

# Geometric Tools Engine Update History

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The version release dates are listed here. Versions released before the current version may be obtained by email request.

- Version 6.8 posted August 9, 2023.
- Version 6.7 posted July 17, 2023.
- Version 6.6 posted May 8, 2023.
- Version 6.5 posted December 14, 2022.
- Version 6.4 posted June 8, 2022.
- Version 6.3 posted April 3, 2022.
- Version 6.2 posted March 7, 2022.
- Version 6.1 posted February 7, 2022.
- Version 6.0 posted January 6, 2022.
- Version 5.15 posted December 21, 2021.
- Version 5.14 posted November 19, 2021.
- Version 5.13 posted September 25, 2021.
- Version 5.12 posted August 1, 2021.
- Version 5.11 posted June 16, 2021.
- Version 5.10 posted May 23, 2021.
- Version 5.9 posted April 26, 2021.
- Version 5.8 posted March 26, 2021.
- Version 5.7 posted March 8, 2021.
- Version 5.6 posted January 14, 2021.
- Version 5.5 posted December 18, 2020.
- Version 5.4 posted November 17, 2020.
- Version 5.3 posted November 5, 2020.
- Version 5.2 posted October 11, 2020.
- Version 5.1 posted September 30, 2020.
- Version 5.0 posted September 15, 2020.
- Version 4.9 posted September 5, 2020.
- Version 4.8 posted August 12, 2020.

- Version 4.7 posted June 24, 2020.
- Version 4.6 posted April 13, 2020.
- Version 4.5 posted January 12, 2020.
- Version 4.4 posted January 4, 2020.
- Version 4.3 posted December 29, 2019.
- Version 4.2 posted December 5, 2019.
- Version 4.1 posted August 29, 2019.
- Version 4.0 posted August 14, 2019.
- Version 3.30 posted December 29, 2019.
- Version 3.29 posted December 5, 2019.
- Version 3.28 posted August 29, 2019.
- Version 3.27 posted August 14, 2019.
- Version 3.26 posted August 1, 2019.
- Version 3.25 posted April 29, 2019.
- Version 3.24 posted April 12, 2019.
- Version 3.23 posted April 4, 2019.
- Version 3.22 posted March 4, 2019.
- Version 3.21 posted January 21, 2019.
- Version 3.20 posted January 9, 2019.
- Version 3.19 posted November 30, 2018.
- Version 3.18 posted October 30, 2018.
- Version 3.17 posted October 19, 2018.
- Version 3.16 posted October 3, 2018.
- Version 3.15 posted September 8, 2018.
- Version 3.14 posted July 17, 2018.
- Version 3.13 posted June 7, 2018.
- Version 3.12 posted February 19, 2018.
- Version 3.11 posted February 8, 2018.
- Version 3.10 posted September 16, 2017.

- Version 3.9 posted June 18, 2017.
- Version 3.8 posted April 2, 2017.
- Version 3.7 posted February 6, 2017.
- Version 3.6 posted January 28, 2017.
- Version 3.5 posted November 28, 2016.
- Version 3.4 posted November 14, 2016.
- Version 3.3 posted September 24, 2016.
- Version 3.2 posted July 6, 2016.
- Version 3.1 posted June 28, 2016.
- Version 3.0 posted June 19, 2016.
- Version 2.5 posted May 26, 2016.
- Version 2.4 posted April 2, 2016.
- Version 2.3 posted March 10, 2016.
- Version 2.2 posted January 30, 2016.
- Version 2.1 posted January 25, 2016.
- Version 2.0 posted September 23, 2015.
- Version 1.14 posted June 7, 2015.
- Version 1.13 posted May 31, 2015.
- Version 1.12 posted April 20, 2015.
- Version 1.11 posted April 5, 2015.
- Version 1.10 posted March 10, 2015.
- Version 1.9 posted February 1, 2015.
- Version 1.8 posted January 5, 2015.
- Version 1.7 posted December 12, 2014.
- Version 1.6 posted November 25, 2014.
- Version 1.5 posted October 25, 2014.
- Version 1.4 posted September 25, 2014.
- Version 1.3 posted September 13, 2014.
- Version 1.2 posted August 29, 2014.

- Version 1.1 posted August 19, 2014.
- Version 1.0 posted August 11, 2014.

The updated files and related notes are provided for the versions in each of the ensuing sections. Each section has a list of changes that occurred to the version number mentioned in that section. Those changes were rolled up into the zip file that was posted for the next version. Files in the **Include** or **Source** folder are abbreviated (file prefix **Gte** removed) for ease of reading. Modified files are colored **gold**, new files are colored **green**, and deleted files are colored **red**. Source code is colored **Violet**.

## 1 Updates to Version 6.8

**December 30, 2023.** Revised the implementation of **MinimalCycleBasis**. The code now computes isolated vertices, filaments, and basis cycles. It also uses exact arithmetic internally to guarantee correctness of the computations. I added more unit tests for the revision than for the previous code version.

**GTE/Mathematics/MinimalCycleBasis.h**

Fixed bugs that were discovered when triangulating a polygon tree. The **Vertex** objects of the **VertexList** had state information from the previous triangulation that affected **DoEarClipping**. The state is now reset to the constructor values in the **Vertex** constructor. The polygon-tree triangulation also was not accumulating the triangles for the multiple **DoEarClipping** calls.

**GTE/Mathematics/TriangulateEC.h**

**December 24, 2023.** The test in **Extract** for adding a tree to the forest needed another Boolean condition. I also realized that the filament extraction will not work for general subgraphs of filaments. I am working to resolve that. The extraction output uses a set of pointers to a **Vertex** structure, so the output can vary between runs because of the sorting order implied by the set of structures. I am also working to resolve that. See issue #80 at my online github repository.

**GTE/Mathematics/MinimalCycleBasis.h**

**December 22, 2023.** The comments indicated that the filaments are extracted by the code. They are removed from the graph but not made available to the user. I added the ability to extract the filaments in case the caller wants them. The file is relatively old, so I took the opportunity to upgrade it to my current design goals. The constructor is a simple one, no longer mimicking a function object. The **Extract** function does the cycle and filament extraction. I also added a new template parameter which is the type of the vertex indices. The type was **int32\_t** but now can be any signed or unsigned integer type of size at least 2 bytes. Thanks to Scott Johnson for (once again) reporting problems such as these.

**GTE/Mathematics/MinimalCycleBasis.h**

**GTE/Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasisWindow2.{h,cpp}**

**December 16, 2023** This is a major rewrite of the previous version. The code is easier to read. I addressed a several technical support items. The duplicate-vertex map has been removed. The PDF [Triangulation by Ear Clipping](#) is a major rewrite and explains why the algorithm is self-sorting regarding bridges that share the same outer-polygon vertex. Various unit tests appear to show that the algorithm is performing correctly.

[GTE/Mathematics/TriangulateEC.h](#)

**December 4, 2023.** The nonmanifold test for a shared edge having opposite orderings for the two triangles sharing the edge was flawed. The `edge` object comes from an `EdgeKey<false>` object so that the edge is  $\langle v_0, v_1 \rangle$  with  $v_0 < v_1$ . The actual ordering depends on the specified triangle vertex order. Instead, the comparison has to be made for the shared edge of the already existing triangle `edge->T[0]` because the vertices for that triangle are ordered.

[GTE/Mathematics/ETManifoldMesh.h](#)

**December 3, 2023.** In `operator()`, the array `reflect` is declared to have 3 Boolean elements but only the first 2 are explicitly initialized. According to the C++ standard, the unspecified element is zero-initialized, set to `false` in this case. I added the third initializer to make it clear that is what was intended.

[GTE/Mathematics/DistPlane3CanonicalBox3.h](#)

**December 2, 2023.** Added new intersection queries for rectangle and linear components (line, ray, segment). Added a sample application to illustrate and for testing.

[GTE/Mathematics/IntrLine3Rectangle3.h](#)  
[GTE/Mathematics/IntrRay3Rectangle3.h](#)  
[GTE/Mathematics/IntrSegment3Rectangle3.h](#)  
[GTE/Samples/Intersection/IntersectLineRectangle/\\*](#)  
[GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}](#)  
[GTE/BuildAll\\*.\\*](#)

Fixed the minor version numbers to show current version is 6.8. Added the new sample to the intersection [CMakeLists.txt](#).

[GTE/CMakeLists.txt](#)  
[GTE/Samples/CMakeLists.txt](#)  
[GTE/Samples/Distance/CMakeLists.txt](#)  
[GTE/Samples/Geometrics/CMakeLists.txt](#)  
[GTE/Samples/Graphics/CMakeLists.txt](#)  
[GTE/Samples/Imagics/CMakeLists.txt](#)  
[GTE/Samples/Intersection/CMakeLists.txt](#)  
[GTE/Samples/Mathematics/CMakeLists.txt](#)  
[GTE/Samples/Physics/CMakeLists.txt](#)  
[GTE/Samples/SceneGraphs/CMakeLists.txt](#)



**November 27, 2023.** Reimplemented the query for distance between two circles in 3D. The previous version used only floating-point arithmetic. The rounding errors when computing derivatives of the degree-8 polynomial were causing extreme inaccuracy in the results. The new code now uses a mixture of floating-point arithmetic and rational arithmetic. The degree-8 polynomial and its derivatives are created using rational arithmetic. Bisection is performed using floating-point arithmetic, but with some initial rational arithmetic to determine sign changes in a polynomial at the endpoints of a potential root-bounding interval.

[GTE/Mathematics/DistCircle3Circle3.h](#)

Added multithreading to the general-degree polynomial root estimator to improve the performance.

[GTE/Mathematics/RootsGeneralPolynomial.h](#)

**November 26, 2023.** Based on reader feedback for [FastOrthogonalComplement.pdf](#), I reordered the vectors in the signatures of the functions listed in the pseudocode and in the actual code (in [Vector3.h](#)). This is the usual convention I have for writing code (inputs first, outputs last). I also modified the actual code function name to [FastComputeOrthogonalComplement](#).

[GTE/Mathematics/Vector3.h](#)

**November 21, 2023.** After thinking harder about the new [Vector3](#) function [ComputeOrthogonalComplement](#), I was able to avoid the square root operation. Given a unit-length vector, you can compute the orthogonal complement with only arithmetic operations. A new PDF has been posted to the website: [FastOrthogonalComplement.pdf](#).

[GTE/Mathematics/Vector3.h](#)

**November 20, 2023.** The [RootsPolynomial<T>::Find](#) function suffered from significant floating-point rounding errors in the computation of the coefficients of the polynomial derivatives. The class allows for type [T](#) to be rational, but the bisection effectively does not converge because the number of bits per rational number is excessively large. This class is now deprecated. The low-degree root finders are now in [RootsLinear.h](#), [RootsQuadratic.h](#), [RootsCubic.h](#), and [RootsQuartic.h](#). Three of these files are listed here because a comment mentioned using Cauchy's bound when in fact the code uses Lagrange's bound.

[GTE/Mathematics/RootsQuadratic.h](#)  
[GTE/Mathematics/RootsCubic.h](#)  
[GTE/Mathematics/RootsQuartic.h](#)  
[GTE/Mathematics/RootsPolynomial.h](#)

The replacement for [RootsPolynomial<T>::Find](#) is [RootsGeneralPolynomial<T>::Solve](#). The algorithm is effectively the same as the deprecated [Find](#), but it uses a mixture of floating-point arithmetic and rational arithmetic. The coefficients of the polynomial derivatives are computed using rational arithmetic to avoid the rounding errors that plagued the deprecated code. When the bisection code consumes these polynomials, rational evaluation is used to determine sign information at the endpoints of an interval. If bisection must occur, the rational coefficients are converted to floating-point, and the resulting rounding errors are significantly smaller than that of the deprecated code. The floating-point-based bisection is fast, so the performance is reasonable in order to get increased accuracy of the root estimates.

GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/RootsGeneralPolynomial.h

Added a new function `ComputeOrthogonalComplement` with a signature different from the other same-named function. The new function computes the basis by computing a unit-length quaternion for a rotation matrix whose last column is a user-specified unit-length vector. The other two columns are extracted from the rotation matrix.

GTE/Mathematics/Vector3.h

The `Rotate` function for a 4-tuple vector did not compile because it uses a `Vector3`-based `Cross` product function. The `Vector3` quantities were replaced by `Vector4` quantities, but the header file `Vector3.h` still needs to be included to access the cross product of two 4-tuple vectors.

GTE/Mathematics/Quaternion.h

Added a member accessor to get a const reference to the polynomial coefficients.

GTE/Mathematics/Polynomial1.h

Added an exception to the `Insert` function that detects whether the vertex ordering for two edges is opposite for the two triangles sharing the edge. If the ordering is not opposite, the mesh is not manifold. The test is exposed by default (`mThrowOnNonmanifoldInsertion` is initially `true`), but you can disable the test by setting the aforementioned Boolean to `false`.

GTE/Mathematics/ETManifoldMesh.h

The `GetGradient` function had a typecast of a `float` to a `size_t` and then assigned it to an `int32_t`. The typecast was changed to a `int32_t`. Fixed Ubuntu gcc compiler warnings/errors: missing `typename` when declaring `topology`, 3 loop variables were `size_t` but needed to be `IndexType`.

GTE/Mathematics/SurfaceExtractorMC.h

Fedora gcc complained about undefined `int32_t` (but Ubuntu gcc did not). Added an include of `cstdint.h`.

GTE/Mathematics/HermiteBiquintic.h  
GTE/Mathematics/HermiteTricubic.h  
GTE/Mathematics/HermiteTriquintic.h

The following warnings/errors occur using `LVM - clang-cl` in Microsoft Visual Studio 2022 version 17.8.0. After these modifications, the Intel C++ Compiler 2023 had no warnings/errors.

An include of `Functions.h` is required; otherwise, the block of functions starting with `atandivpi` become infinitely recursive. The definition of `atandivpi` whose input is `IEEEBinary16` makes a call to `atandivpi` whose argument is typecast to `float`. This works as long as the definition of `atandivpi` in `Functions.h` is accessible. Without it, an implicit `IEEEBinary16` constructor call is made from the `float` input, thus the infinite recursion. The constructor with input of type `double` has variable `temp` that is tagged as not initialized. It is on the next line, but I moved that code into the union initialization.

GTE/Mathematics/IEEEBinary16.h

Two declarations of `Vector3<T> delta` occurred in the code, but the variables are unused. They have been removed.

GTE/Mathematics/DistLine3Circle3.h

Function `ConstrainedTriangulate` had a declaration of `counter` that was used for debugging. Even though it is incremented in the code, the value is not used anywhere else and is flagged as such. It has been removed.

GTE/Mathematics/TriangulateCDT.h

The `operator()` function declared and initialized `numZero`. Even though it is incremented in the code, the value is not used anywhere else and is flagged as such. They have been removed.

GTE/Mathematics/IntrHalfspace3Segment3.h

GTE/Mathematics/IntrHalfspace3Triangle3.h

The LLVM compiler also generates warnings about Intel intrinsics files `emmintrin.h` and `xmmintrin.h`. The projects do not include these headers explicitly, so they must be exposed somewhere in Microsoft's header files.

**October 21, 2023.** Added a code to save binary STL files.

GTE/Mathematics/STLBinaryFile.h

**October 20, 2023.** Added a file loader for binary STL files.

GTE/Mathematics/STLBinaryFile.h

**October 11, 2023.** Reimplemented the `Quaternion<T>::Rotate` functions to use fewer arithmetic operations. Thanks to Robert Eisele for sending me a link to his webpage about the algorithm; the link is provided in the header file.

GTE/Mathematics/Quaternion.h

**September 30, 2023.** Toggling between `double` and `BSRational<UIntegerAP32>` required commenting and uncommenting some code. I added a preprocessor define so that you can toggle by exposing or hiding this define.

GTE/Samples/Geometrics/PolygonBooleanOperations/PolygonBooleanOperationsWindow2.{h,cpp}

**September 28, 2023.** Modified the sample application to use exact rational arithmetic if so desired. `BSPPolygon2<T>` already compiles when `T` is `BSRational<UIntegerAP32>`.

GTE/Samples/Geometrics/PolygonBooleanOperations/PolygonBooleanOperationsWindow2.{h,cpp}

Fixed a problem with segment-arc and ray-arc find-intersection queries that were caused by the line-circle find-intersection query setting only one of the `result.parameter` values when the line and circle are tangent. It is necessary to set both parameter values to the same number, effectively a degenerate interval that is used in interval-interval find-intersection queries used in segment-arc and ray-arc. Thanks to owai on github for reporting the problem, diagnosing it, and fixing it.

GTE/Mathematics/IntrLine2Circle2.h

Removed the deprecation comment about the `Contains` function without the epsilon argument. This function is still useful when you know the point is on the arc so that you do not need the epsilon value.

GTE/Mathematics/Arc2.h

**September 25, 2023.** The `operator<` comparison had an incorrect comparison in it, using `origin` instead of the correct `normal`.

GTE/Mathematics/Hyperplane.h

**September 25, 2023.** Yet more modifications to surface extraction. The index type for the `indices` array were hard-coded as `int32_t`. Some applications have different types for the indices. The `MarchingCubes` and `SurfaceExtractionMC` classes now have template parameters `IndexType` to allow the user to choose whatever type is natural to the application. I back-ported changes made to the GTL version of `MarchingCubes`; for example, `int32_t index[8]` is now `std::array<IndexType, 8> index`.

GTE/Mathematics/MarchingCubes.h

GTE/Mathematics/SurfaceExtractorMC.h

GTE/Samples/Physics/BouncingBall/DeformableBall.cpp

GTE/Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow3.h

**September 24, 2023.** In `SurfaceExtractorMC.h`, the test code used only a positive perturbation and the output is correct. When the perturbation is negative, the order of sign testing needed to be modified to ensure the output is correct. The `BouncingBall` physics sample uses `SurfaceExtractorMC.h`, so it needed a modification to add the perturbation parameter.

