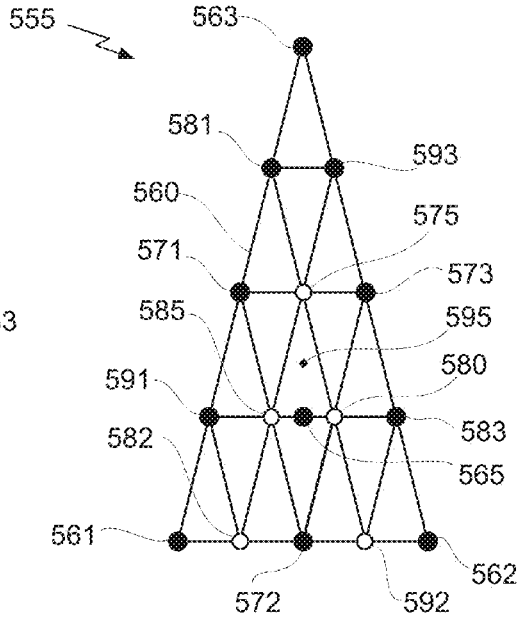

Fig. 5D

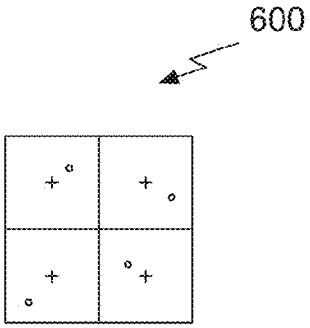

Fig. 6A

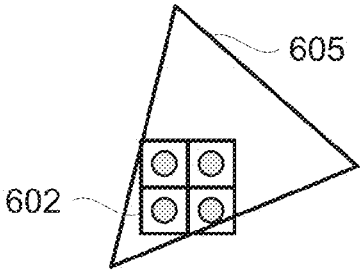

Fig. 6B

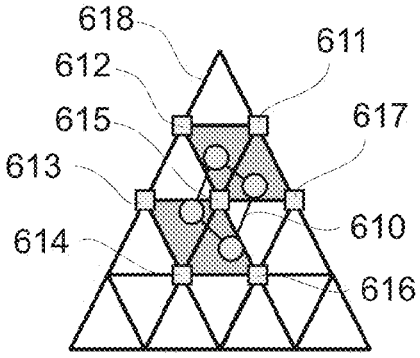

Fig. 6C

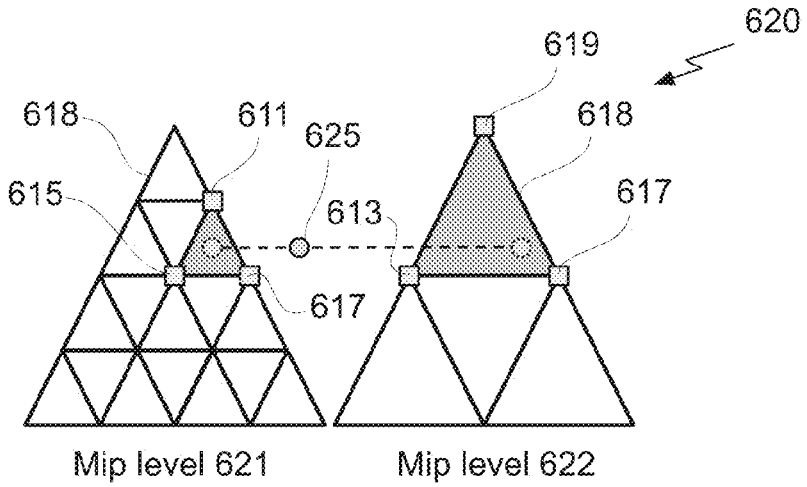

Fig. 6D

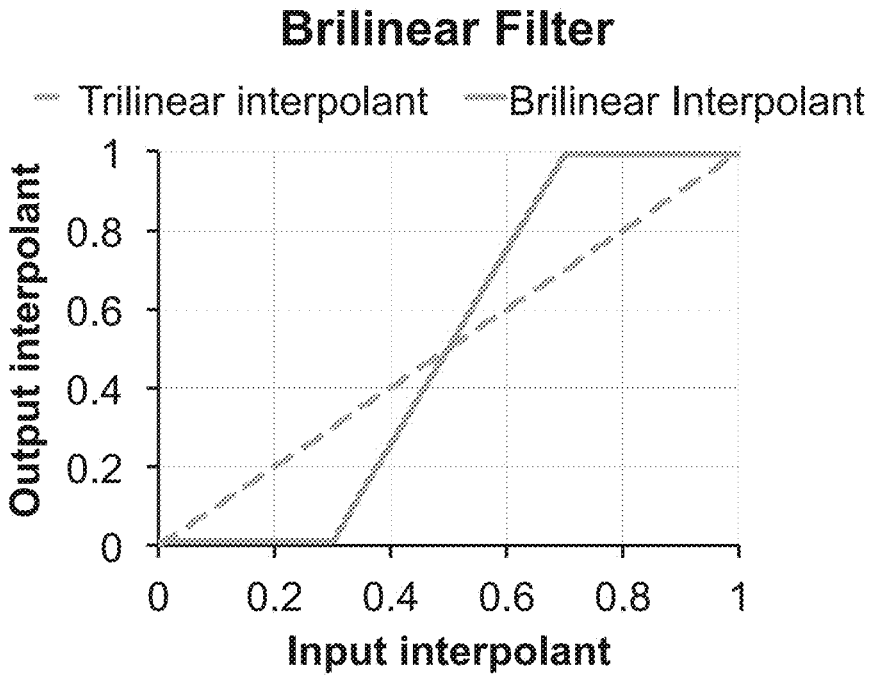
Brilinear Filter
Trilinear interpolant
Brilinear Interpolant
Output interpolant
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
Input interpolant

Fig. 6E

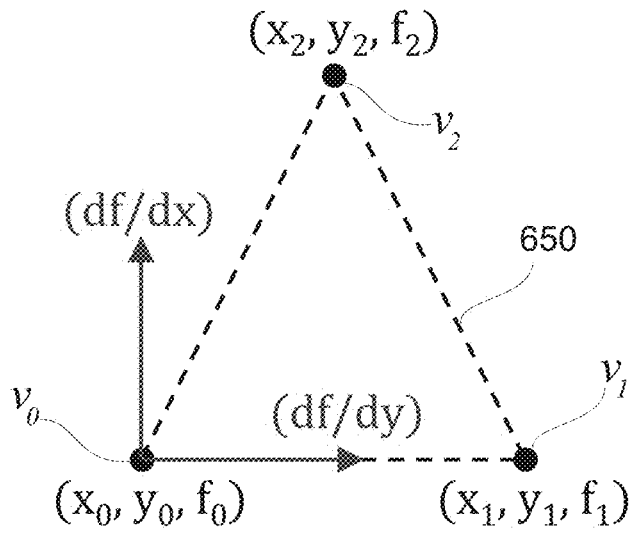
(x_2, y_2, f_2)
v_2
(df/dx)
650
v_0
v_1
(df/dy)
(x_0, y_0, f_0)
(x_1, y_1, f_1)

Fig. 6F

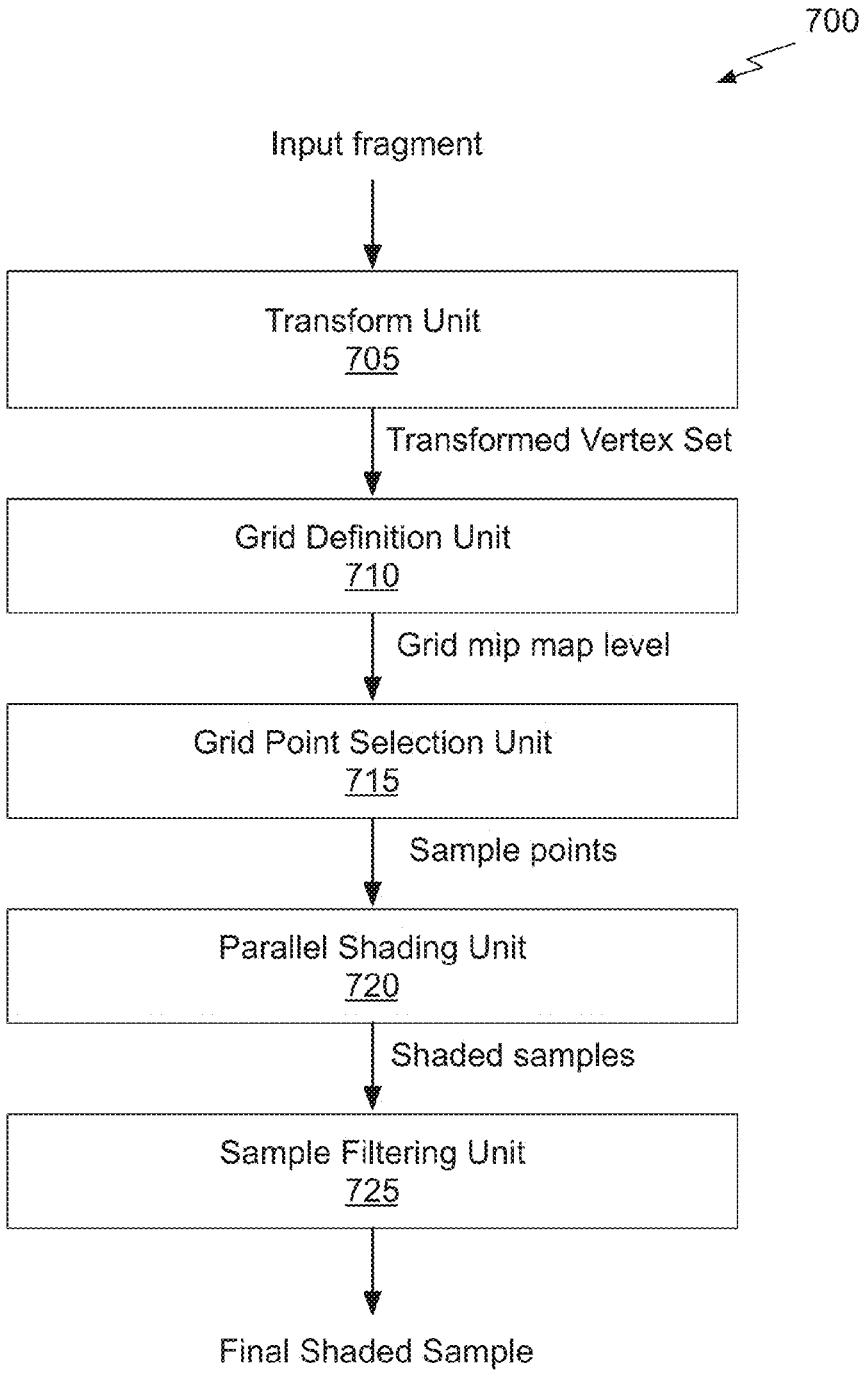
700
Input fragment
Transform Unit
705
Transformed Vertex Set
Grid Definition Unit
710
Grid mip map level
Grid Point Selection Unit
715
Sample points
Parallel Shading Unit
720
Shaded samples
Sample Filtering Unit
725
Final Shaded Sample