GTE/Mathematics/SurfaceExtractorMC.h

GTE/Samples/Physics/BouncingBall/DeformableBall.cpp

**September 23, 2023.** When the single-voxel `Extract` returns `false`, the full-image extraction was supposed to ignore the voxel. Instead it deleted the entire mesh, which is a disastrous bug. The unit tests verified only that the Marching Cubes 256 triangle-lookup table entries are correct, and none of these provided code coverage that would have found the bug. Also, floating-point rounding errors in mesh vertex construction led to small sets of vertices, each set containing vertices that are nearly the same (but should have been the same without the rounding errors). `MakeUnique` is unable to identify these as duplicates. I modified the single-voxel `Extract` function to generate the same vertex on an edge shared by multiple voxels, using a consistent ordering of the voxel corners to ensure that the all constructions of the vertex have the same rounding errors. Finally, the interfaces were modified to have a new parameter `perturb` that allows you to avoid the ignoring of voxels for which at least one corner of the voxel is exactly the input `level` value. Thanks to Scott Johnson for reporting these problems.

GTE/Mathematics/SurfaceExtractorMC.h

**September 17, 2023.** If the mesh is not orientable, [GetBoundaryPolygons](#) had an infinite loop when trying to traverse a triangle strip the connects two consecutive boundary edges. When not orientable, two adjacent triangles are repeatedly visited. I added a trap for this and throw an exception.

GTE/Mathematics/ETManifoldMesh.h

**September 10, 2023.** Added new file for distance queries between 2 circles in 2D.

GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/DistCircle2Circle2.h

Added includes of C++ Standard Library headers to ensure they are always exposed to the file.

GTE/Mathematics/DistLine2Arc2.h  
GTE/Mathematics/DistRay2Arc2.h  
GTE/Mathematics/DistSegment2Arc2.h

**August 28, 2023.** Revised comments. Fixed bugs that were exposed when unit testing ray-arc and segment-arc distance queries. Feature request: Added new distance queries. Sorry for the delay. I struggle with 2-dimensional mathematics. I know I have problems with 3-dimensional mathematics because I get lost walking around my neighborhood. I seem to be most comfortable in 7-dimensional space.

GTE/Mathematics/DistLine2Circle2.h  
GTE/Mathematics/DistRay2Circle2.h  
GTE/Mathematics/DistSegment2Circle2.h  
GTE/Mathematics/DistLine2Arc2.h  
GTE/Mathematics/DistRay2Arc2.h  
GTE/Mathematics/DistSegment2Arc2.h

**August 27, 2023.** The comments in these files indicate the direction vectors do not have to be unit length. This was not true in earlier versions of GTE; that is, the directions had to be unit length. I had modified the comments at one time because I was removing the unit-length constraint. Unfortunately, the code was not modified, so only unit-length vectors worked. My unit tests passed anyway because they all used unit-length directions. The constraint is now removed. The direction vectors do not have to be unit length, the code was corrected, and the unit tests were updated to handle non-unit-length vectors. The line-segment distance query in [DistPointSegment.h](#) is correct.

GTE/Mathematics/DistPointLine.h  
GTE/Mathematics/DistPointRay.h

**August 26, 2023.** When the line intersects the circle in two distinct points, the parameter members of result must be increasingly ordered. They were not always, so a test-and-swap had to be added. I also fixed old comments about the [Result](#) struct.

GTE/Mathematics/Dist2Line2Circle2.h

Added a distance query for segment-circle in 2D.

GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/Dist2Segment2Circle2.h

**August 24, 2023.** The GTMathematicsGPU solutions and projects duplicated the GUID in MSVS 2019 and MSVS 2022. The MSVS 2019 GUID was modified. The GenerateMesh v17 projects were missing references to the GTMathematicsGPU projects (which did not affect the compilation).

GTE/BuildAll.v16.sln  
GTE/BuildAllDX11.v16.sln  
GTE/BuildAllGL45.v16.sln  
GTE/GTMathematicsGPU.v16.sln  
GTE/GTMathematicsGPU.v16.vcxproj  
GTE/Samples/Geometrics/GenerateMeshUVs/GenerateMeshUVsDX11.v16.sln  
GTE/Samples/Geometrics/GenerateMeshUVs/GenerateMeshUVsDX11.v16.vcxproj  
GTE/Samples/Geometrics/GenerateMeshUVs/GenerateMeshUVsGL45.v16.sln  
GTE/Samples/Geometrics/GenerateMeshUVs/GenerateMeshUVsGL45.v16.vcxproj  
GTE/Samples/Physics/BlownGlass/BlownGlassDX11.v16.sln  
GTE/Samples/Physics/BlownGlass/BlownGlassDX11.v16.vcxproj  
GTE/Samples/Physics/BlownGlass/BlownGlassGL45.v16.sln  
GTE/Samples/Physics/BlownGlass/BlownGlassGL45.v16.vcxproj  
GTE/Samples/Physics/Fluids2D/Fluids2DDX11.v16.sln  
GTE/Samples/Physics/Fluids2D/Fluids2DDX11.v16.vcxproj  
GTE/Samples/Physics/Fluids2D/Fluids2DGL45.v16.sln  
GTE/Samples/Physics/Fluids2D/Fluids2DGL45.v16.vcxproj  
GTE/Samples/Physics/Fluids3D/Fluids3DDX11.v16.sln  
GTE/Samples/Physics/Fluids3D/Fluids3DDX11.v16.vcxproj  
GTE/Samples/Physics/Fluids3D/Fluids3DGL45.v16.sln  
GTE/Samples/Physics/Fluids3D/Fluids3DGL45.v16.vcxproj

Removed MSVS 2022 warnings about uninitialized arrays (which clearly are initialized in the code).

GTE/Mathematics/Image2.h  
GTE/Mathematics/Image3.h

**August 20, 2023.** This is a new file that accompanies the revised version of the document [MovingAlongCurveSpecifiedSpeed.pdf](#). It contains an implementation of the algorithms described in the PDF.

GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/ReparameterizeByArclength.h

## 2 Updates to Version 6.7

**August 8, 2023.** After refactoring [Math.h](#), a significant number of GTE files no longer compiled. The files

required headers from the C++ Standard Library, but some of those headers were accessed indirectly by including other GTE files. I fixed those, but then discovered that my instantiation tool had a significant number of source files that included `ArbitraryPrecision.h` in order to instantiate templates based on numeric types `float`, `double`, `BSNumber`, and `BSRational`. The arbitrary precision header itself exposes standard library files that allowed some of the `float`-based and `double`-based templates, but when the arbitrary precision header is hidden, several of these templates failed to compile.

To avoid this mess, I modified nearly every GTE mathematics header file to explicitly include standard library headers for symbols that the header file references. This should protect the distribution from major failure if I refactor headers in the future. I also modified the instantiation tool to allow me to compile with or without arbitrary precision headers. I had already done this in my GTL development track. The number of modified files is so large that I am not listing them here.

Because the number of modified files was so large, I also unified my top-level commenting style. General comments at the top of the header about the file now occur after the `#pragma` statement but before `#include-s` of the headers that the file requires. I had already done this in my GTL development track.

Items modified during the refactor with additional needs are listed below.

New files for computing distance between a line or ray and a circle. The other cases for segment-circle, line-arc, ray-arc, and segment-arc will be posted soon.

```
GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/DistLine2Circle2.h  
GTE/Mathematics/DistRay2Circle2.h
```

Added initialization of some local variables to avoid MSVS code analysis complaint.

```
GTE/Mathematics/BSplineSurfaceFit.h  
GTE/Mathematics/BSplineVolume.h  
GTE/Mathematics/ContEllipse2.h  
GTE/Mathematics/ContEllipsoid3.h  
GTE/Mathematics/Matrix.h  
GTE/Mathematics/FPIInterval.h  
GTE/Mathematics/GMatrix.h  
GTE/Mathematics/IntpThinPlateSpline2.h  
GTE/Mathematics/IntpVectorField2.h  
GTE/Mathematics/Matrix.h  
GTE/Mathematics/NURBSVolume.h  
GTE/Mathematics/RootsBisection1.h  
GTE/Mathematics/SurfaceExtractorMC.h  
GTE/Mathematics/SWInterval.h
```

Replaced a move operation by a copy operation to avoid MSVS code analysis complaint about the moved object now being invalid.

```
GTE/Mathematics/Polynomial1.h
```

The class `Quaternion` is a client of Chebyshev ratios. The interface for `ChebyshevRatio` changed, so the quaternion code needed updating.

GTE/Mathematics/Quaternion.h

Commented out debug preprocessor symbols. If you want any of these, expose them again or add them to your global preprocessor defines.

GTE/Mathematics/APIInterval.h  
GTE/Mathematics/ApprQuery.h  
GTE/Mathematics/BitHacks.h  
GTE/Mathematics/BSNumber.h

Deleted the `GTE.NO.LOGGER` macro, exposing the `LogAssert` statements. This were the only occurrences of the no-logger control.

GTE/Mathematics/ApprPolynomialSpecial2.h  
GTE/Mathematics/ApprPolynomialSpecial3.h  
GTE/Mathematics/ApprPolynomialSpecial4.h

Added pragma block for MSVS 2022 in the function `Convert` in the case of the rounding mode `FE_TONEAREST`. The pragma disables a code analysis warning. This code had been tested and analyzed previously and works fine. I do not understand the code analysis message, which I have added to the pragma block as a comment.

GTE/Mathematics/BSNumber.h

Moved the comparison operators from external scope to class scope to be consistent with the other primitives having class-scope operators.

GTE/Mathematics/CanonicalBox.h

The gcc compilers on Linux complained about a potential uninitialized array (MSVS 2022 did not). The complaint is correct. The `GetVertices` functions return `false` if the Delaunay dimension is not 2. The `GetBarycentrics` functions return `false` if the triangle index `t` is invalid or if the `ComputeBarycentrics` function fails. In all these cases, the output arrays are uninitialized. First, I removed the test for dimension 2 and added an exception in the constructor if the input Delaunay object is not 2-dimensional. Second, I added initialization of the arrays if failure occurs, setting the components all to zero and then returning `false`.

GTE/Mathematics/Delaunay2Mesh.h  
GTE/Mathematics/Delaunay3Mesh.h

Modified `std::abs` calls to `std::fabs` calls.

GTE/Mathematics/IntrAlignedBox3Cone3.h

Converted some loop counters from `int32_t` to `size_t` to avoid MSVS code analysis complaints about 32-bit arithmetic performed on index lookups possibly causing overflow (it does not).



GTE/Mathematics/NaturalCubicSpline.h  
GTE/Mathematics/NaturalQuarticSpline.h  
GTE/Mathematics/UIntegerAP32.h

Replace an `auto` statement by the explicit type for a `std::function` object to avoid a MSVS 2022 code analysis complaint about not being able to determine whether a copy or const reference is asked for.

GTE/Mathematics/RiemannianGeodesic.h

Replaced C-style arrays by `std::array`.

GTE/Mathematics/SurfaceExtractorMC.h

Added precision counter for fused-multiply-add.

GTE/Tools/PrecisionCalculator/PrecisionCalculator.cpp

**August 3, 2023.** Factored `Math.h` into `Constants.h`, `Functions.h`, and `TypeTraits.h`. The `Math.h` file has been removed from the distribution. The constants header contains a small number of commonly used constants. The functions header contains implementations for IEEE recommended functions for convenience. These are for `float` and `double`. The type traits header contains traits for `has_division` and `is_arbitrary_precision`. Some other traits were added, but they are currently only in use in the GTL version. They are useful for eliminating the verbose nature of `std::enable_if` for conditionally selecting implementations based on type (floating-point or rational). The removal of `Math.h` led to many file modifications. Most of the clients of this header simply needed `<cmath>`.

GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/Math.h  
GTE/Mathematics/Constants.h  
GTE/Mathematics/Functions.h  
GTE/Mathematics/TypeTraits.h

I added support for `std::remainder` in `Functions.h` and in the rational arithmetic classes. As it turns out, the factoring of `Math.h` led to discovery of some bugs. `BSNumber.h` and `BSRational.h` implemented the arbitrary precision type trait, setting the value to `true`. These were both missing a leading underscore, so the compiler thought they were new primary templates rather than implementations of the primary templates defined in `TypeTraits.h`.

GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSRational.h

The majority of `Math.h` consisted of special constants for the function estimators such as `ACosEstimate.h` among others. The constants were moved into the estimators files themselves in GTL together with a reduction in code. I back-ported the files from GTL to GTE. **The interfaces have changed for the estimators. They were template classes but are now template functions.** A couple of new files were added, one for computing SLERP and one for computing Chebyshev coefficients that occur in the SLERP formula,  $\sin((1-t)\theta)/\sin(\theta)$  and  $\sin(t\theta)/\sin(\theta)$ .

GTE/Mathematics/ACosEstimate.h  
GTE/Mathematics/ASinEstimate.h  
GTE/Mathematics/ATanEstimate.h  
GTE/Mathematics/ChebyshevRatio.h  
GTE/Mathematics/ChebyshevRatioEstimate.h  
GTE/Mathematics/CosEstimate.h  
GTE/Mathematics/Exp2Estimate.h  
GTE/Mathematics/ExpEstimate.h  
GTE/Mathematics/InvSqrtEstimate.h  
GTE/Mathematics/Log2Estimate.h  
GTE/Mathematics/LogEstimate.h  
GTE/Mathematics/RemezAlgorithm.h  
GTE/Mathematics/RotationEstimate.h  
GTE/Mathematics/SinEstimate.h  
GTE/Mathematics/Slerp.h  
GTE/Mathematics/SlerpEstimate.h  
GTE/Mathematics/SqrtEstimate.h  
GTE/Mathematics/TanEstimate.h

**August 2, 2023.** Added the ability to discard code for fused-multiply-add (`std::fma`) if you know your target machine does not have floating-point hardware support for that instruction. The default is to compile `std::fma`. To discard this and fall back to `x*y+z` using 2 floating-point operations, define the preprocessor symbol `GTE_DISCARD_FMA`. The mechanism is simply to provide a function `gte::FMA` whose body is controlled by the preprocessor symbol.

GTE/Mathematics/Math.h  
GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSRational.h  
GTE/Mathematics/RootsQuadratic.h  
GTE/Mathematics/RootsCubic.h  
GTE/Mathematics/IntrEllipse2Ellipse2.h

**July 29, 2023.** The index `i1` was compared to the upper-bound loop counter for contiguous-open segment meshes. It needed to be `i0`.

GTE/Mathematics/SegmentMesh.h

**July 28, 2023.** Modified the interfaces to allow selection between using bisection or using the closed-form equations for root estimation. Updated the unit tests for code coverage of either selection.

GTE/Mathematics/RootsQuadratic.h  
GTE/Mathematics/RootsCubic.h  
GTE/Mathematics/RootsQuartic.h

Minor changes to avoid Visual Studio 2022 code analysis warnings.

GTE/Mathematics/UIntegerAP32.h

This file is cursed. Last check-in, I merged a line from GTL to GTE. The query result is stored in a struct [Output](#) in GTL but the GTE query result is stored in a struct [Result](#). I then failed to run my instantiation tools which would have trapped the error.

[GTE/Mathematics/DistLine3Circle3.h](#)

**July 23, 2023.** The code ported to GTL had a unit-test failure for [Robust](#) function in the case that the circle center was not the origin. The GTE unit tests did not contain such a case. One block of [Robust](#) code was missing the translation of the closest line point to the original coordinate system.

[GTE/Mathematics/DistLine3Circle3.h](#)

### 3 Updates to Version 6.6

**July 17, 2023.** Added new files for robust root estimation for polynomials of degree 1, 2, 3, and 4. These use exact rational arithmetic for theoretically correct root classification, just as [RootsPolynomial](#) does. Rather than call standard mathematics library functions for the closed-form root equations, bisection is used to avoid magnification of rounding errors inherent in power functions. The document [LowDegreePolynomialRoots.pdf](#) has a major revision to be more clear about the root estimation. This includes avoiding some of the logic tests mentioned at the Wikipedia page for quartic polynomials. The code has been unit tested for 100% coverage.

[GTE/Mathematics/PolynomialRoots.h](#)  
[GTE/Mathematics/RootsLinear.h](#)  
[GTE/Mathematics/RootsQuadratic.h](#) (re-release)  
[GTE/Mathematics/RootsCubic.h](#)  
[GTE/Mathematics/RootsQuartic.h](#)

**July 10, 2023.** Running a [ConsoleApplication](#)-derived object on a laptop with Intel Integrated Graphics (Iris Xe/UHD) and an NVIDIA GeForce RTX 3050, the Intel graphics is identified as the most powerful adapter because that adapter is associated with the primary display. It is not the most powerful. I discovered this when the Intel DLL [igc64.dll](#) threw two exceptions,

```
MONZA::DdiThreadingContext<MONZA::AdapterTraits_Gen12LP>::msg_end  
MONZA::IgcThreadingContext<MONZA::AdapterTraits_Gen12LP>::msg_end
```

during shutdown of the DX11 graphics. I had added code to [WindowApplication](#)-derived objects some time ago to choose a discrete adapter (if available) before choosing the Intel driver. That same code has now been added to the console-based application layer.

[GTE/Applications/MSW/ConsoleSystem.cpp](#)  
[GTE/Applications/MSW/WindowSystem.cpp](#)

Fixed a bug. The clamping of the infinite-cylinder closest point to the finite-cylinder closest point used height  $h$  instead of  $h/2$ . The unit tests associated with these cases were also fixed.

GTE/Mathematics/DistPoint3Cylinder3.h

**June 17, 2023.** Fixed a bug in `DoQueryOneZero` where `sMin` was set incorrectly in the case `tHat > +h/2`.

GTE/Mathematics/IntrCanonicalBox3Cylinder3.h

**June 16, 2023.** Modified the ellipse-ellipse find-intersection query code to be more robust when using floating-point arithmetic. The code still executes with rational arithmetic. Added a sample program for testing the code. The interface for `FIQuery<T,Ellipse2<T>,Ellipse2<T>` changed, so the area-of-intersection code had an obsolete interface removed. Added support for fused-multiply-add instructions.