Fig. 7A

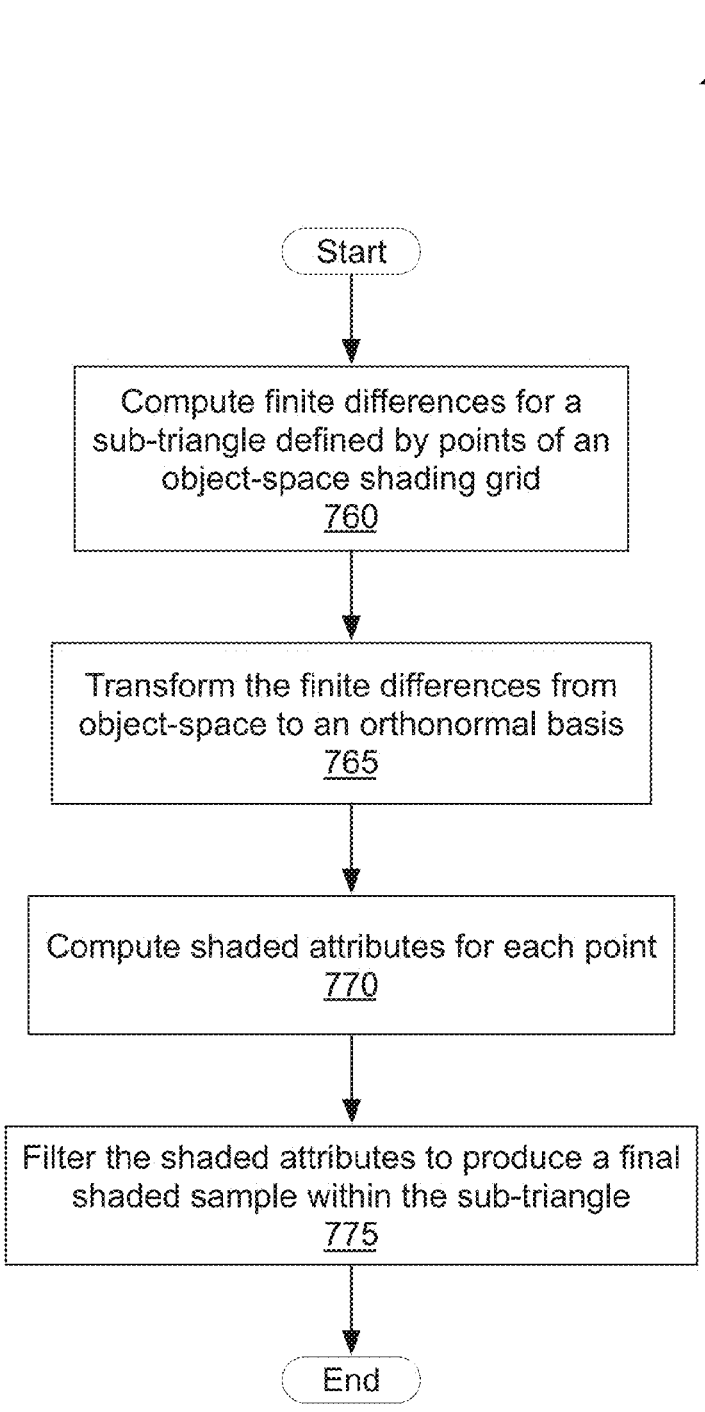
750
Start
Compute finite differences for a sub-triangle defined by points of an object-space shading grid
760
Transform the finite differences from object-space to an orthonormal basis
765
Compute shaded attributes for each point
770
Filter the shaded attributes to produce a final shaded sample within the sub-triangle
775
End

Fig. 7B

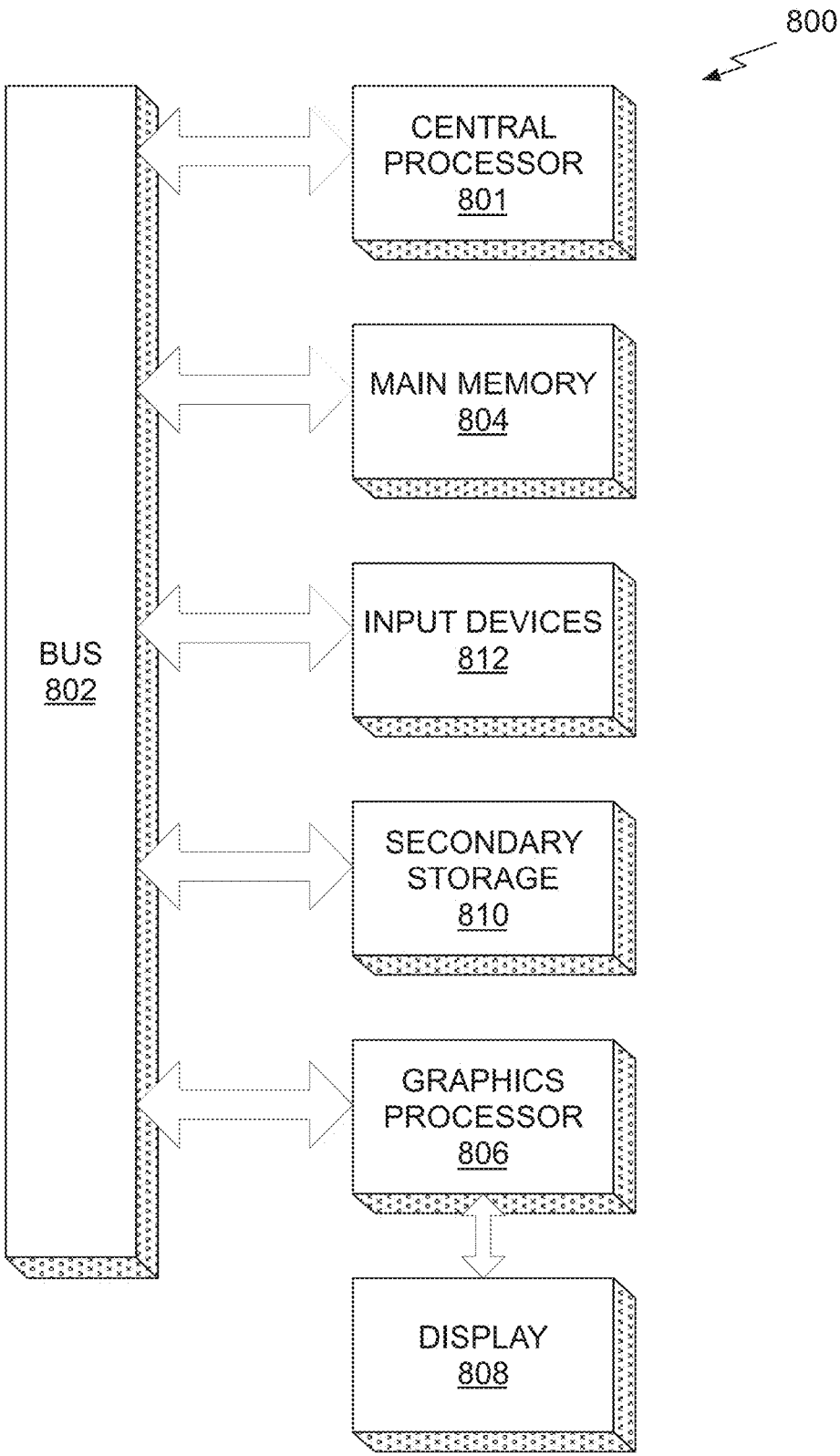
800
CENTRAL PROCESSOR 801
MAIN MEMORY 804
INPUT DEVICES 812
BUS 802
SECONDARY STORAGE 810
GRAPHICS PROCESSOR 806
DISPLAY 808

Fig. 8

SYSTEM, METHOD, AND COMPUTER PROGRAM PRODUCT FOR SHADING USING A DYNAMIC OBJECT-SPACE GRID

CLAIM OF PRIORITY

This application claims the benefit of U.S. Provisional Application No. 62/036,552, titled "Variable-Rate Object-Space Shading With Trilinear Filtering," and filed Aug. 12, 2014, the entire contents of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to graphics processing, and more particularly to shading using a dynamic object-space grid.

BACKGROUND

As the resolution of display devices increases more pixels need to be shaded for each frame. To maintain a high frame rate for high resolution displays, techniques have been developed to avoid unnecessary shading operations. Examples of shading techniques include low-rate screen-space shading, upscaling low-resolution images, and multi-rate screen-space shading.

Low-rate screen-space shading suffers from temporal instability because shading samples are aligned to the screen and not to the object. At low-rates, shading terms may be undersampled and the shaded pixels tend to shimmer and swim or flicker as the camera or object moves. The shimmering and flickering artifacts are especially noticeable on surfaces with specular illumination and high-frequency normal maps. Additionally, evaluating shading terms at rates lower than once per pixel often results in shading at samples lying outside the parent primitive, which may cause visual artifacts in scenes with fine geometric detail.

Upscaling low-resolution images suffers from the problem of having to couple the shading rate with the visibility rate. In other words, the rate at which visibility testing is performed equals the rate at which shading is performed. As a result, lowering the shading rate may also lower the perceived geometric detail in a scene, which is often undesirable.

Multi-rate screen-space shading is a technique that reduces the shading workload by lowering rates for low-frequency parts of the scene. Therefore, the shading rate is scene dependent and not uniform. Multi-rate screen-space shading may not provide a consistently high-performance frame rate. Thus, there is a need for addressing this issue and/or other issues associated with the prior art.

SUMMARY

A system, method, and computer program product are provided for shading using a dynamic object-space grid. The method includes the steps of receiving an object defined by triangle primitives in a three-dimensional (3D) space that is specific to the object and defining an object-space shading grid for a first triangle primitive of the triangle primitives based on coordinates of the first triangle primitive in the 3D space. A shader program is then executed by a processing pipeline to compute a shaded attribute at a point on the object-space shading grid for the first triangle primitive.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates a flowchart of a method for shading using a dynamic object-space grid, in accordance with one embodiment;

FIG. **1**B illustrates a for chart of a method for performing object-space shading, in accordance with one embodiment;

FIG. **2** illustrates a parallel processing unit (PPU), according to one embodiment;

FIG. **3** illustrates the streaming multi-processor of FIG. **2**, according to one embodiment;

FIG. **4** is a conceptual diagram of a graphics processing pipeline implemented by the PPU of FIG. **2**, in accordance with one embodiment;

FIGS. **5**A through **5**C illustrate an object-space mip-mapped shading grid that is defined for a primitive, in accordance with another embodiment;

FIG. **5**D illustrates an object-space shading grid that is defined for a narrow primitive, in accordance with another embodiment;

FIG. **6**A illustrates sample pattern for a pixel, in accordance with one embodiment;

FIG. **6**B illustrates a fragment in screen-space, in accordance with one embodiment;

FIG. **6**C illustrates a footprint of the fragment in object-space, in accordance with one embodiment;

FIG. **6**D illustrates two nearest mip levels of an object-space grid that are used to generate a shaded sample, in accordance with one embodiment;

FIG. **6**E illustrates remapping of interpolants to use one of two nearest mip levels of a mipmapped object-space grid, in accordance with one embodiment;

FIG. **6**F illustrates finite differences on a sub-triangle that are transformed to compute derivatives in an orthonormal basis, in accordance with one embodiment;

FIG. **7**A illustrates a block diagram for identifying points of an object-space grid at which shaded samples will be computed, in accordance with one embodiment;

FIG. **7**B illustrates a flowchart of a method for computing per-sample shaded attributes for pixels, in accordance with one embodiment; and

FIG. **8** illustrates an exemplary system in which the various architecture and/or functionality of the various previous embodiments may be implemented.