GTE/BuildAll\*.sln  
GTE/Mathematics/Math.h  
GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSRational.h  
GTE/Mathematics/IntrEllipse2Ellipse2.h  
GTE/Mathematics/IntrAreaEllipse2Ellipse2.h  
GTE/Samples/Intersection/CMakeLists.txt  
GTE/Samples/Intersection/IntersectEllipses/\*

**June 11, 2023.** Modified the code to initial cone parameters when the caller requests initialization. The previous initialization was an implementation of an algorithm describe in the [LeastSquaresFitting.pdf](#) file, but the mathematics of the file was incorrect. Fixing the mathematics leads to having to compute roots of a degree 10 polynomial. Instead, a simpler method is provided that uses a line-fitting algorithm to determine the relationship between height  $h$  and radial distance  $r$ . The PDF itself has been modified.

GTE/Mathematics/ApprCone3.h

**May 25, 2023.** Added a new class `RootsQuadratic` for robust estimation of roots to quadratic polynomials. The robust versions for cubic and quartic polynomials use this; the work is in progress. The older code in `RootsPolynomial` will remain in GTE for now but will be deprecated in GTL.

GTE/Mathematics/RootsQuadratic.h

Added `number.Negate()` member functions to avoid the verbose `number.SetSign(-number.GetSign())`. `BSRational.SetSign` had an `mValue` block with `GTL_BINARY_SCIENTIFIC_SHOW_DOUBLE` instead of `GTE_BINARY_SCIENTIFIC_SHOW_DOUBLE`. This affected only the visualizer display of `mValue`; the rational number itself is correct.

GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSRational.h

**May 22, 2023.** The line-circle distance code had flawed logic for the case of a line not perpendicular to the plane of the circle and containing the origin. However, the block is entered when the line origin is on the normal line to the plane containing the circle center.

GTE/Mathematics/DistLine3Circle3.h

Two `std::sqrt` calls have arguments that are theoretically nonnegative, but floating-point rounding errors can lead to negative arguments. I added guards against this (clamp to nonnegative). The other `std::sqrt` calls already have the guard. The errant calls were in `SolveDepressedQuartic`. The problem was discovered during the line-circle distance query investigation.

GTE/Mathematics/RootsPolynomial.h

## 4 Updates to Version 6.5

**May 6, 2023.** Ethan Thornburg's modifications to allow disabling exceptions, calling `std::terminate()` instead.

GTE/Mathematics/Logger.h

Fedora 38 with gcc 13.1.1 compiler complained about `std::move` whose argument is a temporary object.

GTE/Mathematics/DisjointIntervals.h

Fedora 38 with gcc 13.1.1 compiler complained about potentially uninitialized variables. Add initialization even though in fact they are initialized before use (metaknowledge about the algorithm).

GTE/Mathematics/MinimalCycleBasis.h

Feature request for code to approximate continuous parametric curves with circular arcs. This includes a sample application. A PDF describing the algorithm is at the Geometric Tools website (`ApproximateCurveByArcs.pdf`).

GTE/BuildAll\*.sln  
GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/ApprCurveByArcs.h  
GTE/Samples/Mathematics/ApproximateBezierCurveByArcs/\*  
GTE/Samples/Mathematics/CMakeLists.txt

Rewrote the biquadratic implementation. The old code had a problem in one computation where subtractive cancellation caused many significant bits to be eliminated. This was the problem in the github issue about intersection of two ellipses, one rotated by  $\pi/4 + \varepsilon$  for a small epsilon. An algebraic identity was used to avoid the subtractive cancellation, and the ellipse-ellipse intersection problem was eliminated. (The problem with ellipse-ellipse intersection for rotation  $\varepsilon$  still exists when you are using floating-point arithmetic. It does not occur with rational arithmetic, but I am rewriting that code to fix the floating-point problems).

GTE/Mathematics/RootsPolynomial.h

Factored out the area computations from `IntrEllipse2Ellipse2.h` for separation of concerns.

GTE/Mathematics/IntrEllipse2Ellipse2.h  
GTE/Mathematics/IntrAreaEllipse2Ellipse2.h

The code for approximating an ellipse and points used the old OBB tree code. Modified it to use the new OBB tree code.

GTE/Mathematics/ApproxCone3EllipseAndPoints.h

Added a recomputation of `mValue` (in debug builds) when using the functions `frexp` and `ldexp` specialized to `BSRational`. Without this, the value was incorrect.

GTE/Mathematics/BSRational.h

**April 11, 2023.** Redesigned the OBB tree of points, factoring out the tree construction to `OBBTree.h`. I also fixed an incorrect sizing of the nodes of the tree. A feature request was made of an OBB tree of triangles, which was easy to implement by derivation from `OBBTree`. The `OBBTreeOfTriangles` class has additional support for computing the intersection of linear component (line, ray, segment) with a triangle mesh. I also added code for computing an OBB of segments.

GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/OBBTree.h  
GTE/Mathematics/OBBTreeOfPoints.h  
GTE/Mathematics/OBBTreeOfSegments.h  
GTE/Mathematics/OBBTreeOfTriangles.h

**March 27, 2023.** Modified `EnableTextures` to bind UAVs in pixel shaders in a single call to `OMSetRenderTargetsAndUnorderedAccessViews`. I included a lengthy comment in `EnableTextures` about why the modification is necessary.

GTE/Graphics/DX11/DX11Engine.cpp

**March 20, 2023.** Fixed a regression when switching from `<set>` to `<unordered_set>`; the hash function and equality operator incorrectly included in these functions the `ProcessedVertex` location member. Also, when the input dataset has duplicated vertices, the `InsertEdge` function needs to replace the vertex indices by the equivalence-class representatives (via `mDuplicates`) before processing the edge. The sample application has another small test dataset, this one with a duplicated vertex.

GTE/Mathematics/Delaunay2.h  
GTE/Mathematics/ConstrainedDelaunay2.h  
GTE/Samples/Geometrics/Delaunay2D/Delaunay2DWindow.cpp

**February 25, 2023.** New file for sorting points in a circular manner about a center point. The website has a PDF describing the algorithm (SortPointsOnCircle.pdf).

GTE/Mathematics/SortPointsOnCircle.h  
GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}

I have a template instantiation tool that was running debug (-g) builds. I added the ability to run release (-O2) builds. The Fedora gcc compiler warned about potentially uninitialized variables in the `FastMarch*` files. It also warned about an out-of-range index in the C++ `std::sort` code in the `DistLine3Circle3` file for the line `std::sort(candidates.begin(), candidates.begin() + numRoots)`. The `numRoots` is known not to exceed 4, but the compiler cannot determine this. I added the line `numRoots = std::min(numRoots, static_cast<size_t>(4))` before the call to `std::sort` to avoid the warning.

GTE/Mathematics/FastMarch{2,3}.h  
GTE/Mathematics/DistLine3Circle3.h

**February 20, 2023.** Eliminated the Fedora gcc12.{1,2}.1 release-build warnings about uninitialized members in `std.function.h`, probably due to incorrect optimization by the compiler. The warnings occurred in release builds of `PVWUpdater.cpp` where the member default constructors were called in the class constructors followed by a `Set` call to assign the members. I removed the `Set` calls and initialize the members directly in the constructor initializer list.

GTE/Graphics/PVWUpdater.cpp

**February 2, 2023.** Added the parent window handle to `Window::Parameters` for GTE on Microsoft Windows. That handle is passed to the `CreateWindow` functions.

GTE/Applications/MSW/Window.{h,cpp}  
GTE/Applications/MSW/WindowSystem.cpp

Added the `OnCopyData` callback for GTE on Microsoft Windows. This allows passing data from one application to another application.

GTE/Applications/WindowApplication.{h,cpp}

Fixed linter complaint suggesting that `.empty()` be used instead of `.size() == 0`.

GTE/Graphics/CLODMeshCreator.h  
GTE/Applications/MSW/WindowSystem.cpp

Added a missing pragma.

GTE/Mathematics/ContTetrahedron3.h

**January 24, 2023.** Added a new file for fitting a rectangle to a convex quadrilateral that is nearly a rectangle. The algorithm uses a least-squares formulation.

GTE/Mathematics/ApprConvexQuadByRect.h  
GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}

**January 17, 2023.** Modified `ETManifoldMesh.h` to conform to commenting standards and choosing `using` instead of `typedef`. Added explicit initialization in the constructors of nested classes. Added braces to default

constructor calls. The most important change is that during unit testing of the port of `ETManifoldMesh` from GTE to GTL, I created a small mesh for which `GetBoundaryPolygons` triggered an assertion (unexpected for a correct implementation of the algorithm). The idea of processing triangle strips at boundary vertices that are shared by 4 or more edge is correct. The code works for the strict definition of manifold mesh, where bow-tie configurations are not allowed. However, GTE has relaxed the constraint and allows bow-ties. For such meshes, the implementation of `GetBoundaryPolygons` is flawed and can lead to failure. Moreover, the approach I used in the implementation is too complicated. I re-implemented the algorithm to be simpler.

GTE/Mathematics/ETManifoldMesh.h

Modified `VETManifoldMesh.h` to conform to commenting standards and explicitly initializing nested class members in their constructors.

GTE/Mathematics/VETManifoldMesh.h

Modified `TSManifoldMesh.h` to conform to commenting standards and choosing `using` instead of `typedef`. Added explicit initialization in the constructors of nested classes. I renamed the `T` member to `S` in the nested class `Triangle`. The other mesh classes use `T` to stand for *Triangle*. Using `T` for *Tetrahedron* makes the code difficult to read at times. Switching to `S` (for *Simplex*) helps with readability. Finally, I added the keyword `virtual` to `Insert` and `Remove` to support a new class `VTSManifoldMesh` that adds vertex manipulation to the base class `TSManifoldMesh`.

GTE/Mathematics/TSManifoldMesh.h  
 GTE/Mathematics/Delaunay3.h  
 GTE/GTMathematics.{v16,v17}.{vcxproj,vcxproj.filters}  
 GTE/Mathematics/VTSManifoldMesh.h

The static 2-manifold class has a member function `GetBoundaryPolygons`, just as the dynamic class `ETManifoldMesh` does. This function has the same flawed implementation mentioned previously. It is now re-implemented using the same approach as in `ETManifoldMesh`.

GTE/Mathematics/StaticVETManifoldMesh2.h

Added a static 3-manifold class for tetrahedra meshes. This is significantly faster than the dynamic classes `TSManifoldMesh` and `VTSManifoldMesh`.

GTE/Mathematics/StaticVTSManifoldMesh3.h

Added newer static manifold mesh classes, `MeshStaticManifold2` and `MeshStaticManifold3`, that perform better than `StaticVETManifoldMesh2` and `StaticVTSManifoldMesh3`. The newer classes are also multithreaded. The older static classes will be deprecated for GTL in favor of the newer static classes.

GTE/Mathematics/MeshStaticManifold2.h  
 GTE/Mathematics/MeshStaticManifold3.h



**Important Note.** `ETManifoldMesh`, `VETManifoldMesh` and `StaticVETManifoldMesh2` store adjacency pointers and indices according to the following design: Let the triangle have ordered vertices  $(V[0], V[1], V[2])$ . The triangle adjacent to edge  $(V[0], V[1])$  is  $A[0]$ . The triangle adjacent to edge  $(V[1], V[2])$  is  $A[1]$  and the triangle adjacent to edge  $(V[2], V[0])$  is  $A[2]$ . The new class `MeshStaticManifold2` uses a different design: The triangle adjacent to edge  $(V[1], V[2])$  is  $A[0]$ , the triangle adjacent to edge  $(V[2], V[0])$  is  $A[1]$  and the triangle adjacent to edge  $(V[0], V[1])$  is  $A[2]$ . That is,  $A[i]$  is the triangle adjacent to the edge opposite vertex  $V[i]$ .

The design for the new 2-manifold triangle meshes is consistent with the design of the 3-manifold tetrahedra meshes `TSManifoldMesh` and `VTSManifoldMesh`. Let the tetrahedron have ordered vertices  $(V[0], V[1], V[2], V[3])$ . The triangle faces are counterclockwise ordered when viewed from outside the tetrahedron,  $T[0] = (V[1], V[2], V[3])$ ,  $T[1] = (V[0], V[3], V[2])$ ,  $T[2] = (V[0], V[1], V[3])$  and  $T[3] = (V[0], V[2], V[1])$ . Each face is opposite the vertex that is not listed in the face. The tetrahedron adjacent to face  $T[i]$  is  $A[i]$ . Unfortunately, I had not noticed previously that the primitive class `Tetrahedron3` assigns the faces in the opposite order:  $T[0] = (V[0], V[2], V[1])$ ,  $T[1] = (V[0], V[1], V[3])$ ,  $T[2] = (V[0], V[3], V[2])$  and  $T[3] = (V[1], V[2], V[3])$ .

The edge and face design in GTL will be consistent and uses the designs of `MeshStaticManifold2` and `MeshStaticManifold3`.

The profiling results are listed next for the 2-manifold classes, running on an Intel i9-10900 CPU. The test triangle mesh has 1048576 vertices and 2097117 triangles.

class	numThreads	milliseconds
VETManifoldMesh	1	8471
StaticVETManifoldMesh2	1	1129
	2	904
	4	817
	8	761
	16	759
MeshStaticManifold2	1	816
	2	629
	4	526
	8	542
	16	551

The profiling results are listed next for the 3-manifold classes, running on an Intel i9-10900 CPU. The test tetrahedron mesh has 262144 vertices and 1765604 tetrahedra.

class	numThreads	milliseconds
VTSManifoldMesh	1	10706
StaticVTSManifoldMesh3	1	2035
	2	1512
	4	1256
	8	1160
	16	1092
MeshStaticManifold3	1	2202
	2	691
	4	507
	8	391
	16	362

**January 11, 2023.** The [Error](#) function and the comment in the file about the error formula were incorrect. They appear to have been copied-and-pasted from the [ApprOrthogonalLine3.h](#) implementation. The error code was introduced in the port from WM5 to GTE1. Thanks to Scott Johnson for informing me about the mistakes.

[GTE/Mathematics/ApprOrthogonalPlane3.h](#)

**January 4, 2023.** The posted file [StaticVETManifoldMesh2.h](#) was out of sync with the development version and was missing the initialization of the members of [mAdjacents](#) to *invalid* (-1). I also modified some comments and added some [const](#) modifiers where necessary.

[GTE/Mathematics/StaticVETManifoldMesh2.h](#)

**January 1, 2023.** New file that provides an additional speed-up to [VETManifoldMeshNR](#) for constructing static vertex-edge-triangle manifold meshes from collections of triangles.

[GTE/GTMathematics.{v16,v17}.vcxproj\\*](#)  
[GTE/Mathematics/StaticVETManifoldMesh2.h](#)

**December 24, 2022.** Feature request for polyline/polygon offset. The code and a sample application has been added.

[GTE/GTMathematics.\\*.\\*](#)  
[GTE/Mathematics/PolylineOffset.h](#)  
[GTE/BuildAll\\*.sln](#)  
[GTE/Samples/Geometrics/CMakeLists.txt](#)  
[GTE/Samples/Geometrics/PolylineOffset/\\*](#)

## 5 Updates to Version 6.4

**December 14, 2022.** The following are modifications based on complaints from ClangCL for v143 MSVS tools regarding unused variables. The unused variables were actually used in the code (for watching during debugging), but the final values were never consumed by the functions.

[GTE/Graphics/Shader.cpp](#) ([handle](#))  
[GTE/Graphics/GL45/GLSLShader.cpp](#) ([blockIndex](#))  
[GTE/Samples/Intersection/IntersectConvexPolyhedra/ConvexPolyhedron.h](#) ([numZero](#))  
[GTE/Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow3.cpp](#) ([hr](#))  
[GTE/Samples/Physics/RoughPlaneParticle1/RoughPlaneParticle1Window2.h](#) ([mSize](#))  
[GTE/Samples/Physics/WrigglingSnake/WrigglingSnakeWindow3.cpp](#) ([t](#))

Added [override](#) to [DrawScreenOverlay](#) to resolve ClangCL complaint.

[GTE/Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow2.h](#)

Added `override` to `DrawScreenOverlay` to resolve ClangCL complaint.

`GTE/Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow2.h`

**December 12, 2022.** Added new code and sample application for 2D find-intersection queries between a linear component (line, ray, segment) and a segment mesh.

`GTE/GTMathematics.*`  
`GTE/Mathematics/IntrLine2SegmentMesh2.h`  
`GTE/Mathematics/IntrRay2SegmentMesh2.h`  
`GTE/Mathematics/IntrSegment2SegmentMesh2.h`  
`GTE/BuildAll*.sln`  
`GTE/Samples/Intersection/CMakeLists.txt`  
`GTE/Samples/Intersection/IntersectRayPolygon/*`

**December 1, 2022.** Added new 2D distance queries for point-circle and point-arc. Also fixed some missing header file references in the `GTMathematics.v16` project.

`GTE/Mathematics/DistPoint2Arc2.h`  
`GTE/Mathematics/DistPoint2Circle2.h`  
`GTE/GTMathematics.{v16,v17}.vcxproj`  
`GTE/GTMathematics.{v16,v17}.vcxproj.filters`

**November 27, 2022.** The `CopyBackBuffer` call mapped `mBackBufferStaging` but failed to unmap it after the copy.

`GTE/Graphics/DX11/DX11Engine.cpp`

**November 11, 2022.** Rolling back the changes from the 4 November 2002 update. The code is faster but the rounding errors cause misclassification of the number of points of intersection. Welcome to the trade-off of floating-point versus rational arithmetic. At some point I need to implement rational arithmetic classes using the GNU Multiprecision Library to take advantage of the better performance for arbitrary precision multiplication. At a later date, I can implement a similar speed-up for `BSNumber` and `BSRational`.

`GTE/Mathematics/IntrEllipse2Ellipse2.h`

**November 4, 2022.** When using `BSRational<UIntegerAP32>` for template type `T`, the number of words used in the `SolveQuartic` root finder can be extremely large—on the order of 100000. This leads to poor performance. The root finder has numerical rounding errors whether `T` is a floating-point type or a rational type, so to avoid the poor performance, the rational-valued quartic coefficients are converted to `double` and then reconverted to `T`. This introduces a small amount of rounding error, but performance is significantly better.