DETAILED DESCRIPTION

Shading using a dynamic object-space grid allows a scene to be shaded at varying rates for each object, with a graceful impact to image quality. An object-space shading system provides improved image quality at per-pixel shading rates, and relatively low reduction in quality at lower shading rates. Because the shading is performed in object-space, object shimmering effects are significantly reduced. Additionally, the visibility rate may be decoupled from the shading rate, so that full-rate visibility (i.e., z-testing per sample) may be performed with variable rate shading.

FIG. **1**A illustrates a flowchart of a method **100** for shading using a dynamic object-space grid, in accordance with one embodiment. At step **110**, an object is received. The object is defined by triangle primitives in three-dimensional (3D) space that is specific to the object. In the context of the present description, the local coordinate system enclosed within each triangle primitive may be defined by barycentric coordinates. In the context of the present description, the 3D space that is specific to the object is a temporally-coherent object-space, where the object is defined by one or more

triangle primitives. World-space includes all of the objects in a scene and therefore is capable of illustrating relative positions of the different objects in the scene. In contrast with object-space, camera-space is a view of the objects in the scene as seen from the camera. In other words, camera-space is specific to the camera. Finally, screen-space is a two-dimensional space that is a projection of the scene onto a two-dimensional plane in camera-space.

At step **120**, an object-space shading grid is defined for a first triangle primitive of the triangle primitives based on coordinates of the first triangle primitive in the 3D space. In the context of the present description, barycentric coordinates define the local coordinate system enclosed within the triangle primitives and the barycentric coordinates also define points of the shading grid, so that the shading grid is a triangular shading grid. Barycentric shading grids may apply to legacy content in real-time rendering, and do not require special scene parameterization, object parameterization, and/or primitive parameterization. Therefore, legacy content may be shaded using a barycentric shading grid in one embodiment, an object-space shading grid is defined for individual primitives and the object-space shading grid for a particular primitive is specific to the primitive.

In one embodiment, the object-space shading grid is mipmapped and one or more levels of the mipmapped object-space shading grid are "sampled" according to a shading rate. However, unlike traditional mipmaps, shaded samples for the higher mip levels (i.e., lower resolution mip levels) are not generated by filtering shaded samples for the lower mip levels (i higher resolution mip levels). Instead, shaded samples for each mip level may be computed dynamically for any particular point at any mip level of the object-space shading grid.

At step **130**, a shader program is then executed by a processing pipeline to compute a shaded attribute at a point on the object-space shading grid for the first triangle primitive. Execution of the shader program at a point on the object-space shading grid corresponds to "sampling" the object-space shading grid and produces a shaded attribute. A single point may be sampled or multiple points may be sampled and filtered to produce the shaded attribute. A shaded sample comprises one or more shaded attributes.

In the context of the present description, the processing pipeline may be a graphics processing pipeline that is implemented by a graphics processor or a general purpose processor, either of which is configured to execute instructions of the shader program. In the context of the present description, a shaded attribute may be one or more of color, depth, texture coordinates, and the like. A surface equation corresponding to a graphics primitive such as a triangle may be evaluated at a sample location (i.e., point) on the object-space shading grid to generate an attribute value.

In one embodiment, shading requests are generated in object-space after visibility calculations have been performed. Each screen-space shading location for an object generates one or more shading requests that sample corresponding points of the object-space shading grid. The object-space shading grid is not necessarily recomputed for each frame, even when the camera position changes. Because the shading grid is defined in object-space, the shading grid need only be recomputed when the shape of the object changes in object-space. Additionally, because the shading calculations are performed using shading grids that are each aligned to primitives, the samples always lie within the respective primitive. Consequently, temporally stable images may be produced and shader aliasing artifacts like specular aliasing may be significantly reduced. When the camera position changes, the points on the shading grid that are sampled for a particular screen-space pixel vary based on the camera position relative to the object. In one embodiment, a screen-space pixel footprint is transformed into object-space to identify the points on the object-space shading grid that are sampled.

FIG. **1B** illustrates a flowchart of a method **150** for performing object-space shading, in accordance with one embodiment. At step **160**, an object is received. The object is defined by vertices of one or more primitives in a 3D space that is specific to the object. In the context of the present description, the 3D space that is specific to the object is a temporally-coherent object-space. In one embodiment, the object is defined by one or more triangle primitives.

At step **170**, a shading sample rate is computed for the primitive based on a screen-space derivative of coordinates of a pixel fragment in the 3D space that is specific to the object. In the context of the present description, the screen-space derivative may be computed using object-space coordinates of a pixel footprint that is transformed from screen-space to the 3D space. In one embodiment, a derivative of the object-space coordinates approximating the pixel footprint is computed to determine the shading sample rate. In one example, the pixel footprint may approach the size of the object, encompassing several primitives, so that the shading rate is low and the object nearly fits within the screen-space pixel. In another example, the pixel footprint may be smaller than the size of a single primitive of the object, so that the shading rate is high and the object covers several screen-space pixels.

At step **180**, a shader program is then executed by a processing pipeline to compute shaded attributes for the primitive according to the shading sample rate. In the context of the present description, execution of the shader program at a point on the object-space shading grid corresponds to "sampling" the object-space shading grid and producing shaded attributes. A single point may be sampled or multiple points may be sampled and filtered to produce the shaded attribute. In one embodiment, an object-space shading grid for the object is mipmapped and one or more levels of the mipmapped object-space shading grid are "sampled" according to the shading rate.

More illustrative information will now be set forth regarding various optional architectures and features with which the foregoing framework may or may not be implemented, per the desires of the user. It should be strongly noted that the following information is set forth for illustrative purposes and should not be construed as limiting in any manner. Any of the following features may be optionally incorporated with or without the exclusion of other features described.

The Reyes rendering architecture introduced and popularized the idea of performing shading calculations in object-space, Reyes renderers use adaptive tessellation to generate shading grids before visibility calculations are performed. Generating object-space shading grids using Reyes-style adaptive tessellation is possible for real-time rendering, but it is costly to finely tessellate every primitive and inefficient to shade before performing visibility calculations. In particular, shading before visibility can be extremely inefficient in scenes with a high degree of visibility and occlusion culling. Furthermore, existing real-time 3D content, consists largely of triangular meshes that typically need to be finely tessellated for processing using a Reyes renderer. Therefore, existing real-time 3D content is not typically compatible with a Reyes renderer or existing object-space renderers.

In contrast, as described herein, shading calculations may be performed in object-space after visibility calculations are performed and without requiring tessellation of the 3D content. Furthermore, no additional parameterization of existing real-time 3D content is needed for shading using an object-space shading grid. Therefore, existing real-time 3D content is compatible with the object-space shading grid technique. A mipmapped object-space shading grid allows shading at multiple rates in a stable, decoupled fashion without temporal artifacts, and exposes opportunities to reuse shading calculations within and across primitives within an object.

In one embodiment, post-visibility screen-space shading locations are transformed into per-triangle object-space shading locations, and then quantized to a triangular mip-mapped object-space shading grid of points. A shaded sample may then be computed for one or more of the points. Each screen-space location maps to a filtered combination of multiple object-space points on the object-space shading grid. A surface shader may be invoked at each one of the multiple object-space points to compute shaded samples. Shaded samples that are shared between different screen space locations (i.e., shaded samples computed at points that are shared between different object-space primitives) may be cached to reduce the number of surface shaders that are invoked. The surface shader outputs (i.e., shaded samples) may be filtered to obtain shaded attributes for pixels, such as final pixel colors.

FIG. **2** illustrates a parallel processing unit (PPU) **200**, according to one embodiment. The various architecture and/or functionality of the various previous embodiments may be implemented within the PPU **200**. While a parallel processor is provided herein as an example of the PPU **200**, it should be strongly noted that such processor is set forth for illustrative purposes only, and any processor may be employed to supplement and/or substitute for the same. In one embodiment, the PPU **200** is configured to execute a plurality of threads concurrently in two or more streaming multi-processors (SMs) **250**. A thread (i.e., a thread of execution) is an instantiation of a set of instructions executing within a particular SM **250**. Each SM **250**, described below in more detail in conjunction with FIG. **3**, may include, but is not limited to, one or more processing cores, one or more load/store units (LSUs), a level-one (L1) cache, shared memory, and the like.

In one embodiment, the PPU **200** includes an input/output (I/O) unit **205** configured to transmit and receive communications (i.e., commands, data, etc.) from a central processing unit (CPU) (not shown) over the system bus **202**. The I/O unit **205** may implement a Peripheral Component Interconnect Express (PCIe) interface for communications over a PCIe bus. In alternative embodiments, the I/O unit **205** may implement other types of well-known bus interfaces.

The PPU **200** also includes a host interface unit **210** that decodes the commands and transmits the commands to the grid management unit **215** or other units of the PPU **200** (e.g., memory interface **280**) as the commands may specify. The host interface unit **210** is configured to route communications between and among the various logical units of the PPU **200**.

In one embodiment, a program encoded as a command stream is written to a buffer by the CPU. The buffer is a region in memory, e.g., memory **204** or system memory, that is accessible (i.e., read/write) by both the CPU and the PPU **200**. The CPU writes the command stream to the buffer and then transmits a pointer to the start of the command stream to the PPU **200**. The host interface unit **210** provides the thread block array management unit (MU) **215** with pointers to one or more streams. The MU **215** selects one or more streams and is configured to organize the selected streams as a pool of pending thread block arrays. The pool of pending thread block arrays may include new thread block arrays that have not yet been selected for execution and thread block arrays that have been partially executed and have been suspended.

A work distribution unit **220** that is coupled between the MU **215** and the SMs **250** manages a pool of active thread block arrays, selecting and dispatching active thread block arrays for execution by the SMs **250**. Pending thread block arrays are transferred to the active thread block array pool by the work **215** when a pending thread block array is eligible to execute, i.e., has no unresolved data dependencies. An active thread block array is transferred to the pending pool when execution of the active thread block array is blocked by a dependency. When execution of a thread block array is completed, the thread block array is removed from the active thread block array pool by the work distribution unit **220**. In addition to receiving thread block arrays from the host interface unit **210** and the work distribution unit **220**, the MU **215** also receives thread block arrays that are dynamically generated by the SMs **250** during execution of a thread block array. These dynamically generated thread block arrays join the other pending thread block arrays in the pending thread block array pool.

In one embodiment, the CPU executes a driver kernel that implements an application programming interface (API) that enables one or more applications executing on the CPU to schedule operations for execution on the PPU **200**. An application may include instructions (i.e., API calls) that cause the driver kernel to generate one or more thread block arrays for execution. In one embodiment, the PPU **200** implements a SIMD (Single-Instruction, Multiple-Data) architecture where each thread block (i.e., warp) in a thread block array is concurrently executed on a different data set by different threads in the thread block. The driver kernel defines thread blocks that are comprised of k related threads, such that threads in the same thread block may exchange data through shared memory. In one embodiment, a thread block comprises 32 related threads and a thread block array is an array of one or more thread blocks that execute the same stream and the different thread blocks may exchange data through global memory.

In one embodiment, the PPU **200** comprises X SMs **250**(X). For example, the PPU **200** may include 15 distinct SMs **250**. Each SM **250** is multi-threaded and configured to execute a plurality of threads (e.g., 32 threads) from a particular thread block concurrently. Each of the SMs **250** is connected to a level-two (L2) cache **265** via a crossbar **260** (or other type of interconnect network). The L2 cache **265** is connected to one or more memory interfaces **280**. Memory interfaces **280** implement 16, 32, 64, 128-bit data buses, or the like, for high-speed data transfer. In one embodiment, the PPU **200** comprises U memory interfaces **280**(U), where each memory interface **280**(U) is connected to a corresponding memory device **204**(U). For example, PPU **200** may be connected to up to 6 memory devices **204**, such as graphics double-data-rate, version 5, synchronous dynamic random access memory (GDDR5 SDRAM).

In one embodiment, the PPU **200** implements a multi-level memory hierarchy. The memory **204** is located off-chip in SDRAM coupled to the PPU **200**. Data from the memory **204** may be fetched and stored in the L2 cache **265**, which is located on-chip and is shared between the various SMs **250**. In one embodiment, each of the SMs **250** also imple-

ments an L1 cache. The L1 cache is private memory that is dedicated to a particular SM **250**. Each of the L1 caches is coupled to the shared L2 cache **265**. Data from the L2 cache **265** may be fetched and stored in each of the L1 caches for processing in the functional units of the SMs **250**.

In one embodiment, the PPU **200** comprises a graphics processing unit (GPU). The PPU **200** is configured to receive commands that specify shader programs for processing graphics data. Graphics data may be defined as a set of primitives such as points, lines, triangles, quads, triangle strips, and the like. Typically, a primitive includes data that specifies a number of vertices for the primitive (e.g., in a model-space coordinate system) as well as attributes associated with each vertex of the primitive. Attributes may include one of more of position, color, surface normal vector, texture coordinates, etc. The PPU **200** can be configured to process the graphics primitives to generate a frame buffer (i.e., pixel data for each of the pixels of the display). The driver kernel implements a graphics processing pipeline, such as the graphics processing pipeline defined by the OpenGL API.

An application writes model data for a scene (i.e., a collection of vertices and attributes) to memory. The model data defines each of the objects that may be visible on a display. The application then makes an API call to the driver kernel that requests the model data to be rendered and displayed. The driver kernel reads the model data and writes commands to the buffer to perform one or more operations to process the model data. The commands may encode different shader programs including one or more of a vertex shader, shader, geometry shader, pixel shader, etc. For example, the MU **215** may configure one or more SMs **250** to execute a vertex shader program that processes a number of vertices defined by the model data. In one embodiment, the MU **215** may configure different SMs **250** to execute different shader programs concurrently. For example, first subset of SMs **250** may be configured to execute a vertex shader program while a second subset of SMs **250** may be configured to execute a pixel shader program. The first subset of SMs **250** processes vertex data to produce processed vertex data and writes the processed vertex data to the L2 cache **265** and/or the memory **204**. After the processed vertex data is rasterized (i.e., transformed from three-dimensional data into two-dimensional data in screen space) to produce fragment data, the second subset of SMs **250** executes a pixel shader to produce processed fragment data, which is then blended with other processed fragment data and written to the frame buffer in memory **204**. The vertex shader program and pixel shader program may execute concurrently, processing different data from the same scene in a pipelined fashion until all of the model data for the scene has been rendered to the frame buffer. Then, the contents of the frame buffer are transmitted to a display controller for display on a display device.

The PPU **200** may be included in a desktop computer, a laptop computer, a tablet computer, a smart-phone (e.g., a wireless, hand-held device), personal digital assistant (PDA), digital camera, a hand-held electronic device, and the like. In one embodiment, the PPU **200** is embodied on a single semiconductor substrate. In another embodiment, the PPU **200** is included in a system-on-a-chip (SoC) along with one or more other logic units such as a reduced instruction set computer (RISC) CPU, a memory management unit (MMU), a digital-to-analog converter (DAC), and the like.

In one embodiment, the PPU **200** may be included on a graphics card that includes one or more memory devices **204** such as GDDR5 SDRAM. The graphics card may be configured to interface with a PCIe slot on a motherboard of a desktop computer that includes, e.g., a northbridge chipset and a southbridge chipset. In yet another embodiment, the PPU **200** may be an integrated graphics processing unit (iGPU) included in the chipset (i.e., Northbridge) of the motherboard.

FIG. **3** illustrates the streaming multi-processor **250** of FIG. **2**, according to one embodiment. As shown in FIG. **3**, the SM **250** includes an instruction cache **305**, one or more scheduler units **310**, a register file **320**, one or more processing cores **350**, one or more double precision units (DPUs) **351**, one or more special function units (SFUs) **352**, one or more load/store units (LSUs) **353**, an interconnect network **380**, a shared memory **370**, and one or more texture unit/L1 caches **390**.

As described above, the work distribution unit **220** dispatches active thread block arrays fir execution on one or more SMs **250** of the PPU **200**. The scheduler unit **310** receives the thread block arrays from the work distribution unit **220** and manages instruction scheduling for one or more thread blocks of each active thread block array. The scheduler unit **310** schedules threads for execution in groups of parallel threads, where each group is called a warp. In one embodiment, each warp includes 32 threads. The scheduler unit **310** may manage a plurality of different thread blocks, allocating the thread blocks to warps for execution and then scheduling instructions from the plurality of different warps on the various functional units (i.e., cores **350**, DPUs **351**, SFUs **352**, and LSUs **353**) during each clock cycle.

In one embodiment, each scheduler unit **310** includes one or more instruction dispatch units **315**. Each dispatch unit **315** is configured to transmit instructions to one or more of the functional units. In the embodiment shown in FIG. **3**, the scheduler unit **310** includes two dispatch units **315** that enable two different instructions from the same warp to be dispatched during each clock cycle. In alternative embodiments, each scheduler unit **310** may include a single dispatch unit **315** or additional dispatch units **315**.

Each SM **250** includes a register file **320** that provides a set of registers for the functional units of the SM **250**. In one embodiment, the register file **320** is divided between each of the functional units such that each functional unit is allocated a dedicated portion of the register file **320**. In another embodiment, the register file **320** is divided between the different warps being executed by the SM **250**. The register file **320** provides temporary storage for operands connected to the data paths of the functional units.

Each SM **250** comprises L processing cores **350**. In one embodiment, the SM **250** includes a large number (e.g., 192, etc.) of distinct processing cores **350**. Each core **350** is a fully-pipelined, single-precision processing unit that includes a floating point arithmetic logic unit and an integer arithmetic logic unit. In one embodiment, the floating point arithmetic logic units implement the IEEE 754-2008 standard for floating point arithmetic. Each SM **250** also comprises M DPUs **351** that implement double-precision floating point arithmetic, N SFUs **352** that perform special functions (e.g., copy rectangle, pixel blending operations, and the like), and P LSUs **353** that implement load and store operations between the shared memory **370** and the register file **320** via the J texture unit/L1 caches **390** and the interconnect network **380**. The J texture unit/L1 caches **390** are coupled between the interconnect network **380** and the shared memory **370** and are also coupled to the crossbar **260**. In one embodiment, the SM **250** includes 64 DPUs **351**, 32 SFUs **352**, and 32 LSUs **353**. In another embodiment, the L1 cache is not included within the texture unit and is instead

included with the shared memory **370** with a separate direct connection to the crossbar **260**.

Each SM **250** includes an interconnect network **380** that connects each of the functional units to the register file **320** and to the shared memory **370** through the interconnect network **380**. In one embodiment, the interconnect network **380** is a crossbar that can be configured to connect any of the functional units to any of the registers in the register file **320**, to any of the texture unit/L1 caches **390**, or the memory locations in shared memory **370**.

In one embodiment, the SM **250** is implemented within a GPU. In such an embodiment, the SM **250** comprises J texture unit/L1 caches **390**. The texture unit/L1 caches **390** are configured to access texture maps (i.e., a 2D array of texels) from the memory **204** and sample the texture maps to produce sampled texture values for use in shader programs. The texture unit/L1 caches **390** implement texture operations such as anti-aliasing operations using mipmaps (i.e., texture maps of varying levels of detail). In one embodiment, the SM **250** includes 16 texture unit/L1 caches **390**. As described further herein, the texture unit/L1 caches **390** are also configured to receive load and store requests from the LSUs **353** and to coalesce the texture accesses and the load and store requests to generate coalesced memory operations that are output to a memory system that includes the shared memory **370**. The memory system may also include the L2 cache **265**, memory **204**, and a system memory (not shown).

The PPU **200** described above may be configured to perform highly parallel computations much faster than conventional CPUs. Parallel computing has advantages in graphics processing, data compression, biometrics, stream processing algorithms, and the like.

FIG. **4** is a conceptual diagram of a graphics processing pipeline **400** implemented by the PPU **200** of FIG. **2**, in accordance with one embodiment. The graphics processing pipeline **400** is an abstract flow diagram of the processing steps implemented to generate 2D computer-generated images from 3D geometry data. As is well-known, pipeline architectures may perform long latency operations more efficiently by splitting up the operation into a plurality of stages, where the output of each stage is coupled to the input of the next successive stage. Thus, the graphics processing pipeline **400** receives input data **401** that is transmitted from one stage to the next stage of the graphics processing pipeline **400** to generate output data **402**. In one embodiment, the graphics processing pipeline **400** may represent a graphics processing pipeline defined by the OpenGL® API or by DirectX 11® by MICROSOFT.

As shown in FIG. **4**, the graphics processing pipeline **400** comprises a pipeline architecture that includes a number of stages. The stages include, but are not limited to, a data assembly stage **410**, a vertex shading stage **420**, a tessellation/primitive assembly stage **430**, a geometry shading stage **440**, a viewport transform stage **450**, a rasterization stage **460**, a fragment shading stage **470**, and a raster operations stage **480**. In one embodiment, the input data **401** comprises commands that configure the processing units to implement the stages of the graphics processing pipeline **400** and process high-order geometric primitives (e.g., patches), as well as simpler geometric primitives (e.g., points, lines, triangles, quads, triangle strips or fans, etc.) to be processed by the stages. The output data **402** may comprise pixel data (i.e., color data) that is written into a frame buffer or other type of surface data structure in a memory. The SMs **250** may be configured by shader program instructions to function as one or more shading stages (e.g., vertex, hull, domain, geometry, and pixel shading stages) and write pixel data to the memory **204**.

The data assembly stage **410** receives the input data **401** that specifies vertex data for high-order geometry. The data assembly stage **410** collects the vertex data defining the high-order graphics geometry in a temporary storage or queue, such as by receiving a command from the host processor that includes a pointer to a buffer in memory and reading the vertex data from the buffer. In one embodiment, a memory system may include one or more of the memory **204**, the L2 cache **265**, and the texture unit/L1 cache **390**. The vertex data is then transmitted to the vertex shading stage **420** for processing.

The vertex shading stage **420** processes vertex data by performing a set of operations (i.e., a vertex shader or a program) once for each of the vertices. Vertices may be, e.g., specified as a 4-coordinate vector associated with one or more vertex attributes. The vertex shading stage **420** may manipulate properties such as position, color, texture coordinates, and the like. In other words, the vertex shading stage **420** performs operations on the vertex coordinates or other vertex attributes associated with a vertex. Such operations commonly including lighting operations (i.e., modifying color attributes for a vertex) and transformation operations (i.e., modifying the coordinate space for a vertex). For example, vertices may be specified using coordinates in an object-coordinate space, which are transformed by multiplying the coordinates by a matrix that translates the coordinates from the object-coordinate space into a world space or a normalized-device-coordinate (NCD) space. The vertex shading stage **420** generates transformed vertex data that is transmitted to the tessellation/primitive assembly stage **430**.