`GTE/Mathematics/IntrEllipse2Ellipse2.h`

**November 2, 2022.** Added a fuzzy containment that tests whether a point is on a circular arc. The non-fuzzy containment requires the point to be on the circle of the arc (or nearly on the circle within floating-point rounding errors).

GTE/Mathematics/Arc2.h

**October 17, 2022.** Back-ported [QuadricSurface](#) from GTL to GTE, both versions unit tested.

GTE/Mathematics/QuadricSurface.h

**September 23, 2022.** Fixed a bug in [ComputeSqrDistance](#) on line 247 (incorrect sign on  $s$ ). Thanks to Tom Foster for reporting the bug.

GTE/Mathematics/IntrCanonicalBox3Cylinder3.h

**August 25, 2022.** Reimplemented the TCB spline code based on the rewrite of the PDF document *Kochanek–Bartels Cubic Splines (TCB Splines)*. I removed the tangent adjustments suggested by Kochanek and Bartels (based on discrete variables), replacing them with adjustments based on continuous variables. I added support for specifying the boundary tangents explicitly rather than duplicating the endpoints of the keyframes and computing the boundary tangents internally. Finally, I added a parameter ( $\lambda$ ) per key frame position to control the speed at those positions and ensure continuity of speed.

GTE/Mathematics/TCBSplineCurve.h

**August 23, 2022.** Feature request for code to compute the minimum-area aligned box that contains a circular arc.

GTE/Mathematics/ContAlignedBox2Arc2.h

**August 16, 2022.** Reset some `std::vector` arrays for re-use of the `operator()` function. Added `mConvexHull3` member and accessor (from Leopard20 at github). Modified the file version.

GTE/Mathematics/MinimumVolumeBox3.h

**July 13, 2022.** The managed library project compiles with the directory structure of GTE, but if folders are moved elsewhere, the managed library needed `$(GTE_PATH)` for the header search path. `GTE_PATH` is an environment variable that stores the path to the top-level folder `GeometricTools/GTE` (see the installation and release notes).

GTE/Samples/CSharpCppManaged/ManagedLibrary/ManagedLibrary.\*;vcxproj

**July 12, 2022.** Removed the file `ManagedObject.h`, consolidating the contents with the managed files `MinimumVolumeBox.{h,cpp}`. Updated the copyright date in the assembly file. Modified the comments in the program file.

GTE/Samples/CSharpCppManaged/CSharpCppManaged\*.sln  
GTE/Samples/CSharpCppManaged/ManagedLibrary/ManagedLibrary.\*  
GTE/Samples/CSharpCppManaged/ManagedLibrary/MinimumVolumeBox.{h,cpp}  
GTE/Samples/CSharpCppManaged/ManagedLibrary/ManagedObject.h  
GTE/Samples/CSharpCppManaged/CSharpApplication/Properties/AssemblyInfo.cs  
GTE/Samples/CSharpCppManaged/CSharpApplication/Program.cs

**July 4, 2022.** The [Window2](#) class was implemented not to allow window resizing. I removed this constraint and added comments in the header file about the responsibilities of an application class derived from [Window2](#). The 2D fluid simulation sample application was modified to illustrate the resizing.

```
GTE/Applications/Window2.{h,cpp}  
GTE/Samples/Physics/Fluids2D/Fluids2DMain.cpp  
GTE/Samples/Physics/Fluids2D/Fluids2DWindow2.{h,cpp}
```

Modified comments that referred to the old file names [GteSOMEFILE.h](#), replacing them by [SOMEFILE.h](#).

```
GTE/Applications/Window2.cpp  
GTE/Graphics/DX11/DX11InputLayout.h  
GTE/Mathematics/ApprCone3.h  
GTE/Mathematics/ApprTorus3.h  
GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSplineReduction.h  
GTE/Mathematics/Cone.h  
GTE/Mathematics/Math.h  
GTE/Mathematics/MinimumAreaCircle2.h  
GTE/Mathematics/MinimumVolumeSphere3.h  
GTE/Mathematics/Quaternion.h  
GTE/Mathematics/SlerpEstimate.h
```

**June 29, 2022.** The [IsOnSurface](#) function is a copy-and-paste error from the implicit curve file. I modified the name to [IsOnCurve](#). I also set the output [curvature](#) on early exit in order not to leave output uninitialized.

```
GTE/Mathematics/ImplicitCurve2.h
```

Greatly simplified the implementation based on a revision of the document [PrincipleCurvature.pdf](#).

```
GTE/Mathematics/ImplicitSurface3.h
```

**June 26, 2022.** Added a new class [VETManifoldMeshNR](#) which represents a vertex-edge-triangle manifold mesh for which triangles are provided as a single batch and NO REMOVE operations are going to be performed on the mesh. [VETManifoldMeshNR](#) significantly outperforms [VETManifoldMesh](#). [VETManifoldMesh](#) is general purpose, allowing triangle insertions and triangle removals. The underlying C++ container classes lead to significant memory allocation/deallocation costs and are also expensive for find operations. It turns out that the design of [VETManifoldMeshNR](#) automatically gives you vertex adjacency information, so there is no [ETManifoldMeshNR](#) implementation. It is a requirement that the input triangles form a manifold mesh with consistently ordered triangles. In most applications, this requirement is already satisfied.

```
GTE/Mathematics/VETManifoldMeshNR.h
```

The [VETManifoldMeshNR](#) class is designed to minimize the allocations. For example, using this class for a collection of 1131652 positions and 2242293 triangles, the CPU times on an Intel (R) Core (TM) i9-10900 are as follows.

	ETManifoldMesh	VETManifoldMeshNR
graph creation	2234 milliseconds	118 milliseconds
connected component labeling	2169 milliseconds	40 milliseconds
get boundary polygons	232 milliseconds	25 milliseconds

Added comments to indicate that **VETManifoldMeshNR** might be a better choice for your application if it meets the preconditions.

GTE/Mathematics/ETManifoldMesh.h  
GTE/Mathematics/VETManifoldMesh.h

## 6 Updates to Version 6.3

**June 8, 2022.** Added new files that contain an efficient implementation of natural cubic splines and natural quintic splines. The PDF documentation has been revised accordingly, <https://www.geometrictools.com/Documentation/NaturalSplines.pdf>. The class **NaturalSplineCurve** will be deprecated in favor of the new classes.

GTE/Mathematics/NaturalCubicSpline.h  
GTE/Mathematics/NaturalQuinticSpline.h

Fixed gcc compiler warnings (signed/unsigned integer comparisons).

GTE/Mathematics/NaturalSplineCurve.h

Fixed gcc errors about the keyword **template** required before the dependent typenames involving the **Degree\*** function calls. The errors occurred with gcc 12.1.1 on Fedora 36 but not with gcc 9.3.0 on Ubuntu or with Microsoft compilers.

GTE/Mathematics/ASinEstimate.h  
GTE/Mathematics/ExpEstimate.h  
GTE/Mathematics/LogEstimate.h

Fixed an error in the deprecated file for **UniqueVerticesTriangles**; the `<array>` header is not explicitly included. This occurred with gcc 12.1.1 on Fedora 36 even though my instantiation tool did not include explicit instantiation for that class. The error did not occur with gcc 9.3.0 on Ubuntu 20.04.1 LTS or Microsoft Visual Studio when running the tool.

GTE/Mathematics/UniqueVerticesTriangles.h

Modified code to avoid a potentially uninitialized variable warning from gcc 12.1.1 on Fedora 36.

GTE/Samples/Geometrics/IncrementalDelaunay2/IncrementalDelaunay2Window2.cpp  
GTE/Samples/Intersection/IntersectTriangles2D/IntersectTriangles2DWindow2.cpp  
GTE/Samples/Mathematics/Interpolation2DWindow3.cpp

Fedora 36 with gcc 12.1.1 complains about potential index-out-of-range because `Evaluate` references all possible elements, but the compiler is unaware that the logic of `Evaluate` is designed to assign only those elements that are valid. For now, I am passing in an array of 3-tuples knowing that only one will be filled in. Added arrays of  $N$ -tuples to avoid the warnings.

GTE/Mathematics/ParametricCurve.h  
GTE/Mathematics/ParametricSurface.h  
GTE/Samples/Mathematics/BSplineCurveReduction/BSplineCurveReductionWindow3.cpp

**June 4, 2022.** The constructor for free or closed splines allocated more than enough elements for `mCoefficients` and the `GetNumPoints()` function returned the number of points based on the size of `mCoefficients`. The constructor for clamped splines allocated exactly the correct number of elements for `mCoefficients`, but then `GetNumPoints()` returned the incorrect number of points. This caused too few points to be processed in clamped splines. This occurred when the optimization was added to minimize memory allocations and deallocations for free splines. The optimization code has been reworked and the same memory optimization was added for closed and clamped splines.

GTE/Mathematics/NaturalSplineCurve.h

**May 30, 2022.** The `IsPowerOfTwo(int32_t)` function called itself (infinite recursion). Modified the static cast to use `uint32_t` as intended.

GTE/Mathematics/BitHacks.h

**May 16, 2022.** In the GTL development, fixed a bug in the `Inverse` function for `Transform<T>` objects. The unit tests were incomplete in that they tested the inverse directly using queries to the internal matrices of `Transform<T>` rather than verifying the correctness of the output of `Inverse`. The corrections were backported to GTE.

GTE/Mathematics/Transform.h

The `RectangleManager` code was copied, pasted and modified to produce the `BoxManager` code. The comments were part of this and the `BoxManager` code referred to rectangles rather than boxes. Also, non-const references in both classes were modified to const references.

GTE/Mathematics/BoxManager.h  
GTE/Mathematics/RectangleManager.h

## 7 Updates to Version 6.2

**April 3, 2022.** By user request, on Microsoft Windows I added virtual `OnWindowsMessage` to `WindowApplication` and called by `WindowSystem::WindowProcedure`. This allows the application to use a third-party UI package, processing windows messages intended for that package. A return value of `true` tells the window procedure not to pass the message to the application window.

GTE/Applications/WindowApplication.{h,cpp}  
GTE/Applications/MSW/WindowSystem.cpp

**April 2, 2022.** Ported the Wild Magic 5 graphics sample [ShadowMaps](#) to GTE6. This is the last of the Wild Magic code I had planned on porting.

GTE/BuildAll\*.\*  
GTE/Samples/Graphics/CMakeLists.txt  
GTE/Samples/Graphics/ShadowMaps/\*  
GTE/Samples/Data/Stone.png

**March 29, 2022.** Ported the Wild Magic 5 [MeshSmoother](#) class to GTE6.

GTE/Mathematics/MeshSmoother.h

**March 28, 2022.** I finally trapped the problem with Windows OpenGL (WGL) where the first-drawn frame is not correct. I added a swap-buffers call immediately after creating the [WGLEngine](#) object (in the application layer), which eliminated the problem.

GTE/Applications/MSW/WindowSystem.cpp

Ported the Wild Magic 5 skinning sample to GTE6.

GTE/BuildAll\*.\*  
GTE/Samples/Graphics/CMakeLists.txt  
GTE/Samples/Graphics/Skinning/\*

Added new constructors to avoid the repeated pattern of default construction of [MeshFactory](#) followed by the [SetVertexFormat](#) call.

GTE/Graphics/MeshFactory.{h,cpp}

Ported the line-torus find-intersection query from Wild Magic5 to GTE6 (at user request). Added a sample application to show that the code is working correctly. Internal unit tests have also been added.

GTE/BuildAll\*.\*  
GTE/GTMathematics\*.\*  
GTE/Mathematics/IntrLine3Torus3.h  
GTE/Samples/Intersection/CMakeLists.txt  
GTE/Samples/Intersection/IntersectLine3Torus3/\*

**March 25, 2022.** The current 2D segment-segment queries use the find-intersection query for two lines, but the segments are converted to center-direction-extent form. The two-point representation has endpoints  $p_0$  and  $p_1$  and the parameterization is  $p_0 + t(p_1 - p_0)$  for  $t \in [0, 1]$ . The center-direction-extent form is  $c + sd$  for  $|s| \leq e$ . The center is  $c = (p_0 + p_1)/2$ , the direction is  $d = (p_1 - p_0)/|p_1 - p_0|$  and the extent is



$e = |p_1 - p_0|/2$ . The computation of  $d$  involves a normalization which generally cannot be computed exactly with rational arithmetic. The computation of  $e$  is also not exact. The segment parameters returned from the queries are relative to  $s$ , not to  $t$ . The old queries are `operator()` functions and still exist. To allow for exact rational computation, I added new queries named `Exact` which uses the two-point form for segments. [In GTL development, I have been eliminating the use of the segment center-direction-extent form.]

GTE/Mathematics/IntrSegment2Segment2.h

The code had a call `Normalize(diff)` that is not necessary because the sign tests dependent on `diff` are (theoretically) independent of the length of `diff`. Removing the normalize call now allows the code to produce theoretically correct results when type `T` is a rational type.

GTE/Mathematics/IntrLine2Line2.h

Replace parenthesized casts by `static_casts`.

GTE/Mathematics/IntrLine2Line2.h  
 GTE/Mathematics/IntrLine2Ray2.h  
 GTE/Mathematics/IntrLine2Segment2.h  
 GTE/Mathematics/IntrRay2Ray2.h  
 GTE/Mathematics/IntrRay2Segment2.h  
 GTE/Mathematics/IntrSegment2Segment2.h

**March 23, 2022.** The `SetRow` function was missing a return statement.

GTE/Mathematics/GMatrix.h

**March 22, 2022.** Added abstract base classes for implicit curves in 2D, class `ImplicitCurve2`, and implicit surface in 3D, class `ImplicitSurface3`. The latter is a port of `ImplicitSurface` from Wild Magic 5. These classes support computation of coordinate frames and curvature information. For parametric curves and surfaces, see `FrenetFrame` and `DarbouxFrame`.

GTE/GTMathematics.\*  
 GTE/Mathematics/ImplicitCurve2.h  
 GTE/Mathematics/ImplicitSurface3.h

Ported the Wild Magic 5 graphics sample `VolumeFog` to GTE6.

GTE/BuildAll\*  
 GTE/GTGraphics.\*.\*  
 GTE/Graphics/GTGraphics.h  
 GTE/Graphics/VolumeFogEffect.{h,cpp}  
 GTE/Samples/Graphics/CMakeLists.txt  
 GTE/Samples/Graphics/VolumeFog/\*  
 GTE/Data/BlueSky.png  
 GTE/Data/Shaders/VolumeFogEffect.{vs,ps}.{hlsl,glsl}

Fixed the minor number in file versions. Looks like versioning is the bane of the month.

```
GTE/Graphics/BoundTree.h
GTE/Graphics/CollisionGroup.h
GTE/Graphics/CollisionMesh.{h,cpp}
GTE/Graphics/CollisionRecord.h
GTE/Graphics/PlanarShadowEffect.{h,cpp}
GTE/Mathematics/ApproxCone3EllipseAndPoints.h
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/FitConeByEllipseAndPoints*.{h,cpp}
GTE/Samples/Physics/CollisionsBoundTree/CollisionsBoundTree*.{h,cpp}
GTE/Samples/Physics/CollisionsMovingSpheres/CollisionsMovingSpheres*.{h,cpp}
GTE/Samples/Physics/CollisionsMovingSphereTriangle/CollisionsMovingSphereTriangle*.{h,cpp}
```

**March 21, 2022.** Ported the Wild Magic 5 sample [CollisionsMovingSphereTriangle](#) to GTE6.

```
GTE/BuildAll*
GTE/Samples/Physics/CMakeLists.txt
GTE/Samples/Physics/CollisionsMovingSphereTriangle/*
```

**March 20, 2022.** Ported the Wild Magic 5 sample [CollisionsMovingSpheres](#) to GTE6. The [CollisionsBoundTree](#) sample should have been in the Physics folder.

```
GTE/BuildAll*
GTE/Samples/SceneGraphs/CMakeLists.txt
GTE/Samples/Physics/CMakeLists.txt
GTE/Samples/Physics/CollisionsMovingSpheres/*
GTE/Samples/SceneGraphs/CollisionsBoundTree/*
GTE/Samples/Physics/CollisionsBoundTree/*
```

Ported the Wild Magic 5 collision detection code to GTE6: [BoundTree](#), [CollisionGroup](#) and [CollisionRecord](#). Added a wrapper class, [CollisionMesh](#), that provides the interface to a [Visual](#)-based triangle mesh to be used at a template parameter for the collision detection code. Added test-intersection and find-intersection queries for moving triangles. Ported the WM5 sample [CollisionsBoundTree](#) to illustrate use of the collision detection.

```
GTE/GTGraphics.{v16,v16}.vcxproj
GTE/GTGraphics.{v16,v16}.vcxproj.filters
GTE/Graphics/GTGraphics.h
GTE/Graphics/CMakeLists.txt
GTE/Mathematics/IntrTriangle3Triangle3.h
GTE/Samples/CMakeLists.txt
GTE/Graphics/BoundTree.h
GTE/Graphics/CollisionGroup.h
GTE/Graphics/CollisionRecord.h
GTE/Graphics/CollisionMesh.{h,cpp}
GTE/Samples/SceneGraphs/CollisionsBoundTree/*
```

I forgot to update the minor version from 1 to 2 when I posted GTE6.2. Time to automate this step.

GTE/CMakeLists.txt  
GTE/Samples/CMakeLists.txt  
GTE/Samples/Distance/CMakeLists.txt  
GTE/Samples/Geometrics/CMakeLists.txt  
GTE/Samples/Graphics/CMakeLists.txt  
GTE/Samples/Imagics/CMakeLists.txt  
GTE/Samples/Intersection/CMakeLists.txt  
GTE/Samples/Mathematics/CMakeLists.txt  
GTE/Samples/Physics/CMakeLists.txt  
GTE/Samples/SceneGraphs/CMakeLists.txt

**March 18, 2022.** Fixed a bug in [ContainsPoint](#). Modified the internal unit tests to include the test that exposes the bug.

GTE/Mathematics/IntrTriangle3Triangle3.h

Removed the MSVS 2015 and MSVS 2017 versions of the C#/managed/C++ projects because I no longer support these compilers. The MSVS 2019 projects still exist. I added projects for MSVS 2022. Fixed the path problem in the MSVS 2019 version (modified environment variable from [GTE4.PATH](#) to [GTE.PATH](#)).