The tessellation/primitive assembly stage **430** collects vertices output by the vertex shading stage **420** and tessellates patches represented by the vertices and control points into geometric primitives, in one embodiment, the tessellation/primitive assembly stage **430** groups the vertices into geometric primitives for processing by the geometry shading stage **440**. For example, the tessellation/primitive assembly stage **430** may be configured to group every three consecutive vertices as a geometric primitive (i.e., a triangle) for transmission to the geometry shading stage **440**. In some embodiments, specific vertices may be reused for consecutive geometric primitives (e.g., two consecutive triangles in a triangle strip may share two vertices). The primitive assembly stage **430** transmits geometric primitives (i.e., a collection of associated vertices) to the geometry shading stage **440**.

The geometry shading stage **440** processes geometric primitives by performing a set of operations (i.e., a geometry shader or program) on the geometric primitives. Geometry shading operations may generate one or more geometric primitives from each geometric primitive. In other words, the geometry shading stage **440** may subdivide each geometric primitive into a finer mesh of two or more geometric primitives for processing by the rest of the graphics processing pipeline **400**. The geometry shading stage **440** transmits geometric primitives to the viewport stage **450**.

The viewport stage **450** performs a viewport transform, culling, and clipping of the geometric primitives. Each surface being rendered to is associated with an abstract camera position. The camera position represents a location of a viewer looking at the scene and defines a viewing frustum that encloses the objects of the scene. The viewing frustum may include a viewing plane, a rear plane, and four clipping planes. Any geometric primitive entirely outside of

the viewing frustum may be culled (i.e., discarded) because the geometric primitive will not contribute to the final rendered scene. Any geometric primitive that is partially inside the viewing frustum and partially outside the viewing frustum may be clipped (i.e., transformed into a new geometric primitive that is enclosed within the viewing frustum. Furthermore, geometric primitives may each be scaled based on depth of the viewing frustum. All potentially visible geometric primitives are then transmitted to the rasterization stage **460**.

The rasterization stage **460** converts the 3D geometric primitives into 2D fragments. The rasterization stage **460** may be configured to utilize the vertices of the geometric primitives to setup a set of surface equations from which various attributes can be interpolated. In one embodiment, the surface equations are plane equations in the form Ax+By+C, where x and y are sample locations and A, B, and C are plane equation parameters. In other embodiments, a surface equation specifies a high-order surface such as a patch. The rasterization stage **460** may also compute a coverage mask for a plurality of pixels that indicates whether one or more screen-space sample locations for the plurality of pixels intersect the geometric primitive.

The rasterization stage **460** may be configured to perform early z-testing based on per-vertex depth values to remove geometric primitives that will not be visible. Early z-testing avoids processing pixels for a graphics primitive that is behind, and therefore, occluded by another graphics primitive. Early z-testing is performed before shading operations, to avoid the expense of performing shading operations that will not contribute to the final color values of pixels in the image. The shading operations produce shaded fragments representing color data for the graphics primitives that cover at least one sample of a pixel and survived the early z testing. After the shading operations, comprehensive z-testing may be performed to remove shaded fragments that are occluded and therefore not visible in the image, so that color data for the non-visible shaded fragments are not written to a pixel of the image. The rasterization stage **460** transmits fragment data including the coverage masks and interpolated per-vertex attributes to the fragment shading stage **470**.

The fragment shading stage **470** processes fragment data by performing a set of operations i.e., a fragment shader or a program) on each of the fragments. The fragment shading stage **470** may generate shaded fragment data (i.e., shaded attributes such as color values) for the fragment such as by performing lighting operations or sampling texture maps using interpolated texture coordinates for the fragment. The shaded fragment data may be per-sample shaded attributes where one or more samples within a pixel share the same computed shaded attribute value or where a shaded attribute value is computed for each sample location within a pixel. The fragment shading stage **470** generates per-sample shaded fragment data that is transmitted to the raster operations stage **480**. The fragment shading stage **470** is described in further detail in conjunction with FIGS. **5**A-E, **6**A-F, **7**A, and **7**B.

The raster operations stage **480** may perform various operations on the shaded fragment data such as performing alpha tests, Z-test, stencil tests, and blending the shaded fragment data with other pixel data corresponding to other fragments associated with the pixel. When the raster operations stage **480** has finished processing the shaded fragment data to produce pixel data (i.e., the output data **402**), the pixel data may be written to a display surface (i.e., render target such as a frame buffer, a color buffer, Z-buffer, or the like). The raster operations stage **480** may perform per-sample z-testing so that visible fragment data is written to the frame buffer and obscured fragment data is not written to the frame buffer.

It will be appreciated that one or more additional stages may be included in the graphics processing pipeline **400** in addition to or in lieu of one or more of the stages described above. Various implementations of the abstract graphics processing pipeline may implement different stages. Furthermore, one or more of the stages described above may be excluded from the graphics processing pipeline in some embodiments (such as the geometry shading stage **440**). Other types of graphics processing pipelines are contemplated as being within the scope of the present disclosure. Furthermore, any of the stages of the graphics processing pipeline **400** may be implemented by one or more dedicated hardware units within a graphics processor such as PPU **200**. Other stages of the graphics processing pipeline **400** may be implemented by programmable hardware units such as the SM **250** of the PPU **200**.

The Dynamic Object-Space Grid

As previously explained in conjunction with FIG. **1**A, an object-space shading grid is defined for the object based on coordinates of triangle primitives in the object-space. In the context of the present description, barycentric coordinates may define the local coordinate system enclosed within triangle primitives and the barycentric coordinates may also define points of the shading grid, so that the shading grid is a triangular shading grid.

FIGS. **5**A-**5**C illustrate a mipmapped object-space shading grid that is defined for a primitive **500**, in accordance with another embodiment. FIG. **5**A illustrates a mip level **510** of the mipmapped object-space shading grid that is defined for a primitive **500**, in accordance with another embodiment. The triangular primitive **500** is defined by the vertices **501**, **502**, and **503** and the mip level **510** of the mipmapped object-space shading grid is the coarsest mip level. In contrast with a conventional mipmapped texture map, in one embodiment only vertex positions define each level of the shading grid. In other words, no attribute data, such as color is associated with the vertices. The mipmapped object-space shading grid is a framework of points at which attributes may be computed rather than an array of texel or attribute values. In one embodiment, points of the mipmapped object-space shading grid are not stored and are instead generated from the primitives defining objects as needed to compute shaded samples. In such an embodiment, the mipmapped object-space shading grid is a procedural object-space shading grid.

In one embodiment, each of the vertices **501**, **502**, and **503** is associated with a set of barycentric coordinates. Each of the vertices **501**, **502**, and **503** is also a point (i.e., intersection) in the object-space shading grid that is defined for the primitive **500**. The object-space shading grid may be used to compute a shaded sample at the sample location **505**A. In one embodiment, shaded values are computed for the grid points at vertices **501**, **502**, and **503** and interpolation is used to compute the shaded sample at the sample location **505**A. In one embodiment, barycentric interpolation is used to compute the shaded sample at the sample location **505**A. The sample location **505**A corresponds to a sample location in screen space that has been transformed into the object-space specific to the primitive **500**. The object-space shading grid is "sampled" according to a shading rate that is computed based on a specified shading rate (i.e., the number of samples specified for each screen-space pixel) and screen-

space derivatives of the Object-space coordinates of the input fragment. Unlike the specified shading rate, the computed shading rate may vary within each parent primitive and is therefore a dynamic shading rate. The primitive **500** is a "parent" primitive that may be divided into sub-primitives (e.g., triangles) as shown in FIGS. **5**B and **5**C. The computed shading rate for a sub-primitive that comprises two or more sub-primitives may also vary within the sub-primitive. Importantly, the computed shading rate may also differ from the visibility rate. The visibility rate is the number of samples for which z-tests are performed during early and/or late z-testing. In one embodiment, the visibility rate and the specified shading rate may each be fixed and the computed shading rate may vary so that the computed shading rate for a first set of primitives is greater than the visibility rate for the first set of primitives and the computed shading rate for a second set of primitives may be less than or equal to the visibility rate for the second set of primitives.

In one embodiment, the object-space shading grid is mipmapped and one or more levels of the mipmapped object-space shading grid are sampled according to the computed shading rate. In traditional mipmapping, texels at coarse levels of the mipmap are computed by recursively filtering the texels at finer levels. Consequently, the texel(s) at the coarsest mip level depend on all texels at the finest level and are not known until the finest level texel values are available. While possible, it is impractical to use the same technique for computing shaded values for the grid points of a mipmapped shading grid. Rather than pre-computing the shaded values for each point of a mipmapped shading grid, the shaded values are computed as needed (i.e., dynamically) to generate a shaded sample. Similarly, the points of the mipmapped shading grid are deterministic and may also be defined dynamically.

FIG. **5**B illustrates another mip level **520** of the object-space mipmapped shading grid that is defined for the primitive **500**, in accordance with another embodiment. In one embodiment, the sub-triangles are substantially equal in area. Additional vertices **511**, **512**, and **513** are determined in the mip level **520** of the object-space shading grid to define four sub-triangles. Each of the vertices **501**, **502**, **503**, **511**, **512**, and **513** is also a point (i.e., intersection) in the mipmapped object-space shading grid that is defined for the primitive **500**. In one embodiment, shaded values are computed for the grid points at vertices **501**, **511**, and **512** and interpolation (e.g. barycentric interpolation) is used to compute the shaded sample at the sample location **505**B. The sample location **505**B is substantially coincident with the sample location **505**A relative to the vertices **501**, **502**, and **503**. In one embodiment, a first shaded sample is computed at the sample location **505**B using the mip level **520** and a second shaded sample is computed at the sample location **505**A using the mip level **510**. The first and second shaded samples are then interpolated to compute the final shaded sample at the sample location **505**B.

FIG. **5**C illustrates yet another mip level **530** of the object-space mipmapped shading grid that is defined for the primitive **500**, in accordance with another embodiment. Additional vertices **521**, **522**, **523**, **531**, **532**, **533**, **540**, **545**, and **550** are determined in the mip level **530** of the object-space shading grid. Each of the vertices **521**, **522**, **523**, **531**, **532**, **533**, **540**, **545**, and **550** is also a point (i.e., intersection) in the mipmapped object-space shading grid that is defined for the primitive **500**. In one embodiment, shaded values are computed for the grid points at vertices **522**, **531**, and **550** and interpolation is used to compute the shaded sample at the sample location **505**C. The sample location **505**C is substantially coincident with the sample locations **505**A and **505**B relative to the vertices **501**, **502**, and **503**. In one embodiment, a first shaded sample is computed at the sample location **505**C using the mip level **530** and a second shaded sample is computed at the sample location **505**B using the mip level **520**. The first and second shaded values are then interpolated to compute the final shaded sample at the sample location **505**C.

In one embodiment, FIGS. **5**A-**5**C illustrate three levels of barycentric subdivision for the primitive **500** and the object-space shading grid is a barycentric shading grid. At the coarsest level shown in FIG. **5**A, shaded values are computed for the grid points that are coincident with the three vertices **501**, **502**, and **503** of the parent primitive **500**. To obtain each subsequent higher-resolution level, the previous level is subdivided into substantially congruent sub-triangles. In contrast, the generation of a mipmapped texture map processes (e.g. filters) the highest resolution texture map to produce each subsequent lower-resolution level. As shown in FIGS. **5**A, **5**B, and **5**C, binary subdivision is used to subdivide each triangle at a level into 4 sub-triangles at a finer level. It is not necessary for barycentric shading grids to employ binary subdivision, so other sub-division schemes may be used. For example, in another embodiment, each triangle is subdivided into 9 sub-triangles at a finer level.

In contrast with a texture map, a barycentric shading grid for a primitive is fully contained within the domain of the triangle primitive, whereas texture maps often span multiple triangles. A barycentric shading grid is defined using barycentric coordinates of the parent primitive, so a barycentric shading grid does not require an external parameterization. In contrast, texture maps rely on parameterization using texture coordinates.

FIG. **5**D illustrates an object-space shading grid **555** that is defined for a narrow primitive **560**, in accordance with another embodiment. Vertices **561**, **562**, and **563** define the primitive **560** and are points in the mipmapped object-space shading grid that is defined for the primitive **560**. Additional vertices **565**, **571**, **581**, **591**, **572**, **582**, **592**, **573**, **583**, **593**, **575**, **580**, **585**, **582**, and **592** are determined in the object-space shading grid **555**. Each of the vertices **565**, **571**, **581**, **591**, **572**, **582**, **592**, **573**, **583**, **593**, **575**, **580**, **585**, **582**, and **592** is also a point (i.e., intersection) in the object-space shading grid **555** that is defined for the primitive **560**.

Use of the object-space shading grid **555** differs compared with the mipmapped object-space grid shown in FIGS. **5**A, **5**B, and **5**C because shaded values are not computed at the "virtual" points **575**, **580**, **585**, **582**, and **592**. Instead, when a shaded value is needed at one of the virtual points **575**, **580**, **585**, **582**, and **592**, shaded values are computed at neighboring points and interpolated to compute a shaded value at the respective virtual point. In one embodiment, linear interpolation is used to compute a shaded value at one or more of the virtual points **575**, **580**, **585**, **582**, and **592**. For example, a shaded value at the virtual point **585** may be computed by interpolating shaded values computed at the points **591** and **565**. Similarly, a shaded value at the virtual point **575** may be computed by interpolating shaded values computed at the points **571** and **573**. A shaded value at the sample location **595** may be computed by interpolating shaded values computed at virtual points **575**, **585**, and **580**.

Referring back to FIGS. **5**A, **5**B, and **5**C, the sample locations **505**A, **505**B, and **505**C, respectively within the object-space shading grid is used to interpolate the shaded values at the points on the object-space shading grid. When a mipmapped object-space shading grid is used, it is also necessary to determine which level(s) of the mipmapped

object-space shading grid are sampled. In one embodiment, the computed shading rate is used to determine one or more levels of the mipmapped object-space shading grid that are sampled.

Sampling the Object-Space Shading Grid

Following rasterization, the input that is received for shading is a screen-space pixel fragment. When a square shaped pixel is completely covered by a primitive of an object, the pixel fragment is square shaped. When a square shaped pixel is partially covered by a primitive of an object, the pixel fragment may be polygon shaped. The input fragment is transformed from screen-space into object-space to produce a footprint of the input fragment in object-space. Based on the specified shading rate for the input fragment (e.g., samples per pixel), the mip level of the object-space shading grid is identified that best approximates the footprint. In one embodiment, screen-space derivatives of the object-space barycentric coordinates of the input pixel fragment are used to estimate the size of a sub-triangle whose area and sample count approximates the specified shading rate. In other words, screen-space derivatives of the pixel fragment footprint's barycentric coordinates in object-space are used to calculate the computed shading rate.

FIG. **6**A illustrates sample pattern for a pixel **600**, in accordance with one embodiment. In one embodiment, the sample pattern for the pixel **600** comprises four sub-pixel samples located at the center of each quadrant (shown as cross-hairs in FIG. **6**A). In another embodiment, the sample pattern for the pixel **600** may be jittered (i.e., randomly distributed throughout the pixel) in order to alleviate the aliasing artifacts. As shown in FIG. **6**A, the jittered sample locations for each pixel may be shown by the small circles offset from each quadrant's center.

FIG. **6**B illustrates a pixel fragment **602** in screen-space, in accordance with one embodiment. In one embodiment, the pixel fragment **602** comprises a single pixel, such as the pixel **600** with four sub-pixel sample locations (shown as circles). In another embodiment, the pixel fragment **602** comprises four pixels, each with one sub-pixel sample location. The pixel fragment **602** is a portion of the primitive **605** that has passed visibility testing (i.e., early z testing).

FIG. **6**C illustrates a footprint **610** of the pixel fragment **602** in object-space, in accordance with one embodiment. The input pixel fragment **602** is transformed from screen-space to produce the footprint **610** in object-space. In one embodiment, the footprint **610** is defined by barycentric coordinates.

The primitive **605** is shown in object-space as primitive **618**. The object-space shading grid that is defined for primitive **618** comprises sixteen sub-triangles. In one embodiment, the object-space shading grid shown in FIG. **6**C is one level of a mipmapped object-space shading grid for the primitive **618**. To shade the four sample locations of the footprint **610**, shaded values should be computed for points **611**, **612**, **613**, **61.4**, **615**, **616**, and **617** of the object-space shading grid. In one embodiment, each of the points **611**, **612**, **613**, **614**, **615**, **616**, and **617** is defined by barycentric coordinates. As shown in FIG. **6**C, the shaded values computed at points **611**, and **614** are shared between two of the shaded sample locations defining the footprint **610** and the shaded value computed at point **615** is shared between all four of the shaded sample locations defining the footprint **610**. The reuse of shaded values helps to amortize the shading computations over multiple shading requests.

Optimistically assuming that each shaded value will typically be shared between 6 sub-triangles, the sample count for each sub-triangle may be set to ½. Given the specified screen-space shading rate of R shading samples per pixel, N is computed, where N is the approximate number of per-edge subdivisions such that the area of the enclosing sub-triangle Δ_N is approximately

$$\Delta_N = \frac{1}{2 \cdot R}$$

Therefore, N identifies the mip level of the mipmapped object-space shading grid that should be used to compute the shaded samples for a footprint.

The two nearest powers of 2 to N may be used identify two mip levels of the object-space shading grid. A linear interpolant between the two mip levels may be determined that corresponds to the footprint of the input pixel fragment. In one embodiment, N may be computed using derivatives of the coordinates of the pixel fragment footprint in object-space. The derivatives of the object-space barycentric coordinates of a pixel fragment F provide an estimate of the rate of change of the extent of a parent triangle primitive T in the pixel fragment's neighborhood. For example, derivatives of the Object-space barycentric coordinates of the footprint **610** may be used to estimate the rate of change of the extent of primitive **605** in object-space. Consider virtual triangle T_d with identical derivatives at F, but uniform derivatives across T_d. If $\{d\alpha, d\beta, d\gamma\}$ represent the barycentric derivatives, $\{h_A, h_B, h_C\}$ as defined below represent the three altitudes of T_d measured in pixels.

$$\{d\alpha, d\beta, d\gamma\} = \left\{\left(\frac{d\alpha}{dx}, \frac{d\alpha}{dy}\right), \left(\frac{d\beta}{dx}, \frac{d\beta}{dy}\right), \left(\frac{d\gamma}{dx}, \frac{d\gamma}{dy}\right)\right\}$$

$$\{h_A, h_B, h_C\} = \left\{\frac{1}{|d\alpha|}, \frac{1}{|d\beta|}, \frac{1}{|d\gamma|}\right\}$$

The altitudes of T_d may be used to estimate the area of T_d in pixels Δ_d:

$$\Delta_d = \frac{1}{\sqrt{\left(\frac{1}{h_A} + \frac{1}{h_B} + \frac{1}{h_C}\right)}} \cdot \frac{1}{\sqrt{\left(-\frac{1}{h_A} + \frac{1}{h_B} + \frac{1}{h_C}\right)}} \cdot \frac{1}{\sqrt{\left(\frac{1}{h_A} - \frac{1}{h_B} + \frac{1}{h_C}\right)}} \cdot \frac{1}{\sqrt{\left(\frac{1}{h_A} + \frac{1}{h_B} - \frac{1}{h_C}\right)}} = \frac{1}{\sqrt{(|d\alpha| + |d\beta| + |d\gamma|)}} \cdot \frac{1}{\sqrt{(-|d\alpha| + |d\beta| + |d\gamma|)}} \cdot \frac{1}{\sqrt{(|d\alpha| - |d\beta| + |d\gamma|)}} \cdot \frac{1}{\sqrt{(|d\alpha| + |d\beta| - |d\gamma|)}}$$

Δ_d may be used to estimate the area of a sub-triangle after N_d per-edge subdivisions $\Delta_{N,d}$ and substitute its relation with specified shading rate R:

$$\Delta_{N,d} = \frac{\Delta_d}{N_d^2} = \frac{1}{2 \cdot R}$$

Thus, Δ_d and R, N_d may be estimated as:

$$N_d = \sqrt{2 \cdot \Delta_d \cdot R}$$

N_d obtained above is not necessarily consistent across the shared edge between triangles and inconsistencies can produce visual seams along triangle edges. To avoid seam artifacts, an edge-consistent level of subdivision may be blended near triangle edges. In one embodiment, a precomputed per-vertex average incident area is interpolated at the fragment F:

$$\Delta_{avg} = \alpha \cdot \Delta_{avg}^{0} + \beta \cdot \Delta_{avg}^{1} + \gamma_{avg}^{2}$$

Dividing Δ_{avg} by T's world-space area Δ_{ws} provides an edge-consistent Δ_c and corresponding N_d near triangle edges. A dynamic blend factor may be used such that the size of the blend region P_{blend} can be specified in pixels.

$$\Delta_c = \Delta_d \cdot \frac{\Delta_{avg}}{\Delta_{ws}}$$

$$N_c = \sqrt{2 \cdot \Delta_c \cdot R}$$

$$f_{smooth} = LinearStep\left(0.0 \frac{P_{blend}}{N_d}, \min(\alpha, \beta, \gamma)\right)$$

$$N = (1 - f_{smooth}) \cdot N_c + f_{smooth} \cdot N_d$$

In addition to identifying the two nearest mipmap levels of the object-space shading grid using N, the sub-triangles that enclose the barycentric coordinates defining the pixel fragment footprint in object-space need to be identified to compute the shaded values and the shaded samples.

FIG. **6**D illustrates two nearest mip levels of a mipmapped object-space grid **620** that are used to generate a shaded sample for the sample location, in accordance with one embodiment. Based on the value of N that is calculated for the primitive **605**, the mip levels **621** and **622** of the object-space shading grid are identified and a linear interpolant is determined. The sample location **625** lies within a first sub-triangle defined by points **611**, **615**, and **617** and within a second sub-triangle defined by points **619**, **617**, and **613**.

Given a discretized mip level N, the enclosing sub-triangle for the fragment F:

$$\{k_\alpha, k_\beta, k_\gamma\} = \{\lfloor \alpha \cdot N \rfloor, \lfloor \beta \cdot N \rfloor, \lfloor \gamma \cdot N \rfloor\},$$

$\{k_\alpha, k_\beta, k_\gamma\}$ uniquely identifies a sub-triangle. If $(k_\alpha + k_\beta + k_\gamma)$ is even, it represents an inverted sub-triangle (facing against the parent triangle), otherwise the sub-triangle aligns the parent triangle.