GTE/Samples/CSharpCppManaged/CSharpCppManaged.{v14,v15}.sln  
GTE/Samples/CSharpCppManaged/CSharpApplication/CSharpApplication.{v14,v15}.csproj  
GTE/Samples/CSharpCppManaged/CppLibrary/CppLibrary.{v14,v15}.\*  
GTE/Samples/CSharpCppManaged/ManagedLibrary/ManagedLibrary.{v14,v15}.\*  
GTE/Samples/CSharpCppManaged/CppLibrary/CppLibrary.v16.vcxproj  
GTE/Samples/CSharpCppManaged/CSharpCppManaged.v16.sln  
GTE/Samples/CSharpCppManaged/CSharpApplication/CSharpApplication.v16.csproj  
GTE/Samples/CSharpCppManaged/CppLibrary/CppLibrary.v16.\*  
GTE/Samples/CSharpCppManaged/ManagedLibrary/ManagedLibrary.v16.\*

**March 13, 2022.** The [Math.h](#) file generated compiler errors when I used one of the inline non-templated functions (needed [<cstdint>](#)). The [UniqueVerticesTriangles.h](#) file generated compiler errors when I tried to use it (needed [<set>](#)). This file is deprecated, but until it is removed it needs to compile. I updated my internal instantiation tool to handle these files appropriately.

GTE/Mathematics/Math.h  
GTE/UniqueVerticesTriangles.h

## 8 Updates to Version 6.1

**March 7, 2022.** The planar reflection constructor had out-of-order initialization of members, and gcc on Linux complained about this. The Microsoft compilers (2019/2022) did not complain. I also removed a block of code in the constructor (unexposed in a conditional compilation block) that was moved to a class member function.

GTE/Graphics/PlanarReflectionEffect.cpp

The change to the interface for `PlanarReflectionEffect` required changes to the bouncing ball sample application.

`GTE/Samples/Physics/BouncingBall/BouncingBallWindow3.{h,cpp}`

The `MinimumWidthPoints2` class is templated with class `T`. It contained a line `using RotatingCalipers = typename RotatingCalipers<T>` which Microsoft compilers allow. The gcc compilers complained about the `typename`, so I removed it. I removed two unused variables. There was a sign mismatch in a loop counter.

`GTE/Mathematics/MinimumWidthPoints2.h`

Removed unused lines of code (old iterator code that was replaced by range-based iteration) and fixed a sign mismatch in a loop. Removed the declaration for `static constexpr maxFloat = std::numeric_limits<float>::max();` and now use the `max()` value itself in the code. I must be missing something about declaring class-member `constexpr` values; the loader for gcc complained that `maxFloat` is undefined. The Microsoft compilers (2019/2022) never complain about such a declaration.

`GTE/Graphics/CLODMeshCreator.h`

An unreferenced variable for the camera position needed to be accessed in two lines of code rather than re-lookup the variable.

`GTE/Samples/Physics/DLODNodes/DLODNodesWindow3.cpp`

The gcc compiler complained about the compound Boolean expression in the `GTE_ASSERT` statement in `SwitchNode::SetActiveChild`. It wanted parentheses around the `and` expression.

`GTE/Graphics/SwitchNode.cpp`

The CMake list of source files needed to be updated for `PlanarShadowEffect.cpp`, `SwitchNode.cpp`, `CLODMesh.cpp` and `DLODNode.cpp`.

`GTE/Graphics/CMakeLists.txt`

**March 6, 2022.** I wrote a GTE6 sample application for planar shadows that is similar to the one for Wild Magic 5. I revised the planar reflections code so that the two effects have essentially the same design.

`GTE/BuildAll*.sln`

`GTE/Graphics/PlanarShadowEffect.{h,cpp}`

`GTE/Graphics.h`

`GTE/Samples/Graphics/PlanarShadows/PlanarShadows*.vcxproj`

`GTE/Samples/Graphics/PlanarShadows/PlanarShadows*.vcxproj.filter`

`GTE/Samples/Graphics/PlanarShadows/PlanarShadowsMain.cpp`

`GTE/Samples/Graphics/PlanarShadows/PlanarShadowsWindow3.{h,cpp}`

`GTE/Samples/Graphics/PlanarShadows/PlanarShadows.code-workspace`

`GTE/Samples/Graphics/PlanarShadows/CMakeLists.txt`

```

GTE/Samples/Graphics/PlanarShadows/CMakeSample.sh
GTE/Samples/Graphics/PlanarShadows/cmake-variants.json
GTE/Samples/Graphics/PlanarShadows/.vscode/launch.json
GTE/Samples/Graphics/PlanarShadows/.vscode/settings.json
GTE/Samples/Graphics/CMakeLists.txt
GTE/Graphics/PlanarReflectionEffect.{h,cpp}
GTE/Samples/Graphics/PlanarReflections/PlanarReflectionsMain.cpp
GTE/Samples/Graphics/PlanarReflections/PlanarReflectionsWindow3.{h,cpp}

```

**March 4, 2022.** I wrote a GTE6 sample application for planar reflections that is similar to the one for Wild Magic 5. The `PlanarReflectionEffect` drawing function had a bug. It needed to set the back-face stencil parameters in addition to the front-face stencil parameters. Without the back-face parameters, the reflection caster was drawn on both sides of the reflection plane.

```

GTE/BuildAll*.sln
GTE/Samples/Graphics/PlanarReflections/PlanarReflections*.vcxproj
GTE/Samples/Graphics/PlanarReflections/PlanarReflections*.vcxproj.filter
GTE/Samples/Graphics/PlanarReflections/PlanarReflections.cpp
GTE/Samples/Graphics/PlanarReflections/PlanarReflectionsWindow3.{h,cpp}
GTE/Samples/Graphics/PlanarReflections/PlanarReflections.code-workspace
GTE/Samples/Graphics/PlanarReflections/CMakeLists.txt
GTE/Samples/Graphics/PlanarReflections/CMakeSample.sh
GTE/Samples/Graphics/PlanarReflections/cmake-variants.json
GTE/Samples/Graphics/PlanarReflections/.vscode/launch.json
GTE/Samples/Graphics/PlanarReflections/.vscode/settings.json
GTE/Samples/Graphics/CMakeLists.txt
GTE/PlanarReflectionEffect.{h,cpp}

```

After looking at the requirements for the feature request, I modified the return value of `MinimumWidthPoints2::operator()` to be `OrientedBox2<T>` to be consistent with the minimum-area box code. The sample application now draws the minimum-area box and the minimum-width box for comparison.

```

GTE/Mathematics/MinimumWidthPoints2.h
GTE/Samples/Geometrics/MinimumAreaBox2DWindow2.{h,cpp}

```

**March 3, 2022.** Added an implementation of the rotating calipers algorithm, class `RotatingCalipers`. The goal was to refactor `MinimumAreaBox2` to pull out the rotating calipers. However, this does not work because the minimum-area algorithm uses a pair of rotating calipers that work together. Added a new class `MinimumWidthPoints2` that uses the rotating calipers algorithm to compute the width of a 2D point set. For now I have modified the `MinimumAreaBox2D` sample application to show also the results from computing the width of a point set. I also cleaned up the comments to use current formatting rules. And I added functions to allow passing `std::vector` inputs rather than raw pointers.

```

GTE/Mathematics/RotatingCalipers.h
GTE/Mathematics/MinimumWidthPoints2.h
GTE/Mathematics/MinimumAreaBox2.h
GTE/Mathematics/GTMathematics*.vcxproj

```

GTE/Mathematics/GTMathematics\*.vcxproj.filters  
GTE/Samples/Geometrics/MinimumAreaBox2DWindow2.{h,cpp}

The [ConvexHull2](#) class was supposed to have switched from [FPIInterval](#) to [SWInterval](#), but I apparently overlooked this. The [FPIInterval](#) class uses floating-point hardware operations to support interval arithmetic; however, the GCC compiler ignores the changes to the floating-point environment (it does not support modifying the rounding mode of the FPU). The [SWInterval](#) class implements interval arithmetic and rounds using software operations.

GTE/Mathematics/ConvexHull2.h

Two class members were not initialized by the constructor.

GTE/Graphics/DLODNode.cpp

**February 25, 2022.** Feature request to fit a cone to known elliptical cross sections and some additional points ([ApprCone3EllipseAndPoints](#)). If the cross sections are provided as point samples approximately on the ellipses, the new code also includes a class to extract points for each ellipse because the points might be stored in a file in some unknown order ([ApprCone3ExtractEllipses](#)). 3D ellipses are then fit to each subset of points in order to obtain the ellipse input to [ApprCone3EllipseAndPoints](#). A PDF has been added to the documentation to describe the fitting algorithm, [FitConeToEllipseAndPoints.pdf](#).

GTE/BuildAll\*.sln  
GTE/Mathematics/GTMathematics\*.vcxproj  
GTE/Mathematics/GTMathematics\*.vcxproj.filters  
GTE/Mathematics/ApprCone3EllipseAndPoints.h  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/FitConeByEllipseAndPoints\*.vcxproj  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/FitConeByEllipseAndPoints\*.vcxproj.filter  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/FitConeByEllipseAndPointsMain.cpp  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/FitConeByEllipseAndPointsWindow3.{h,cpp}  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/Data/CircleAndVertex.txt  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/Data/OneCircleOneEllipse.txt  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/Data/TwoEllipses.txt  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/Data/TwoPartialEllipses.txt  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/FitConeByEllipseAndPoints.code-workspace  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/CMakeLists.txt  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/CMakeSample.sh  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/cmake-variants.json  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/.vscode/launch.json  
GTE/Samples/Mathematics/FitConeByEllipseAndPoints/.vscode/settings.json  
GTE/Samples/Mathematics/CMakeLists.txt

**February 24, 2022.** Ported the WM5 classes [ClodMesh](#), [CreateClodMesh](#) and [CollapseRecord](#) to GTE6 classes [CLODMesh](#), [CLODMeshCreator](#) and [CLODCollapseRecord](#). Ported the WM5 sample [ClodMeshes](#) to the GTE6 sample [CLODMeshes](#).

GTE/BuildAll\*.sln  
GTE/Graphics/GTGraphics.h

```

GTE/Graphics/GTGraphics*.vcxproj
GTE/Graphics/GTGraphics*.vcxproj.filters
GTE/Graphics/CLODMeshCreator.h
GTE/Graphics/CLODMesh.{h,cpp}
GTE/Graphics/CLODCollapseRecord.h
GTE/Samples/SceneGraphs/CLODMeshes/CLODMeshes*.vcxproj
GTE/Samples/SceneGraphs/CLODMeshes/CLODMeshes*.vcxproj.filter
GTE/Samples/SceneGraphs/CLODMeshes/CLODMeshesMain.cpp
GTE/Samples/SceneGraphs/CLODMeshes/CLODMeshesWindow3.{h,cpp}
GTE/Samples/SceneGraphs/CLODMeshes/Data/FunctionX64Y64R8.png
GTE/Samples/SceneGraphs/CLODMeshes/CLODMeshes.code-workspace
GTE/Samples/SceneGraphs/CLODMeshes/CMakeLists.txt
GTE/Samples/SceneGraphs/CLODMeshes/CMakeSample.sh
GTE/Samples/SceneGraphs/CLODMeshes/cmake-variants.json
GTE/Samples/SceneGraphs/CLODMeshes/.vscode/launch.json
GTE/Samples/SceneGraphs/CLODMeshes/.vscode/settings.json
GTE/Samples/SceneGraphs/CMakeLists.txt

```

**February 11, 2022.** Modified the [GenerateProject](#) tool to generate the Visual Studio Code workspace files for sample applications.

```

GTE/Tools/GenerateProject/GenerateProject.*
GTE/Tools/GenerateProject/ProjectTemplateVSCode.{h,cpp}

```

Added missing [\\*.code-workspace](#) files to the recently ported physics samples.

```

GTE/Samples/Physics/BouncingSpheres/BouncingSpheres.code-workspace
GTE/Samples/Physics/BouncingTetrahedra/BouncingTetrahedra.code-workspace
GTE/Samples/Physics/RoughPlaneFlatBoard/RoughPlaneFlatBoard.code-workspace
GTE/Samples/Physics/RoughPlaneParticle1/RoughPlaneParticle1.code-workspace
GTE/Samples/Physics/RoughPlaneParticle2/RoughPlaneParticle2.code-workspace
GTE/Samples/Physics/RoughPlaneSolidBox/RoughPlaneSolidBox.code-workspace
GTE/Samples/Physics/RoughPlaneThinRod1/RoughPlaneThinRod1.code-workspace
GTE/Samples/Physics/RoughPlaneThinRod2/RoughPlaneThinRod2.code-workspace
GTE/Samples/Physics/WaterDropFormation/WaterDropFormation.code-workspace
GTE/Samples/Physics/WrigglingSnake/WrigglingSnake.code-workspace

```

Ported the [SwitchNode](#) class and [SwitchNodes](#) sample application from Wild Magic 5 to Geometric Tools Engine 6.

```

GTE/BuildAll*.sln
GTE/Graphics/GTGraphics.h
GTE/Graphics/GTGraphics*.vcxproj
GTE/Graphics/GTGraphics*.vcxproj.filters
GTE/Graphics/SwitchNode.{h,cpp}
GTE/Samples/SceneGraphs/SwitchNodes/SwitchNodes*.vcxproj

```

```

GTE/Samples/SceneGraphs/SwitchNodes/SwitchNodes*.vcxproj.filter
GTE/Samples/SceneGraphs/SwitchNodes/SwitchNodesMain.cpp
GTE/Samples/SceneGraphs/SwitchNodes/SwitchNodesWindow3.{h,cpp}
GTE/Samples/SceneGraphs/SwitchNodes/SwitchNodes.code-workspace
GTE/Samples/SceneGraphs/SwitchNodes/CMakeLists.txt
GTE/Samples/SceneGraphs/SwitchNodes/CMakeSample.sh
GTE/Samples/SceneGraphs/SwitchNodes/cmake-variants.json
GTE/Samples/SceneGraphs/SwitchNodes/.vscode/launch.json
GTE/Samples/SceneGraphs/SwitchNodes/.vscode/settings.json
GTE/Samples/SceneGraphs/CMakeLists.txt

```

Ported the **DLODNode** (dynamic level of detail node) class and **DLODNodes** sample application from Wild Magic 5 to Geometric Tools Engine 6.

```

GTE/BuildAll*.sln
GTE/Graphics/GTGraphics.h
GTE/Graphics/GTGraphics*.vcxproj
GTE/Graphics/GTGraphics*.vcxproj.filters
GTE/Graphics/DLODNode.{h,cpp}
GTE/Samples/SceneGraphs/DLODNodes/DLODNodes*.vcxproj
GTE/Samples/SceneGraphs/DLODNodes/DLODNodes*.vcxproj.filter
GTE/Samples/SceneGraphs/DLODNodes/DLODNodesMain.cpp
GTE/Samples/SceneGraphs/DLODNodes/DLODNodesWindow3.{h,cpp}
GTE/Samples/SceneGraphs/DLODNodes/DLODNodes.code-workspace
GTE/Samples/SceneGraphs/DLODNodes/CMakeLists.txt
GTE/Samples/SceneGraphs/DLODNodes/CMakeSample.sh
GTE/Samples/SceneGraphs/DLODNodes/cmake-variants.json
GTE/Samples/SceneGraphs/DLODNodes/.vscode/launch.json
GTE/Samples/SceneGraphs/DLODNodes/.vscode/settings.json
GTE/Samples/SceneGraphs/CMakeLists.txt

```

## 9 Updates to Version 6.0

**February 7, 2022.** Fixed a compiler error on Linux for a mismatch in **size\_t** and **int32\_t**. Changed the type of **mNumCtrlPoints** and **mDegree** to **size\_t**.

```

GTE/Samples/Physics/WrigglingSnake/WrigglingSnakeWindow3.h

```

**February 6, 2022.** Ported the Wild Magic 5 physics sample **BouncingTetrahedra** to GTE. The port of **BouncingSpheres** was modified so that the two samples have the same conceptual framework.

```

GTE/Samples/Physics/BouncingTetrahedra/BouncingTetrahedra*.vcxproj
GTE/Samples/Physics/BouncingTetrahedra/BouncingTetrahedra*.vcxproj.filter
GTE/Samples/Physics/BouncingTetrahedra/BouncingTetrahedraMain.cpp
GTE/Samples/Physics/BouncingTetrahedra/BouncingTetrahedraWindow3.{h,cpp}

```



```

GTE/Samples/Physics/BouncingTetrahedra/PhysicsModule.{h,cpp}
GTE/Samples/Physics/BouncingTetrahedra/RigidPlane.{h,cpp}
GTE/Samples/Physics/BouncingTetrahedra/RigidTetrahedron.{h,cpp}
GTE/Samples/Physics/BouncingTetrahedra/Initial.txt
GTE/Samples/Physics/BouncingSpheres/BouncingSpheres*.vcxproj
GTE/Samples/Physics/BouncingSpheres/BouncingSpheres*.vcxproj.filter
GTE/Samples/Physics/BouncingSpheres/BouncingSpheresMain.cpp
GTE/Samples/Physics/BouncingSpheres/BouncingSpheresWindow3.{h,cpp}
GTE/Samples/Physics/BouncingSpheres/PhysicsModule.{h,cpp}
GTE/Samples/Physics/BouncingSpheres/BouncingSpheresMain.cpp
GTE/Samples/Physics/BouncingSpheres/BouncingSpheresWindow3.{h,cpp}
GTE/Samples/Physics/BouncingSpheres/RigidPlane.{h,cpp}
GTE/Samples/Physics/BouncingSpheres/RigidSphere.{h,cpp}
GTE/Samples/Physics/BouncingSpheres/Initial.txt

```

I factored out the impulse computations from the physics samples and moved them to [RigidBody](#). The code now can be shared by the applications.

```
GTE/Mathematics/RigidBody.h
```

The [Tetrahedron3](#) class has additional framework to support computing normals at features (vertices, edges, faces). The [DistPoint3Tetrahedron3](#) query was modified because of an interface change in [Tetrahedron3](#).

```

GTE/Mathematics/Tetrahedron3.h
GTE/Mathematics/DistPoint3Tetrahedron3.h

```

The algorithm I implemented for distance between tetrahedra was not robust because of testing for containment of vertices of one tetrahedron in another. I modified it to test centroids instead.

```
GTE/Mathematics/DistTetrahedron3Tetrahedron3.h
```

Added a new file for the test-intersection query between tetrahedra using the method of separating axes. This allowed for better performance in [BouncingTetrahedra](#) compared to using distance between tetrahedra.

```
GTE/Mathematics/IntrTetrahedron3Tetrahedron3.h
```

Fixed comments in the file.

```
GTE/Mathematics/IntrOrientedBox3OrientedBox3.h
```

**February 3, 2022.** Added missing projects from the MSVS 2019 build-all solutions. Added new build-all solutions for MSVS 2022.

```

GTE/BuildAll.v16.sln
GTE/BuildAllDX11.v16.sln

```

GTE/BuildAllGL45.v16.sln  
GTE/BuildAll.v17.sln  
GTE/BuildAllDX11.v17.sln  
GTE/BuildAllGL45.v17.sln

**February 1, 2022.** Added new file that implements tetrahedron-tetrahedron query. This is needed for the port of [BouncingTetrahedra](#) from Wild Magic 5 to Geometric Tools Engine.

GTE/Mathematics/DistTetrahedron3Tetrahedron3.h

Modified the interfaces for computing barycentric coordinates. The raw arrays `bary[]` were replaced by `std::array` objects.

GTE/Mathematics/Vector2.h  
GTE/Mathematics/Vector3.h  
GTE/Mathematics/Delaunay2Mesh.h  
GTE/Mathematics/Delaunay3Mesh.h  
GTE/Mathematics/DistPoint3Tetrahedron3.h  
GTE/Mathematics/IntpQuadraticNonuniform2.h  
GTE/Mathematics/PlanarMesh.h  
GTE/Samples/Mathematics/Interpolation2D/Interpolation2DWindow3.cpp

Added a function for computing the centroid of a tetrahedron.

GTE/Mathematics/Tetrahedron3.h

Updated a comment to be consistent with other distance-query comments.

GTE/Mathematics/DistTriangle3Triangles.h

Updated project files that reference the newly added mathematics header files.

GTE/Mathematics/GTMathematics.\*.{vcxproj,vcxproj.filters}

**January 31, 2022.** Added new file that implements point-in-tetrahedron query. This is needed for the port of [BouncingTetrahedra](#) from Wild Magic 5 to Geometric Tools Engine.

GTE/Mathematics/ContTetrahedron3.h

**January 30, 2022.** The point-tetrahedron distance query code failed to compile because of a mismatch in index type. (Reorganization of my internal tools caused the template instantiation tool not to launch when [Tetrahedron3](#) was modified.)

GTE/Mathematics/DistPoint3Tetrahedron3.h

**January 26, 2022.** I modified the sample application to allow the spheres to spin based on angular momentum, taking into account transfer of momentum during colliding contact. This required a different algorithm for impulsive function construction than what is in “Game Physics, 2nd edition” (Section 6.2.2). The algorithm details are in a new document at my website, [ComputingImpulsiveForces.pdf](#). I also added friction to stop eventually the spheres from sliding and spinning when they are on the floor. Eliminated the texture seam by hacking it to a toroidal texture. Modified the RigidBody interface for simpler presentation of the Runge-Kutta solver steps and to make it clear the dependency between physics parameters and quantities derived from them (to support synchronizing the state).

```
GTE/Mathematics/RigidBody.h
GTE/Samples/Physics/BouncingSpheres/BouncingSpheresMain.cpp
GTE/Samples/Physics/BouncingSpheres/BouncingSpheresWindow3.{h,cpp}
GTE/Samples/Physics/BouncingSpheres/PhysicsModule.{h,cpp}
GTE/Samples/Physics/BouncingSpheres/Initial.txt
GTE/Samples/Data/BallTextureWrap.png
```

**January 17, 2022.** The function `FitIndexed` has tests for the components of `mean` being finite floating-point numbers. The test for `mean[2]` was missing.

```
GTE/ApprOrthogonalPlane3.h
```

Converted the `GetFaceIndices` function to `static` because the indices for the triangular faces are the same no matter which tetrahedron. Added also the static function `GetAllFaceIndices` to access the entire array of indices as a single object; this is useful for index buffers associated with tetrahedra.

```
GTE/Tetrahedron3.h
```

**January 16, 2022.** I replaced the hard-coded physics time steps by a physics clock that requires the simulation to run at 60 frames per second. I also added comments that the physics implementation is based on Section 6.6 of my Game Physics book (2nd edition).

```
GTE/Samples/Physics/BouncingSpheres/BouncingSpheresWindow3.{h,cpp}
```

**January 14, 2022.** I ported the Wild Magic 5 physics sample BouncingSpheres to GTE 5. The sample illustrates impulsed-based physics for a collection of spheres. I refactored the code so that the physics portion is isolated to the `PhysicsModule.*` files. Update the CMake list of projects for physics.

```
GTE/Samples/Physics/BouncingSpheres/BouncingSpheres*.*
GTE/Samples/Physics/BouncingSpheres/PhysicsModule.{h,cpp}
GTE/Samples/Physics/CMakeLists.txt
```

The function `SetMass` had type `float` instead of the template parameter `Real`.

```
GTE/Mathematics/RigidBody.h
```

**January 12, 2022.** I ported the Wild Magic 5 physics sample WaterDropFormation to GTE 6. Update the CMake list of projects for physics.

```
GTE/Samples/Physics/WaterDropFormation/WaterDropFormation*.*
GTE/Samples/Physics/WaterDropFormation/RevolutionSurface.{h,cpp}
GTE/Samples/Physics/CMakeLists.txt
```

Fixed the file versions to show 6.1 instead of 6.0 to be consistent with my versioning rules.

```
GTE/Samples/Physics/RoughPlaneParticle1/RoughPlaneParticle1*.*
GTE/Samples/Physics/RoughPlaneParticle1/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneParticle2/RoughPlaneParticle2*.*
GTE/Samples/Physics/RoughPlaneParticle2/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneThinRod1/RoughPlaneThinRod1*.*
GTE/Samples/Physics/RoughPlaneThinRod1/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneThinRod2/RoughPlaneThinRod2*.*
GTE/Samples/Physics/RoughPlaneThinRod2/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneFlatBoard/RoughPlaneFlatBoard*.*
GTE/Samples/Physics/RoughPlaneFlatBoard/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneSolidBox/RoughPlaneSolidBox*.*
GTE/Samples/Physics/RoughPlaneSolidBox/PhysicsModule.{h,cpp}
GTE/Samples/Physics/WrigglingSnake/WrigglingSnake*.*
GTE/Samples/Physics/WrigglingSnake/TubeSurface.{h,cpp}
```

Added hyperlinks to the website PDF that describes some simple friction-based algorithms.

```
GTE/Samples/Physics/RoughPlaneParticle1/RoughPlaneParticle1.h
GTE/Samples/Physics/RoughPlaneParticle2/RoughPlaneParticle2.h
GTE/Samples/Physics/RoughPlaneThinRod1/RoughPlaneThinRod1.h
GTE/Samples/Physics/RoughPlaneThinRod2/RoughPlaneThinRod2.h
GTE/Samples/Physics/RoughPlaneFlatBoard/RoughPlaneFlatBoard.h
GTE/Samples/Physics/RoughPlaneSolidBox/RoughPlaneSolidBox.h
```

**January 11, 2022.** I ported the Wild Magic 5 physics sample WrigglingSnake to GTE 6. Updated the CMake list of projects for physics.

```
GTE/Samples/Physics/WrigglingSnake/WrigglingSnake*.*
GTE/Samples/Physics/WrigglingSnake/TubeSurface.{h,cpp}
GTE/Data/Snake.png
GTE/Samples/Physics/CMakeLists.txt
```

**January 10, 2022.** I ported the Wild Magic 5 physics samples to GTE 6, the ones involving friction.

```
GTE/Samples/Physics/RoughPlaneParticle1/RoughPlaneParticle1*.*
GTE/Samples/Physics/RoughPlaneParticle1/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneParticle2/RoughPlaneParticle2*.*
GTE/Samples/Physics/RoughPlaneParticle2/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneThinRod1/RoughPlaneThinRod1*.*
GTE/Samples/Physics/RoughPlaneThinRod1/PhysicsModule.{h,cpp}
```

```

GTE/Samples/Physics/RoughPlaneThinRod2/RoughPlaneThinRod2*.*
GTE/Samples/Physics/RoughPlaneThinRod2/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneFlatBoard/RoughPlaneFlatBoard*.*
GTE/Samples/Physics/RoughPlaneFlatBoard/PhysicsModule.{h,cpp}
GTE/Samples/Physics/RoughPlaneSolidBox/RoughPlaneSolidBox*.*
GTE/Samples/Physics/RoughPlaneSolidBox/PhysicsModule.{h,cpp}

```

I removed the post-build copies of the executables to the folder [GeometricTools/GTE/Executable](#). The tools are used infrequently enough that I now run them from their [.Output](#) folders. Naturally, you can manually copy the executables to where you want them.

```

GTE/Tools/BitmapFontCreator/BitmapFontCreator*.vcxproj
GTE/Tools/GenerateProject/GenerateProject*.vcxproj

```

**January 9, 2022.** I added projects and solutions for Microsoft Visual Studio 2022. I removed the Microsoft Visual Studio 2015 projects and solutions because that version of the IDE reached mainstream end date on October 13, 2020. Microsoft Visual Studio 2017 reaches its mainstream end date on April 12, 2022. However, I have also removed the Microsoft Visual Studio 2017 projects and solutions because I do not have enough time to maintain so many versions of the compiler. From now on, I will support two versions of MSVS, the current one (whatever that is) and the previous one.

The Tools folder has various projects that were expanded to include projects and solutions for MSVS 2022. The [GenerateProject](#) tool has been modified to generate only MSVS 2019 and MSVS 2022 projects and solutions.

```

GTE/Tools/BitmapFontCreator/BitmapFontCreator.v17.*
GTE/Tools/BitmapFontCreator/BitmapFontCreator.v16.vcxproj
GTE/Tools/ChangePlatformToolset/ChangePlatformToolset.v17.*
GTE/Tools/ChangePlatformToolset/ChangePlatformToolset.v16.vcxproj
GTE/Tools/FiniteDifferences/FiniteDifferencesDX11.v17.*
GTE/Tools/FiniteDifferences/FiniteDifferencesGL45.v17.*
GTE/Tools/FiniteDifferences/FiniteDifferencesDX11.v16.vcxproj
GTE/Tools/FiniteDifferences/FiniteDifferencesGL45.v16.vcxproj
GTE/Tools/GenerateApproximations/GenerateApproximations.v17.*
GTE/Tools/GenerateApproximations/GenerateApproximations.v16.vcxproj
GTE/Tools/GenerateOpenGLWrapper/GenerateOpenGLWrapper.v17.*
GTE/Tools/GenerateOpenGLWrapper/GenerateOpenGLWrapper.v16.vcxproj
GTE/Tools/GenerateOpenGLWrapper/GenerateOpenGLWrapper.cpp
GTE/Tools/PrecisionCalculator/PrecisionCalculator.v17.*
GTE/Tools/PrecisionCalculator/PrecisionCalculator.v16.vcxproj
GTE/Tools/RotationApproximation/RotationApproximationDX11.v17.*
GTE/Tools/RotationApproximation/RotationApproximationGL45.v17.*
GTE/Tools/RotationApproximation/RotationApproximationDX11.v16.vcxproj
GTE/Tools/RotationApproximation/RotationApproximationGL45.v16.vcxproj

```

The [GenerateProject](#) tool now creates project, solutions, filter files and source files only for MSVS 2019 and MSVS 2022.

```

GTE/Tools/GenerateProject/GenerateProject.v17.*
GTE/Tools/GenerateProject/GenerateProject.v16.{vcxproj,vcxproj.filters}
GTE/Tools/GenerateProject/GenerateProject.cpp
GTE/Tools/GenerateProject/ProjectTemplate.{h,cpp}
GTE/Tools/GenerateProject/ProjectTemplate.v17.{h,cpp}
GTE/Tools/GenerateProject/ProjectTemplate.v16.{h,cpp}
GTE/Tools/GenerateProject/ProjectTemplate.v15.{h,cpp}
GTE/Tools/GenerateProject/ProjectTemplate.v14.{h,cpp}

```

**January 3, 2022.** Version 6.0 is posted. The major revision is based on running the code analysis tools for Microsoft Visual Studio 2019 16.11.8 and for ClangCL. The reported issues were addressed with the exception of some incorrect warnings from MSVS 2019. For now, the incorrect warnings are encapsulated by `#pragma` commands and will be removed in the GTL development track.

The MSVS code analysis tool is not robust. Sometimes warnings occur in both the Output and Error List windows. Sometimes they occur in only one or the other window (but not both). And sometimes they do not occur in either window, but the 3-dot markers show up in source files that are opened after which the warnings show up in the Error List window. As I discover source files where the warnings show up only when the source file is opened, I will fix the issues. I believe most of these will be warnings about potentially uninitialized variables, typically for class objects whose default constructors should be called but MSVS seems to believe the class members are not initialized. This is the case for the `Vector` classes, but in the code using these classes, the members are set soon after the declaration. I was hoping the tool would figure out that the member initialization was deferred. (If I were to allocate a `std::vector` of `Vector` with a very large number of elements, and the code fills them in by loading data from a file, it would be a shame to waste all that time having the constructor initialize the members only to fill them in again from the loaded data.)

Another tool issue occurred with `SymmetricEigensolver.h`, in the `GetEigenvector` function. I have comments in that file about why the tool report is incorrect. For a long time I have been able to ignore the warning because code using it compiles fine, even with `treat warnings as errors`. The warnings occurred as part of a regular source-code build. For the first time I ran the code analyzer explicitly from the MSVS IDE menu on a source file that contains only the include of the aforementioned header file. The report now includes more warnings that appear to be based on the same incorrect diagnosis. The original warning was about a potential out-of-range index, and the Error List window allows you to drop-down a list of steps and assumptions to support the diagnosis. The new warning is about the same issue but for some reason displays a list of line numbers that show up in the drop-down list. After these new warnings occurred, I can no longer successfully build code using the eigensolver. I had to add `#pragma` commands to prevent the warnings. After that, a couple of other files generated similar warnings that had to be disabled using `#pragma` commands.

I had also spent a lot of time eliminating the warning about preferring scoped enumerations over unscoped ones. The unscoped ones typically defined enumerants that were used as array indices (in the DX11 and GL45 engine code). This is not allowed with scoped enumerations. I replaced the unscoped enumerations with nested `struct`, each structure containing constant expressions of the form `static uint32_t constexpr someName = someValue;`. MSVS 2019 and ClangCL provided with MSVS 2019 allowed this modification, but unfortunately gcc on my Linux boxes did not. Searching stackoverflow, it appears that C++ considers such `structs` to be *incomplete*. I actually got linker errors about the various constants referenced by the sample applications but not found in the libraries linked to the applications. I restored the unscoped enumerations and disabled the code analysis warning number in the project settings.

A couple of the sample applications use `BSRational<UIntegerFP<N>>` where `N` is large. These lead to code

analysis warnings about `/analyze:stacksize numKBs` indicating that `numKBs` is larger than the maximum stack size and the you should consider moving data from the stack to the heap. The samples have run correctly without stack overflow errors, so it is not clear to me what the problem is. Regardless, I modified the project settings and specified `numKBs` large enough to avoid the warnings. When I switched to using ClangCL, the compiler complains it cannot find files and lists the name `/analyze:stacksize`. It appears that ClangCL does not understand this analysis tool option. Unfortunately, with *treat warnings as errors*, those sample applications will not compile. So I removed the setting of `numKBs` and then disabled the code analysis warning number in the project settings.

## 10 Updates to Version 5.15

**January 3, 2022.** To remove Microsoft Visual Studio 2019 code analysis warnings, an extremely large number of files were modified. I am posting these as GTE 6.0. I suspect that even more changes are necessary because the code analysis tool is not robust. Sometimes warnings show up in the Output and Error List windows. Sometimes they show up only in the Output window or only in the Error List window. And sometimes they do not show up in either; I have to open a file with an issue (typically an “auto cannot deduce references” warning) and see the three-dot notification below the offending variable. I also had to suppress some warnings with pragmas because my analysis shows the code is correct, but I was unable to modify the code to eliminate the warnings.

The graphics engine is the main system that had many changes. The typical issues are listed next and are some what annoying to deal with.

1. Prefer scoped enumerations over unscoped ones. I used unscoped enumerations as indices into arrays for DX11 and OpenGL 4.5. If I modified these to scoped enumerations, you cannot use them for indexing. I choose to replace such enumerations by structs with constexpr values for the indices. The trade-off is that you loose the strict typing the enumerations give you when passing variables to functions.
2. The `auto cannot deduce references` shows up a lot. I had `auto vbuffer = someObject→GetVertexBuffer()`. The return value is a shared ptr, so I do not care that a copy is made (with an increment on the reference count), even though the code analysis warning says I should consider otherwise. I modified these anyway to `auto const& vbuffer = someObject→GetVertexBuffer()`.
3. The final annoying issue is the use of `int` indices for STL container classes that use `size_t` indices. This is not a problem until you have index arithmetic enclosed with the `[]`. The complaint is that the 4-byte arithmetic can lead to overflow before typecasting to an 8-byte value. This has plagued me for years, because I had chosen to use `int` as the natural index into arrays. I added a lot of ugly static casts. As I am porting the code to GTL, I am fixing this problem. In GTE you will have to live with the ugly casts for now.
4. I replaced the `unsigned T` types by those in `cstdint`.

Some code analysis issues I fixed were relevant in that there were potential bugs.

**December 29, 2021.** The following modifications are based on warnings from ‘LLVM - clang-cl’ provided with Microsoft Visual Studio 2019.

Removed the unused variable `mTextColor`.