The barycentric coordinates within the enclosing sub-triangle $\{\alpha_N, \beta_N, \gamma_N\}$ may also be obtained using the expression for α_N:

$$\alpha_N = \begin{cases} 1 + \lfloor \alpha \cdot N \rfloor - (\alpha \cdot N), & \text{if inverted sub-triangle} \\ (\alpha \cdot N) - \lfloor \alpha \cdot N \rfloor, & \text{otherwise} \end{cases}$$

FIG. **6**E illustrates remapping of linear interpolants to use one of two nearest mip levels of a mipmapped object-space grid, in accordance with one embodiment. As previously explained, a linear interpolant between the two closest mip levels may be determined that corresponds to the footprint of the input pixel fragment. In one embodiment, when the linear interpolant is close to 0 or 1, the linear interpolant is remapped so that only one of the two mip levels is used, reducing the number of shaded values and shaded samples that are computed. For example, referring to FIG. **6**D, the shaded sample for the sample location **625** may be computed by interpolating the shaded values computed for either points **611**, **615**, and **617** or points **613**, **617**, and **619**. As shown in FIG. **6**E, when the linear interpolant is 0.0-0.3, only points of the coarser mip level are used (e.g., mip level **622**) and when the linear interpolant is 0.7-1.0 only points of the finer mip level are used (e.g., mip level **621**).

After the points in the grid that are needed to compute the shaded sample are identified, shader invocations are launched at each point. In one embodiment, shaded values computed at the points of the object-space grid are stored in a cache or memory, so that shaded values that have already been computed are not recomputed. In one embodiment, requests from several fragments may be aggregated, duplicates may be identified and removed, and shader evaluations may then be launched for execution in a data-parallel fashion.

When the specified shading rate is lower than the rate of visibility, the footprint of nearby pixel fragments generally have a significant overlap. To avoid redundant shader evaluations for the overlapping points on the Object-space grid, the output of shader evaluation should be reused. When the footprint of a pixel fragment has been computed, the output may be checked to determine if any of the requested shaded values is either already computed or currently being computed. For such shaded values, shader evaluations are not launched and instead the already available output is used or the output of a current evaluation is used when the evaluation is finished. In one embodiment, reuse is achieved using a cache that contains previously computed shaded values and also identifies requests that are incomplete.

The shaded values that are output may also be shared between primitives (parent primitives and/or sub-triangles. In one embodiment, whenever two primitives share an edge or a vertex, the points of the object-space grids for the two primitives that lie on the shared edge/vertex are co-located. If a surface shader is driven by per-vertex attributes, shader inputs at the shared points are also identical. In such a scenario, the shaded values for the shared points may be reused between multiple (primitives. Cross-primitive reuse is especially beneficial for scenes with small triangles, where the proportion of shading samples lying on edges or vertices is high. In one embodiment, for extremely dense meshes, vertex shading may be used.

Object-Space Shading

When the object-space shading grid is a barycentric grid, the points that are shaded always belong to the same base triangle. As a consequence, evaluating attributes at a point can be accomplished by barycentric interpolation of the primitive vertex attributes. Shaders often utilize derivatives to estimate the extent of the current shading element (e.g., pixel, pixel group), which is useful in appropriately filtering to produce intermediate attribute values. Screen-space shading systems, such as modern GPUs, typically compute attribute derivatives using finite differences across 2×2 pixel quad shading elements. In contrast, object-space shading systems typically obtain derivatives based on the size of the object-space shading element, e.g. sub-triangle. However, actual sizes of object-space shading elements do not usually match the specified shading rate perfectly, which can result in discontinuous derivatives. Additionally, the shapes of a

pixel and a pixel quad in screen space (square or rectangular) may be quite different compared with the shape of an object-space shading element (triangular) which can result in derivative mismatches. Consequently, in one embodiment, the Object-space derivatives are adjusted to account for the specified shading rate. Derivatives adjusted in this manner are also known as smooth derivatives.

For shading using barycentric shading grids, derivatives may be computed using finite differences across sub-triangles in the shading grid. When finite differences are used, derivative operations on arbitrary functions may be performed, including dependent functions like texture fetches. In one embodiment, shaded samples are computed for points in groups of 3 or 4 to ensure that finite differences are available to compute the derivatives. When finite differences are computed for pixel quads, the finite differences belong to an orthonormal basis. In contrast, finite differences computed fir a group of points of a barycentric shading grid do not belong to an orthonormal basis. As a result, the derivatives are recalculated on an orthonormal basis before the shaded sample (e.g. attribute) generated.

In one embodiment, finite differences are transformed to an orthonormal basis using the following technique. Given a function $f(x,y)$, with values f_0, f_1, and, f_2 at the three vertices $v_0=(x_0, y_0)$, $v_1=(x_1, y_1)$, and $v_2=(x_2, y_2)$ of a sub-triangle, the partial derivatives

$$\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right)$$

may be computed on an orthonormal basis.

FIG. **6**F illustrates finite differences on a sub-triangle that are transformed to compute derivatives in an orthonormal basis, in accordance with one embodiment. The sub-triangle **650** is defined by the three vertices v_0, v_1, and v_2.

Assuming f to be linear in the region:

$$f_1 = f_0 + \frac{\partial f}{\partial x}\cdot(x_1 - x_0) + \frac{\partial f}{\partial y}\cdot(y_1 - y_0)$$

$$f_2 = f_0 + \frac{\partial f}{\partial x}\cdot(x_2 - x_0) + \frac{\partial f}{\partial y}\cdot(y_2 - y_0)$$

This system of equations can be expressed as $Af'=B$, where:

$$A = \begin{pmatrix} x_1 - x_0 & y_1 - y_0 \\ x_2 - x_0 & y_2 - y_0 \end{pmatrix}$$

$$B = \begin{pmatrix} f_1 - f_0 \\ f_2 - f_0 \end{pmatrix}$$

$$f' = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right)^T$$

The system of equations may be solved for non-degenerate triangles using Cramer's rule:

$$\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right) = \left(\frac{A_{11}B_0 - A_{01}B_1}{|A|}, \frac{A_{00}B_1 - A_{10}B_0}{|A|}\right)$$

For object space derivatives, A is constructed assuming $(x_1-x_0)=1$ and $(y_1-y_0)=0$, and set (x_2-x_0) and (y_2-y_0) using the ratio of lengths and the angle between (v_2-v_0) and (v_2-v_0).

In order to provide consistent derivatives that closely correspond to the specified shading rate, screen-space can be optionally used as the orthonormal basis while the derivatives are recalculated. Using screen-space helps obtain accurate screen-space derivatives, but at the cost of extra computation.

When screen-space derivatives are computed, A is constructed to correspond to the actual screen-space locations of the vertices of the sub-triangle. Let these locations be S_0, S_1, and S_2 respectively.

$$A = \begin{pmatrix} S_x^1 - S_x^0 & S_y^1 - S_y^0 \\ S_x^2 - S_x^0 & S_y^2 - S_y^0 \end{pmatrix}$$

The terms of A are screen-space coordinates, estimated by transforming vertices of the local triangle. In other words,

$$S_x^i = -\frac{H \cdot V_x^i}{2 \cdot V_z^i \cdot \tan\left(\frac{\theta}{2}\right)} = -f_s \cdot \frac{V_x^i}{V_z^i}$$

$$S_y^i = -\frac{H \cdot V_y^i}{2 \cdot V_z^i \cdot \tan\left(\frac{\theta}{2}\right)} = -f_s \cdot \frac{V_y^i}{V_z^i}$$

Where V_x^i, V_y^i, V_z^i are the eye-space coordinates of the local triangle, H is the height of the viewpoint in pixels, and θ is the vertical field of view. Substituting H and θ into A, produces:

$$A = -f_s \cdot \begin{pmatrix} \frac{V_x^1}{V_x^1} - \frac{V_x^0}{V_x^0} & \frac{V_y^1}{V_z^1} - \frac{V_y^0}{V_z^0} \\ \frac{V_x^2}{V_x^2} - \frac{V_x^0}{V_x^0} & \frac{V_y^2}{V_z^2} - \frac{V_y^0}{V_z^0} \end{pmatrix}$$

Then δ^i is defined as the following:

$$\delta^i = V_i - V_0 = \frac{V_i^{par} - V_0^{par}}{N} = \frac{\Delta^i}{N}$$

Where V_i^{par} are the parent triangle's vertices in eye space, and $\Delta^i=(V_i^{par}-V_0^{par})$. V_i^{par} is then substituted into A. For brevity only A_{00} is shown for the next few steps. Other entries of A are similar in form.

$$A_{00} = -f_s\left(\frac{V_x^0 + \delta_x^1}{V_z^0 + \delta_z^1} - \frac{V_x^0}{V_z^0}\right) = -f_s\left(\frac{V_z^0 \cdot \delta_x^1 - V_x^0 \cdot \delta_z^1}{V_z^0 \cdot (V_z^0 + \delta_z^1)}\right)$$

Approximating $V_z^0 \sim (V_z^0 + \delta_z^i)$ in the denominator:

$$A_{00} = -\frac{f}{V_z^0} \cdot \left(\delta_x^1 - \frac{V_x^0}{V_z^0} \cdot \delta_z^1 \right)$$
$$= -\frac{f_s}{N \cdot V_z^0} \cdot \left(\Delta_x^1 - \frac{V_x^0}{V_z^0} \cdot \Delta_z^1 \right)$$
$$= -K \cdot \left(\Delta_x^1 - \frac{V_x^0}{V_z^0} \cdot \Delta_z^1 \right)$$

Thus, A is now:

$$A = -K \cdot \begin{pmatrix} \Delta_x^1 - \frac{V_x^0}{V_z^0} \cdot \Delta_z^1 & \Delta_y^1 - \frac{V_y^0}{V_z^0} \cdot \Delta_z^1 \\ \Delta_x^2 - \frac{V_x^0}{V_z^0} \cdot \Delta_z^2 & \Delta_y^2 - \frac{V_y^0}{V_z^0} \cdot \Delta_z^2 \end{pmatrix}$$

|A| is computed as:

$$|A| = K^2 \cdot \left(\begin{vmatrix} \Delta_x^1 & \Delta_y^1 \\ \Delta_x^2 & \Delta_y^2 \end{vmatrix} + \frac{V_x^0}{V_z^0} \cdot \begin{vmatrix} \Delta_y^1 & \Delta_z^1 \\ \Delta_y^2 & \Delta_z^2 \end{vmatrix} + \frac{V_y^0}{V_z^0} \cdot \begin{vmatrix} \Delta_z^1 & \Delta_x^1 \\ \Delta_z^2 & \Delta_x^2 \end{vmatrix} \right)$$

All three determinants in the above expression are per-triangle constants, so the determinants only need to be computed once per triangle. Thus

$$\frac{1}{|A|}$$

can be computed more easily than directly transforming vertices of the sub-triangle from object-space to screen-space. Computing derivatives in this fashion amortizes the computation required to compute one derivative across the triangle.