GTE/Samples/Intersection/AllPairsTriangles/AllPairsTrianglesWindow3.h

The `BouncingBall` sample creates a `PlanarReflectionEffect` via a `std::unique_ptr`. To do so requires `PlanarReflectionEffect` to implement a virtual destructor because it has a virtual member function (`Draw`).

GTE/Graphics/PlanarReflectionEffect.h

The `BSplineInterpolation` sample creates a `IntpBSplineUniform<double,Controls,1>` object whose first parameter is the degree of the fit. That parameter had braces which are not needed.

GTE/Samples/Imagics/BSplineInterpolation/BSplineInterpolation.cpp

Removed the unused variable `mCurrentIndex`.

GTE/Samples/Geometrics/Delaunay2D/Delaunay2DWindow.{h,cpp}  
GTE/Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunayWindow2D.{h,cpp}

Removed the unused variable `mLightWorldDirection`.

GTE/Samples/Physics/FoucaultPendulum/FoucaultPendulumWindow3.{h,cpp}

Removed unused variable `mNumSlices`.

GTE/Samples/Physics/MassSprings3D/GpuMassSpringVolume.{h,cpp}

The `mTIQuery` is used only when the preprocessor symbol `USE_TIQUERY_OVERRIDE` is defined. Moved the define to the header file and defined `mTIQuery` only when the preprocessor symbol is defined.

GTE/Samples/Intersection/IntersectTriangleBox/IntersectTriangleBoxWindow3.{h,cpp}

Added `override` to functions `OnMouseClicked`, `OnMouseMotion` and `OnCharPress`.

GTE/Samples/Intersection/MovingCircleRectangle/MovingCircleRectangleWindows.h

Removed unused `this` as a capture parameter in `DrawPath`.

GTE/Samples/Mathematics/ShortestPath/ShortestPathWindow2.cpp

Removed the unused variable `mLightWorldDirection`.

GTE/Samples/Physics/SimplePendulumFriction/SimplePendulumFrictionWindow3.{h,cpp}

Removed the unused variable `mTextColor`.



GTE/Samples/Geometrics/VertexCollapseMesh/VertexCollapseMeshWindow3.{h,cpp}

**December 28, 2021.** Improved the performance of [Delaunay3](#) by using the newly modified [TSManifoldMesh](#) and by including interval arithmetic with the rational arithmetic in [ToPlane](#) and [ToCircumsphere](#) to amortize the cost of the computations. In many cases, interval arithmetic can determine the signs of determinants using only floating-point arithmetic which avoids the more expensive rational-only arithmetic. For a user-supplied dataset of over 3000 points and executing on an Intel i9-10900 processor, the following measurements were made for `float` with compute type `BSNumber< UIntegerFP32<44>>` and for `double` with compute type `BSNumber< UIntegerFP32<330>>`. The old code `Delaunay3<InputType,ComputeType>` required 3611 milliseconds for `float` input and 3858 milliseconds for `double`. The new code `Delaunay3<T>` required 1274 milliseconds for `float` and 1280 milliseconds for `double`. The old code is deprecated, to be removed in GTL, but the current file still contains it in addition to the new code.

GTE/Mathematics/Delaunay3.h  
GTE/Samples/Geometrics/Delaunay3DWindow3.{h,cpp}

Improved the performance of [TSManifoldMesh](#), replacing `std::map` by `std::unordered_map`, replacing `std::shared_ptr` by `std::unique_ptr` and replacing `std::weak_ptr` by raw pointers.

GTE/Mathematics/TSManifoldMesh.h

Updated some comments. The maximum values of `N` listed for `UIntegerFP32` with `double` input were incorrect (much too large).

GTE/Mathematics/Delaunay2.h

## 11 Updates to Version 5.14

**December 21, 2021.** Removed the LCP solver approach for the test-intersection query between a box and a finite cylinder. The approach turned out to work correctly when using exact arithmetic but in some configurations had significant rounding errors when using floating-point arithmetic. The code has been modified using the third algorithm described in [Intersection of a Box and a Finite Cylinder](#).

GTE/Mathematics/IntrCanonicalBox3Cylinder3.h  
GTE/Mathematics/IntrAlignedBox3Cylinder3.h  
GTE/Mathematics/IntrOrientedBox3Cylinder3.h  
GTE/Mathematics/IntrPlane3Cylinder3.h

**December 20, 2021.** Removed unused variables (warnings by clang). The `OPENGL_VERSION_1_1` constant is required on Linux, but it is unused on Windows. I moved that constant to a conditional block for Linux.

GTE/Applications/GLX/WindowSystem.{h,cpp}  
GTE/Graphics/MorphController.cpp  
GTE/Graphics/GL45/GL45.cpp  
GTE/Graphics/GL45/GL45InputLayout.{h,cpp}

Added required `override` modifier to virtual functions (warnings by clang).

```
GTE/Applications/GLX/Window.h
GTE/Graphics/GraphicsEngine.h
GTE/Graphics/DX11/DX11Engine.h
GTE/Graphics/GL45/GL45Engine.h
```

The CMake `option` commands had incorrect commas in 140 of the CMakeLists.txt files.

```
GTE/Applications/CMakeLists.txt
GTE/Graphics/CMakeLists.txt
GTE/MathematicsGPU/CMakeLists.txt
GTE/Samples/*/CMakeLists.txt
```

Clang complained about using `(char*)0 + offset`. I replaced this with `reinterpret_cast<char*>(offset)`.

```
GTE/Graphics/GL45/GL45Engine.cpp
```

Clang complained that the `programHandle` to the `GL45InputLayout` constructor is unused. I deleted the name as per the standards. I will remove the parameter altogether once I rewrite the graphics code.

```
GTE/Graphics/GL45/GL45InputLayout.cpp
```

Clang suggested using braces to initialize subobjects in the `ConfiguraionTable` at the end of the file.

```
GTE/Mathematics/MarchingCubes.h
```

Clang complained that the `YFunction` lambda has a `this` parameter but does not use it. Removed that parameter.

```
GTE/Mathematics/RootsBisection2.h
```

Clang complained about various Microsoft header structures. Added zeroing of the `PROPBAG2 option`. Added parentheses to the declaration of `PROPBAG2 option` and `VARIANT varValue`. Clang complains that `varValue` does not have members `vt`, `boolVal` or `bVal`. Microsoft headers indicate they do exist (and the WICFileIO code has worked for years). The code probably needs to use the `CCom*` class to encapsulate `VARIANT` and use that. More importantly, the Windows SDK header files need a serious upgrade.

```
GTE/Applications/MSW/WICFileIONative.cpp
```

Removed include of `Logger.h` because the header file does not use it.

```
GTE/Mathematics/Cylinder3.h
```

Clarified a comment about vertex extraction.

GTE/Mathematics/AlignedBox.h

**December 1, 2021.** The source code failed when the plane normal and cylinder axis direction were parallel. The mathematical derivation in the document [IntersectionPlaneCylinder.pdf](#) was incorrect because it overlooked the singularity when computing the major axis of the ellipse of intersection. The PDF was rewritten and describes a different major axis construction. The new source code implements this. Moreover, it also now supports both finite and infinite cylinders (test-intersection and find-intersection queries).

GTE/Mathematics/IntrPlane3Cylinder3.h

Added a comment that you cannot specify plane.origin and plane.constant independently (with an example of why not).

GTE/Mathematics/Hyperplane.h

**November 28, 2021.** Added implementations of two algorithms in *Geometric Tools for Computer Graphics* (Sections 8.6 and 8.7) at user request. The implementation for the algorithm of Section 8.6 differs from that of the book—a simpler approach is used, described in the file comments. The book has pseudocode for the algorithm in Section 8.7, but there are numerous errors. I have added the corrections to the book correction page at the website. The approach I used is described in the file comments.

GTE/GTMathematics.\*.{vcxproj,vcxproj.filters}

GTE/Mathematics/CircleThroughTwoPointsSpecifiedRadius.h (Section 8.6)

GTE/Mathematics/CircleThroughPointSpecifiedTangentAndRadius.h (Section 8.7)

MSVS 2015 complained that `std::greater` was undefined. I added the include of header `<functional>` to access the definition. MSVS 2015 also complained about unchecked iterators when using `std::copy`. I replaced the `std::copy` calls by C++ loops.

GTE/Mathematics/SingularValueDecomposition.h

I will be quite happy when MSVS 2015 reaches end-of-life.

## 12 Updates to Version 5.13

**November 19, 2021.** The bookkeeping for decomposing the bidiagonal matrix into a block matrix with bidiagonal blocks was not working correctly when a superdiagonal entry was zero. I decided to revisit every piece of the SVD code and updated the unit tests to ensure the code is working properly. The output of the SVD now produces only a singular-value matrix with diagonal elements occurring in descending order. The interfaces were modified slightly.

GTE/Mathematics/SingularValueDecomposition.h

The November 2, 2021 entry fixed a bug in the non-deprecated version of [FillRegion](#). I also added that fix to the deprecated version in case folks are still using it.

GTE/Mathematics/TriangulateCDT.h

The revision of [Logger.h](#) removed the implicit include of `<limits>` that [ETManifoldMesh.h](#) requires.

GTE/Mathematics/ETManifoldMesh.h

Added definitions of [zero](#) and [one](#) but forgot to use them in the code.

GTE/Mathematics/IntrLine2Segment2.h

I removed `static int32_t constexpr INTERIOR_VERTEX = -1` from the header file. On Fedora 34 with gcc 11.1.1, the linker complained that this symbol is undefined, which is incorrect given it is a `constexpr`. Without the change, gcc 9.3.0 on Ubuntu 20.04.1 LTS does not generate the linker error.

GTE/Mathematics/GenerateMeshUV.h

**November 11, 2021.** I removed the [Logger](#) class to avoid linker errors about duplicate symbols when the class is used in separate modules that are linked to an application. The issue was reported by someone using Unreal Engine 5 (Plugins/Experimental/GeometryProcessing in the GeometryAlgorithms module) and trying to link in the mathematics code from GTE. The problem is that the [LogAssert](#) and [LogError](#) macros contain [Logger](#) constructor calls, but the compiler does not always inline the calls. The new code in [Logger.h](#) contains only macros. The logging system no longer supports [LogInformation](#) or [LogWarning](#) messages. The system does throw C++ exceptions. If you disable C++ exceptions and undefine the macros, be aware that not throwing exceptions causes program flow to continue in an unknown—and most likely—unsafe state. I have retained the name of [Logger.h](#) even though no logging occurs; the file name in GTL will be [Exceptions.h](#). I removed all the [LogReporter](#) code in the sample applications, replacing them by try-catch blocks so that an unhandled exception leads to its associated message displayed in the application command window. The modified sample application files (`*Main.cpp`) are numerous and not listed here.

GTE/Mathematics/Logger.h  
GTE/Mathematics/LogToFile.h  
GTE/Mathematics/LogToStdOut.h  
GTE/Mathematics/LogToStringArray.h  
GTE/Applications/GTApplications.h  
GTE/Applications/Common/LogReporter.{h,cpp}  
GTE/Applications/MSW/LogToMessage.{h,cpp}  
GTE/Applications/MSW/LogToOutputWindow.{h,cpp}

Various library files are affected by the [Logger](#) redesign, mainly eliminating [LogWarning](#) and [LogInformation](#). The [RootBisection2](#) class needed a member [mNoGuaranteeForRootBound](#) and an accessor for the caller to determine information that used to be reported by the logging system.

GTE/Mathematics/BoundingSphere.h  
GTE/Mathematics/ConformalMapGenus0.h  
GTE/Mathematics/RootsBisection1.h  
GTE/Mathematics/RootsBisection2.h

```

GTE/Mathematics/UIntegerALU32.h
GTE/Applications/Environment.{h,cpp}
GTE/Graphics/DX11/DX11Buffer.cpp
GTE/Graphics/DX11/DX11InputLayoutManager.cpp
GTE/Graphics/GL45/GL45Buffer.cpp
GTE/Graphics/GL45/GL45Engine.cpp
GTE/Graphics/GL45/GL45InputLayoutManager.cpp
GTE/Graphics/GL45/GL45SamplerState.cpp
GTE/Graphics/GL45/GL45TextureArray.cpp
GTE/Graphics/Resource.cpp

```

The `Logger.h` file had an include of `<set>` that was used indirectly by various files. Those files need the explicit include. The `Delaunay2.h` file had an include of `FPIInterval.h` that is not needed.

```

GTE/Mathematics/AdaptiveSkeletonClimbing3.h
GTE/Mathematics/Delaunay2.h
GTE/Mathematics/ETNonmanifoldMesh.h
GTE/Mathematics/GenerateMeshUV.h
GTE/Mathematics/PlanarMesh.h
GTE/Mathematics/UniqueVerticesSimplices.h

```

Eliminated dependency on GTE. Modified the preprocessor defines of constants to `UINT constexpr`.

```

GTE/Graphics/DX11/DX11.{h,cpp}

```

Modified hard-coded exceptions to include file name, function name and line number. Modified the preprocessor defines of constants to `int constexpr`.

```

GTE/Graphics/GL45/GL45.{h,cpp}

```

The Microsoft Visual Studio 2019 code analysis tool generates a large number of warnings. Even though I have been eliminating them in the GTL development track, I want to eliminate them from the GTE track because the 2 tracks will exist simultaneously for a while.

I had designed Wild Magic and Geometric Tools Engine to use `int` indices into various classes, most notably `Vector` and `Matrix`. The use of `size_t` indices in the C++ Standard Library causes a lot of problems. Specifically for 64-bit builds where `size_t` is an 64-bit unsigned integer, any 32-bit integer arithmetic used to compute indices generates warnings. Replacing all these is a giant pain in the arse. I do not know the rationale for C++ standards to use `size_t`, but in my naive view I would have preferred a signed type. Loops that decrement the loop counter are problematic because a termination condition of `i ≥ 0` is not sufficient. It is what it is, so I am eliminating the warnings by static casts in GTE but using `size_t` in GTL.

```

GTE/Mathematics/GMatrix.h
GTE/Mathematics/Polynomial1.h
GTE/Mathematics/ApprEllipseByArcs.h
GTE/Mathematics/ApprPolynomial2.h
GTE/Mathematics/ApprPolynomial3.h

```

GTE/Mathematics/ApprPolynomial4.h  
 GTE/Mathematics/ApprPolynomialSpecial2.h (also fixed out-of-range loop counter)  
 GTE/Mathematics/ApprPolynomialSpecial3.h  
 GTE/Mathematics/ApprPolynomialSpecial4.h  
 GTE/Mathematics/UIntegerFP32.h  
 GTE/Mathematics/CLODPolyline.h  
 GTE/Mathematics/ConvexHull2.h  
 GTE/Mathematics/Delaunay2.h  
 GTE/Mathematics/Delaunay3.h  
 GTE/Mathematics/ExtremalQuery3.h  
 GTE/Mathematics/ExtremalQuery3BSP.h  
 GTE/Mathematics/GenerateMeshUV.h  
 GTE/Mathematics/MinimalCycleBasis.h  
 GTE/Mathematics/NearestNeighborQuery.h  
 GTE/Mathematics/SplitMeshByPlane.h  
 GTE/Mathematics/TriangulateEC.h  
 GTE/Mathematics/BasisFunction.h  
 GTE/Mathematics/BezierCurve.h  
 GTE/Mathematics/BSplineCurveFit.h  
 GTE/Mathematics/BSplineReduction.h  
 GTE/Mathematics/BSplineSurface.h  
 GTE/Mathematics/BSplineSurfaceFit.h  
 GTE/Mathematics/NaturalSplineCurve.h  
 GTE/Mathematics/NURBSSurface.h  
 GTE/Mathematics/ParametricCurve.h  
 GTE/Mathematics/RiemannianGeodesic.h  
 GTE/Mathematics/TCBSplineCurve.h  
 GTE/Mathematics/DistOrientedBox3Cone3.h  
 GTE/Mathematics/DistPoint3ConvexPolyhedron3.h  
 GTE/Mathematics/AdaptiveSkeletonClimbing2.h  
 GTE/Mathematics/AdaptiveSkeletonClimbing3.h  
 GTE/Mathematics/CurveExtractor.h  
 GTE/Mathematics/Image2.h  
 GTE/Mathematics/Image3.h  
 GTE/Mathematics/PdeFilter1.h  
 GTE/Mathematics/PdeFilter2.h  
 GTE/Mathematics/PdeFilter3.h  
 GTE/Mathematics/SurfaceExtractor.h  
 GTE/Mathematics/SurfaceExtractorCubes.h  
 GTE/Mathematics/IntpAkima1.h  
 GTE/Mathematics/IntpAkimaNonuniform1.h  
 GTE/Mathematics/IntpAkimaUniform1.h  
 GTE/Mathematics/IntpAkimaUniform2.h  
 GTE/Mathematics/IntpAkimaUniform3.h  
 GTE/Mathematics/IntpBSplineUniform.h  
 GTE/Mathematics/IntpLinearNonuniform2.h  
 GTE/Mathematics/IntpLinearNonuniform3.h  
 GTE/Mathematics/IntrArc2Arc2.h

GTE/Mathematics/Integration.h  
 GTE/Mathematics/LCPSolver.h  
 GTE/Mathematics/LDLTDecomposition.h  
 GTE/Mathematics/LinearSystem.h  
 GTE/Mathematics/MinimizeN.h  
 GTE/Mathematics/QuarticRootsQR.h  
 GTE/Mathematics/RootsPolynomial.h  
 GTE/Mathematics/SingularValueDecomposition.h  
 GTE/Mathematics/SymmetricEigensolver.h  
 GTE/Mathematics/UnsymmetricEigenvalues.h  
 GTE/Mathematics/Polygon2.h  
 GTE/Mathematics/IndexAttribute.h  
 GTE/Mathematics/PlanarMesh.h  
 GTE/Mathematics/RevolutionMesh.h  
 GTE/Mathematics/BoxManager.h  
 GTE/Mathematics/MassSpringCurve.h  
 GTE/Mathematics/MassSpringSurface.h  
 GTE/Mathematics/MassSpringVolume.h  
 GTE/Mathematics/RectangleManager.h

The following list are files that contain constructors that do not initialize class members. Sometimes the MSVS code analysis tool will complain about constructor calls such as `MyClass object;`, saying that `object` might not be initialized. In some cases `object` is initialized but the tool seems not to dig deeply enough to figure this out.