FIG. **7**A illustrates a block diagram **700** for identifying points of an object-space shading grid at which shaded samples will be computed, in accordance with one embodiment. An input fragment that is defined by vertices in screen-space is received by a transform unit **705**. The input fragment is at least one sub-pixel in size and may be larger than one or more pixels. The input fragment is a portion of an object that includes one or more primitives. When early z-testing is performed, the portion of the object corresponds to a visible portion of the object. The transform unit **705** transforms the vertices from screen space to object space to produce a transformed vertex set corresponding to the input fragment. The transformed vertices define a footprint of the input fragment in object-space.

A grid definition unit **710** receives the transformed vertex set and defines an object-space shading grid for each primitive that is covered by the footprint. In one embodiment, a separate, primitive-specific object-space shading grid is defined for each primitive. In another embodiment, an object-space shading grid is defined for two or more primitives that are covered by the footprint. The one or more object-space shading grids for a primitive or primitives may be successively subdivided into sub-triangles to generate a mipmapped object-space shading grid for the respective primitive or primitives. The grid definition unit **710** identifies at least one mip level to be sampled based on the footprint. In one embodiment, the grid definition unit **710** identifies at least one mip level having sub-triangles that most closely match the area of the footprint. In one embodiment, the grid definition unit **710** computes the value N and identifies the at least one grid mip level based on N. In one embodiment, when two or more grid mip levels are identified, the grid definition unit **710** also computes the linear interpolant needed to compute a shaded sample based on the shaded values corresponding to two or more grid mip levels.

A grid point selection unit **715** receives the at least one grid mip level and identifies one or more sub-triangles that intersect the sample locations, where the sample locations are the vertices that define the footprint. The grid point selection unit **715** selects points of the object-space shading grid for which shaded values are computed. The selected points are "sample points" corresponding to vertices of a sub-triangle that encloses a sample location.

After the points of the object-space shading grid at which shaded values will be computed are identified, a shaded value may be computed for each point. A parallel shading unit **720** receives the sample points and launches a shader to compute a shaded value at each sample point. The computed shaded samples may comprise one or more shaded attributes associated with the input fragment. In one embodiment, the shaded values are computed as described in conjunction with FIG. **7**B.

The shaded values may then be filtered by a sample filtering unit **725** based on the linear interpolant related to N and the sample location relative to the sample points (i.e., vertices of the enclosing sub-triangle). In one embodiment, a shaded sample is computed using barycentric interpolation within a first mip level and a second mip level to generate a first and second shaded sample. The first and second shaded samples are then interpolated based on the linear interpolant related to N to produce the final shaded sample.

FIG. **7**B illustrates a flowchart of a method **750** for computing per-sample shaded attributes for pixels, in accordance with one embodiment. Performing the method steps, in any order, is contemplated as being within the context of this disclosure. One or more of the steps shown in FIG. **7**B may be performed by the parallel shading unit **720** shown in FIG. **7**A. At step **760**, finite differences for a sub-triangle defined by points of an object-space shading grid are computed. In one embodiment, the processing pipeline may be the graphics processing pipeline **400** and the fragment shading stage **470** may be implemented by an SM **250** that is configured to execute instructions of the shader program. At step **765**, the finite differences are transformed from object space to an orthonormal basis. In one embodiment, the orthonormal basis is screen space. At step **770**, shaded attributes are computed for each point. At step **775**, the shaded attributes are filtered to produce a final shaded sample within the sub-triangle. In one embodiment, step **775** is performed by the sample filtering unit **725** shown in FIG. **7**A.

Because the shading is performed in object-space the temporal artifacts may be reduced, producing images that appear to be higher quality even when the shading rate is reduced. Additionally, the shading rate may vary across an object and even within a primitive. The shading rate may also vary independent of the visibility rate. Finally, because the object-space shading grid is in object space, the shading grid does not necessarily change with each movement of the camera. Instead, the shading grid is updated when the object geometry changes.

FIG. **8** illustrates an exemplary system **800** in which the various architecture and/or functionality of the various previous embodiments may be implemented. As shown, a

system **800** is provided including at least one central processor **801** that is connected to a communication bus **802**. The communication bus **802** may be implemented using any suitable protocol, such as PCI (Peripheral Component Interconnect), PCI-Express, AGP (Accelerated Graphics Port), HyperTransport, or any other bus or point-to-point communication protocol(s). The system **800** also includes a main memory **804**. Control logic (software) and data are stored in the main memory **804** which may take the form of random access memory (RAM).

The system **800** also includes input devices **812**, a graphics processor **806**, and a display **808**, i.e. a conventional CRT (cathode ray tube), LCD (liquid crystal display), LED (light emitting diode), plasma display or the like. User input may be received from the input devices **812**, e.g., keyboard, mouse, touchpad, microphone, and the like. In one embodiment, the graphics processor **806** may include a plurality of shader modules, a rasterization module, etc. Each of the foregoing modules may even be situated on a single semiconductor platform to form a graphics processing unit (GPU).

In the present description, a single semiconductor platform may refer to a sole unitary semiconductor-based integrated circuit or chip. It should be noted that the term single semiconductor platform may also refer to multi-chip modules with increased connectivity which simulate on-chip operation, and make substantial improvements over utilizing a conventional central processing unit (CPU) and bus implementation. Of course, the various modules may also be situated separately or in various combinations of semiconductor platforms per the desires of the user.

The system **800** may also include a secondary storage **810**. The secondary storage **810** includes, for example, a hard disk drive and/or a removable storage drive, representing a floppy disk drive, a magnetic tape drive, a compact disk drive, digital versatile disk (DVD) drive, recording device, universal serial bus (USB) flash memory. The removable storage drive reads from and/or writes to a removable storage unit in a well-known manner.

Computer programs, or computer control logic algorithms, may be stored in the main memory **804** and/or the secondary storage **810**. Such computer programs, when executed, enable the system **800** to perform various functions. The memory **804**, the storage **810**, and/or any other storage are possible examples of computer-readable media.

In one embodiment, the architecture and/or functionality of the various previous figures may be implemented in the context of the central processor **801**, the graphics processor **806**, an integrated circuit (not shown) that is capable of at least a portion of the capabilities of both the central processor **801** and the graphics processor **806**, a chipset (i.e., a group of integrated circuits designed to work and sold as a unit for performing related functions, etc.), and/or any other integrated circuit for that matter.

Still yet, the architecture and/or functionality of the various previous figures may be implemented in the context of a general computer system, a circuit board system, a game console system dedicated for entertainment purposes, an application-specific system, and/or any other desired system. For example, the system **800** may take the form of a desktop computer, laptop computer, server, workstation, game consoles, embedded system, and/or any other type of logic. Still yet, the system **800** may take the form of various other devices including, but not limited to a personal digital assistant (PDA) device, a mobile phone device, a television, etc.

Further, while not shown, the system **800** may be coupled to a network (e.g., a telecommunications network, local area network (LAN), wireless network, wide area network (WAN) such as the Internet, peer-to-peer network, cable network, or the like) for communication purposes.

While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of a preferred embodiment should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. A method comprising:

receiving an object defined by a plurality of triangle primitives in a three-dimensional (3D) space that is specific to the object;

defining an object-space shading grid for at least one of the plurality of triangle primitives based on coordinates at vertices of the at least one triangle primitive in the 3D space,

wherein a shape of an object-space shading element corresponds to a shape of the at least one triangle primitive, wherein the object-space shading grid comprises at least one object-space shading element; and

executing, by a processing pipeline, a shader program to compute a shaded value at a point on the object-space shading grid for a first triangle primitive.

2. The method of claim **1**, wherein the vertices comprise a first vertex, a second vertex, and a third vertex that define the first triangle primitive and the point corresponds to the first vertex.

3. The method of claim **2**, further comprising:

executing, by the processing pipeline, the shader program to compute a second shaded value at a second point that corresponds to the second vertex; and

executing, by the processing pipeline, the shader program to compute a third shaded value at a third point that corresponds to the third vertex.

4. The method of claim **3**, further comprising computing a shaded sample at a location within the first triangle by interpolating the first, second, and third shaded values.

5. The method of claim **1**, wherein the object-space shading grid comprises an additional level comprising only vertex positions of four sub-triangles produced by bisecting each edge of the first triangle primitive.

6. The method of claim **5**, wherein the additional level of the object-space shading grid is dynamically generated during execution of the shader program.

7. The method of claim **1**, wherein the object-space shading grid is mipmapped such that each higher resolution mip level is generated by subdividing a lower resolution mip level into substantially congruent sub-triangles within the first triangle primitive.

8. The method of claim **7**, further comprising:

transforming a screen-space pixel into the 3D space that is specific to the object to generate a footprint; and

identifying a first mip level of the mipmapped object-space shading grid that includes a sub-triangle having an area that most closely approximates an area of the footprint.

9. The method of claim **8**, further comprising identifying a second mip level of the mipmapped object-space shading grid that includes a sub-triangle having an area that closely approximates the area of the footprint.

10. The method of claim 9, further comprising executing the shader program to compute a second shaded value at a second point on the object-space shading grid for the sub-triangle.

11. The method of claim 10, wherein the sub-triangle is defined by the point, the second point on the object-space shading grid, and a third point on the object-space shading grid.

12. The method of claim 11, further comprising:

executing the shader program to compute a third shaded value at the third point for the sub-triangle; and

computing a shaded sample at a sample location within the sub-triangle based on the shaded value, the second shaded value, and the third shaded value.

13. The method of claim 1, further comprising:

transforming a screen-space pixel into the 3D space that is specific to the object to generate a footprint defined by at least a first sample location; and

determining that a sub-triangle within the first triangle encloses the first sample location.

14. The method of claim 13, further comprising, executing the shader program to compute a second shaded value at a second point on the object-space shading grid that corresponds to a first vertex of the sub-triangle.

15. The method of claim 1, further comprising updating the object-space grid in response to a change in a shape of the first triangle primitive.

16. The method of claim 1, further comprising computing a dynamic shading rate for the first triangle primitive that varies within the first triangle primitive and is used to sample the object-space shading grid for the first triangle primitive.

17. A system comprising:

a processing pipeline that is configured to:

receive an object defined by a plurality of triangle primitives in a three-dimensional (3D) space that is specific to the object;

define an object-space shading grid for at least one of the plurality of triangle primitives based on coordinates at vertices of the at least one triangle primitive in the 3D space,

wherein a shape of an object-space shading element corresponds to a shape of the at least one triangle primitive, wherein the object-space shading grid comprises at least one object-space shading element; and

execute a shader program to compute a shaded value at a point on the object-space shading grid for a first triangle primitive.

18. The system of claim 17, wherein the object-space shading grid is mipmapped such that each higher resolution mip level is generated by subdividing a lower resolution mip level into substantially congruent sub-triangles within the first triangle primitive.

19. The system of claim 17, wherein the object-space shading grid comprises an additional level comprising only vertex positions of four sub-triangles produced by bisecting each edge of the first triangle primitive.

20. A non-transitory computer-readable storage medium storing instructions that, when executed by a processor, causes the processor to perform steps comprising:

receiving an object defined by a plurality of triangle primitives in a three-dimensional (3D) space that is specific to the object;

defining an object-space shading grid for at least one of the plurality of triangle primitives based on coordinates at vertices of the at least one triangle primitive in the 3D space,

wherein a shape of an object-space shading element corresponds to a shape of the at least one triangle primitive, wherein the object-space shading grid comprises at least one object-space shading element; and

executing, by a processing pipeline, a shader program to compute a shaded value at a point on the object-space shading grid for a first triangle primitive.

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