GTE/Applications/Environment.h  
 GTE/Mathematics/BandedMatrix.h  
 GTE/Mathematics/ConvertCoordinates.h  
 GTE/Mathematics/GVector.h  
 GTE/Mathematics/GMatrix.h  
 GTE/Mathematics/Matrix.h (for nested class `Table`, initialized `mStorage` to zero)  
 GTE/Mathematics/Quaternion.h  
 GTE/Mathematics/Rotation.h  
 GTE/Mathematics/Transform.h  
 GTE/Mathematics/Vector2.h (initialized `max[2]` in `IntrinsicVector2`)  
 GTE/Mathematics/Vector3.h (initialized `max[3]` in `IntrinsicVector3`)  
 GTE/Mathematics/UIntegerFP32.h  
 GTE/Mathematics/ConformalMapGenus0.h  
 GTE/Mathematics/Delaunay3.h (in `SearchInfo`)  
 GTE/Mathematics/ExtremalQuery3.h  
 GTE/Mathematics/ExtremalQuery3BSP.h  
 GTE/Mathematics/MinimumAreaBox2.h  
 GTE/Mathematics/MinimumVolumeBox3.h  
 GTE/Mathematics/BasisFunction.h (in `BasisFunctionInput`)  
 GTE/Mathematics/BSplineGeodesic.h  
 GTE/Mathematics/EllipsoidGeodesic.h  
 GTE/Mathematics/ParametricSurface.h  
 GTE/Mathematics/AdaptiveSkeletonClimbing3.h (in `TVertex`)

GTE/Mathematics/CurveExtractor.h  
 GTE/Mathematics/PdeFilter.h  
 GTE/Mathematics/SurfaceExtractor.h  
 GTE/Mathematics/SurfaceExtractorCubes.h (in TVertex and VETable)  
 GTE/Mathematics/IntpThinPlateSpline2.h  
 GTE/Mathematics/IntpThinPlateSpline3.h  
 GTE/Mathematics/IntrAlignedBox2AlignedBox2.h (in TQuery::Result, FQuery::Result)  
 GTE/Mathematics/IntrAlignedBox2Circle2.h (in TQuery::Result, FQuery::Result)  
 GTE/Mathematics/IntrAlignedBox2OrientedBox2.h (in TQuery::Result)  
 GTE/Mathematics/IntrArc2Arc2.h (in FQuery::Result)  
 GTE/Mathematics/IntrCircle2Arc2.h (in FQuery::Result)  
 GTE/Mathematics/IntrCircle2Circle2.h (in TQuery::Result, FQuery::Result)  
 GTE/Mathematics/IntrDisk2Sector2.h (in TQuery::Result)  
 GTE/Mathematics/IntrEllipse2Ellipse2.h (in FQuery::Result and EllipseInfo)  
 GTE/Mathematics/IntrHalfspace2Polygon2.h (in FQuery::Result)  
 GTE/Mathematics/IntrLine2AlignedBox2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrLine2Arc2.h (in TQuery::Result)  
 GTE/Mathematics/IntrLine2Circle2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrLine2OrientedBox.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrOrientedBox2Circle2.h (in TQuery::Result)  
 GTE/Mathematics/IntrOrientedBox2Cone2.h (in TQuery::Result)  
 GTE/Mathematics/IntrOrientedBox2OrientedBox.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrOrientedBox2Sector2.h (in TQuery::Result)  
 GTE/Mathematics/IntrRay2AlignedBox2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrRay2Arc2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrRay2Circle2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrRay2OrientedBox2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrRay2Ray2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrRay2Segment2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrRay2Triangle2.h (in FQuery::Result)  
 GTE/Mathematics/IntrSegment2AlignedBox2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrSegment2Arc2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrSegment2Circle2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrSegment2OrientedBox2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrSegment2Segment2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrSegment2Triangle2.h (in FQuery::Result)  
 GTE/Mathematics/IntrTriangle2Triangle2.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrOrientedBox2Cone2.h (in TQuery::Result)  
 GTE/Mathematics/IntrAlignedBox3AlignedBox3.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrAlignedBox3Cone3.h (in TQuery::Result)  
 GTE/Mathematics/IntrAlignedBox3Sphere3.h (in TQuery::Result and FQuery::Result)  
 GTE/Mathematics/IntrCapsule3Capsule3.h (in TQuery::Result)  
 GTE/Mathematics/IntrConvexMesh3Plane3.h (in FQuery::Result)  
 GTE/Mathematics/IntrEllipsoid3Ellipsoid3.h (in TQuery::Result)  
 GTE/Mathematics/IntrHalfspace3Capsule3.h (in TQuery::Result)  
 GTE/Mathematics/IntrHalfspace3Cylinder3.h (in TQuery::Result)  
 GTE/Mathematics/IntrHalfspace3Ellipsoid3.h (in TQuery::Result)  
 GTE/Mathematics/IntrHalfspace3OrientedBox3.h (in TQuery::Result)



GTE/Mathematics/IntrHalfspace3Segment3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrHalfspace3Sphere3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrHalfspace3Triangle3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrLine3Cone3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrLine3Plane3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrLine3Triangle3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrOrientedBox3Cone3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrOrientedBox3Cylinder3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrOrientedBox3Frustum3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrOrientedBox3Sphere3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrPlane3Capsule3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrPlane3Cylinder3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrPlane3Ellipsoid3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrPlane3OrientedBox3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrPlane3Plane3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrPlane3Sphere3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrPlane3Triangle3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3AlignedBox3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3Capsule3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3Cone3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3Cylinder3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3Ellipsoid3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3OrientedBox3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3Plane3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3Sphere3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrRay3Triangle3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3AlignedBox3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3Capsule3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3Cone3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3Cylinder3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3Ellipsoid3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3OrientedBox3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3Plane3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3Sphere3.h (in [FIQuery::Result](#))  
 GTE/Mathematics/IntrSegment3Triangle3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSphere3Cone3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSphere3Frustum3.h (in [TIQuery::Result](#))  
 GTE/Mathematics/IntrSphere3Sphere3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/IntrSphere3Triangle3.h (in [FIQuery::Result](#) and [FIQuery::ExactResult](#))  
 GTE/Mathematics/IntrTriangle3OrientedBox3.h (in [TIQuery::Result](#) and [FIQuery::Result](#))  
 GTE/Mathematics/Mesh.h  
 GTE/Mathematics/SymmetricEigensolver.h (in [SortItem](#))  
 GTE/Mathematics/UnsymmetricEigenvalues.h

The following list are files that contain unscoped enumerations [enum Name](#). I modified these to be scoped [enum class Name](#).

GTE/Mathematics/EulerAngles.h ([EulerResult](#))

GTE/Mathematics/Rotation.h ([RepresentationType](#), new name is [Type](#))  
 GTE/Mathematics/GenerateMeshUV.h ([INTERIOR\\_VERTEX](#) modified to a [constexpr](#))  
 GTE/Mathematics/PrimalQuery2.h ([OrderType](#))  
 GTE/Mathematics/QuadricSurface.h ([Classification](#))  
 GTE/Mathematics/PdeFilter.h ([ScaleType](#))  
 GTE/Mathematics/IntrArc2Arc2.h (enum of [FIQuery](#) modified to [enum class Configuration](#))  
 GTE/Mathematics/IntrEllipse2Ellipse2.h (enum of [TIQuery](#) modified to [enum class Classification](#))  
 GTE/Mathematics/IntrEllipse2Ellipse2.h (enum of [AreaResult](#) modified to [enum class Configuration](#))  
 GTE/Mathematics/IntrAlignedBox3Cone3.h (enum to [static size\\_t constexpr](#))  
 GTE/Mathematics/IntrEllipsoid3Ellipsoid3.h (enum to [enum class Classification](#))

Replaced [auto desc](#) by [auto const& desc](#). I intended a copy but a const reference is sufficient.

GTE/Graphics/DX11/DX11Engine.cpp

Added a cast to [GLintptr](#) in the buffer file. Added a cast of [size\\_t](#) to the engine file.

GTE/Graphics/GL45/GL45Buffer.cpp  
 GTE/Graphics/GL45/GL45Engine.cpp

The code analysis tool generates a warning for expressions such as

```
int i0 = 1, i1 = 2;
double d = static_cast<double>(i1 - i0);
```

stating that [i1 - i0](#) is the difference of 4-byte quantities and is being cast to an 8-byte quantity. To avoid the warning,

```
int i0 = 1, i1 = 2;
double d = static_cast<double>(i1) - static_cast<double>(i0);
```

I do not believe such a warning should be generated.

GTE/Mathematics/BSNumber.h  
 GTE/Mathematics/OBBTreeForPoints.h  
 GTE/Mathematics/Histogram.h  
 GTE/Mathematics/IntpBSplineUniform.h  
 GTE/Mathematics/IntpBSplineUniform.h  
 GTE/Mathematics/IntpBicubic.h  
 GTE/Mathematics/IntpBilinear.h  
 GTE/Mathematics/IntpTricubic.h  
 GTE/Mathematics/IntpTrilinear.h  
 GTE/Mathematics/RevolutionMesh.h

Other casts appear to be required. The [UIntegerALU32](#) needs a cast of [1](#) to [static\\_cast<size\\_t>\(1\)](#) in a shift operation. The [UIntegerAP32](#) needs a cast in the constructor with [uint64\\_t](#) argument and in [SetNumBits](#).

GTE/Mathematics/UIntegerALU32.h  
GTE/Mathematics/UIntegerAP32.h

Added `noexcept` to the move constructor and move assignment operator.

GTE/Mathematics/BSPPolygon2.h  
GTE/Mathematics/DisjointIntervals.h  
GTE/Mathematics/DisjointRectangles.h  
GTE/Mathematics/Image.h  
GTE/Mathematics/Image2.h  
GTE/Mathematics/Image3.h

Modified macro arguments involving `level` to use `std::to_string(level)`. In `GL45SamplerState`, removed the argument `samplerState→filter` from the `LogError` message. The `filter` will eventually become a scoped enumeration.

GTE/Graphics/GL45/GL45TextureArray.cpp  
GTE/Graphics/GL45/GL45TextureSingle.cpp  
GTE/Graphics/GL45/GL45SamplerState.cpp

Added comments about MSVS 2019 code analysis warnings that appear to be incorrect.

GTE/Mathematics/SymmetricEigensolver.h  
GTE/Mathematics/Hyperellipsoid.h

The files had hard-coded `throw` calls. These were replaced with `LogAssert` or `LogError` macros.

GTE/Mathematics/PlanarMesh.h  
GTE/Mathematics/TetrahedraRasterizer.h

Added the ability to specify an infinite cylinder using interfaces rather than setting the height to a maximum value.

GTE/Mathematics/Cylinder.h

**November 2, 2021.** In `FillRegion`, accessing `tkey` from the front of `regionQueue` using a const reference is incorrect, because the next line of code is a pop of the queue. A copy must be made of the front of the queue. Thanks to Aaron Barony for tracking down the problem.

GTE/Mathematics/TriangulateCDT.h

**October 20, 2021.** The project settings had incorrect paths to the dependent libraries and to the GTE header files.

GTE/Tools/FiniteDifferences/FiniteDifferences\*.{vcxproj,sln}

**October 19, 2021.** Added a new file to build libraries and samples together on Linux.

GTE/CMakeLibrariesAndSamples.sh

**October 17, 2021.** Modified `enum Type` to `enum class Type`.

GTE/Mathematics/BSPrecision.h  
GTE/Tools/PrecisionCalculator/PrecisionCalculator.cpp

Added initialization of class members to the constructor. Switched to using `int32_t` instead of `int`.

GTE/Mathematics/ConvexMesh3.h

Replaced `SomeClass<3, T>` by `SomeClass3<T>` for consistency when implementing 3-dimensional algorithms.

GTE/Mathematics/DistOrientedBox3Cone3.h

GTE `Vector` constructors do not initialize their data (GTL does). Added an initialization of `closest`.

GTE/Mathematics/DistPoint3Circle3.h  
GTE/Mathematics/DistPointTriangle3.h

Added initialization of class members to the `Result` constructor.

GTE/Mathematics/DistPoint3ConvexPolyhedron3.h  
GTE/Mathematics/DistLine3Circle3.h  
GTE/Mathematics/DistCircle3Circle3.h  
GTE/Samples/Distance/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow3.cpp

Modified the `Result` to have a squared-distance member and an array of two closest points, the input point and the closest cylinder point. Added initialization of class members to the `Result` constructor.

GTE/Mathematics/DistPoint3Cylinder3.h

Modified the `Result` to have an array of two closest points, the input point and the closest frustum point. Added initialization of class members to the `Result` constructor.

GTE/Mathematics/DistPoint3Frustum3.h

**October 15, 2021.** Ported the GTE code to GTL with modifications in both tracks, more comments and unit tests.

GTE/Mathematics/IntrLine2Line2.h  
GTE/Mathematics/IntrLine2Ray2.h  
GTE/Mathematics/IntrLine2Segment2.h

The application created an index buffer for each tetrahedron, but only one is needed and can be shared by all tetrahedra. The vertex buffer for each tetrahedron created enough space for all the points in the dataset, but only 4 vertices are needed per buffer.

GTE/Samples/Geometrics/Delaunay3D/Delaunay3DWindow3.{h,cpp}

Modified the `axis` member to be of type `std::array`. Moved the initialization of `axis` to the initializer portion of the constructor.

GTE/Mathematics/Ellipse3.h

Modified `enum Result` to `enum class Result`. Added initialization to the `Variable` constructor.

GTE/Mathematics/LCPSolver.h

**October 12, 2021.** The `numTriangles1` variable was initialized incorrectly.

GTE/Mathematics/SeparatePoints3.h

**September 30, 2021.** Fixed a bug where the return value was not of type `Result`. The `Result` constructor had an input `inEpsilon`, but the caller of `operator()(...)` has no chance to specify this. The operator function now has a third parameter `epsilon`, defaulted to 0 to avoid breaking application code. The addition of `explicit` to the `Result` constructor in `IntrTriangle3Cylinder3` appears to be unnecessary because all branches the code can take have `return` of a `Result` object. It is not possible to reach the end of the if-else statements without exiting, so there is no need for a return statement as the last line of the function. However, I modified the code to set `result.intersect` in each of the blocks and added a single return statement as the last line.

GTE/Mathematics/IntrOrientedBox3OrientedBox3.h

GTE/Mathematics/IntrAlignedBox3OrientedBox3.h

GTE/Mathematics/IntrTriangle3Cylinder3.h

**September 29, 2021.** Several of the `result` members in the `FIQuery` were uninitialized. Added initialization in the default constructor for `Result`. Removed the `isPoints` member (not essential to the query), setting `numIntersections` to the maximum `size_t` to indicate when the circle is contained fully by the plane.

GTE/Mathematics/IntrPlane3Circle3.h

## 13 Updates to Version 5.12

**September 25, 2021.** The August 24, 2021 modification replaced the GTE `Math.h` by the C++ header `<cmath>`. The eigensolver code also needs `<limits>` which `Math.h` provided. The code compiled with Microsoft Visual Studio 2019 (latest) and Ubuntu 20.04.1 LTS gcc 9.3.0 but not Fedora 34 gcc 11.1.1.

GTE/Mathematics/SymmetricEigensolver3x3.h

The function `GetUyy` had `F[zp1][yp1][zp1]`, but it should be `F[zp1][yp1][xp1]`.

`GTE/Mathematics/PdeFilter3.h`

**September 23, 2021.** An occurrence of `float` should have been `Real` in the second `Extract` function.

`GTE/Mathematics/SurfaceExtractorMC.h`

The expressions in `GetGradient` using the `float` number `1.0f` needed to have `(Real)1`.

`GTE/Mathematics/SurfaceExtractorCubes.h`

Fixed a comment about the constraints on the number of control points.

`GTE/Mathematics/BSplineCurveFit.h`

The `mask` type in the constructors was `bool const*`, which is from old code that was ported. The type should be instead `int const*`.

`GTE/Mathematics/PdeFilter1.h`  
`GTE/Mathematics/PdeFilter2.h`  
`GTE/Mathematics/PdeFilter3.h`  
`GTE/Mathematics/CurvatureFlow2.h`  
`GTE/Mathematics/CurvatureFlow3.h`  
`GTE/Mathematics/GaussianBlur2.h`  
`GTE/Mathematics/GaussianBlur3.h`  
`GTE/Mathematics/GradientAnisotropic2.h`  
`GTE/Mathematics/GradientAnisotropic3.h`

**September 20, 2021.** In the tests for modifying `DistPoint3Circle3.h`, the `Logger.h` header was implicitly included in the environment before the query header file. The inclusion must be explicit.

`GTE/Mathematics/DistPoint3Circle3.h`

**September 19, 2021.** The source code did not match the description for computing the distance robustly in the PDF entitled *Distance to Circles in 3D* PDF (Section 2). It computed a closest point first, which was not robust, and then computed the distance using the input point and that closest point. The robustness problem occurs when the input point is nearly on the normal line `C+tN`, where `C` is the circle center and `N` is a unit-length normal to the plane of the circle. The distance computation now matches the PDF and is robust. The closest-point code was revised to be robust, and the PDF was expanded to describe the new code.

`GTE/Mathematics/DistPoint3Circle3.h`

**September 7, 2021.** Two loops in `DoLeastSquares` had incorrect upper bounds.

GTE/Mathematics/ApprPolynomialSpecial3.h

The last blocks of code in function `ApprCone3::ComputeInitialCone`. The roots were supposed to be searched for the minimum, but the code for updating `minItem` did not update the `minError`. The quartic roots are generally stored in increasing order except when a repeated root 0 is found (for the depressed quartic). The cone fitting should not lead to a root of 0, so the previous code worked. The least-squares fitting PDF was updated accordingly.

GTE/Mathematics/ApprCone3.h

**September 6, 2021.** Implemented the test-intersection query for two finite cylinders that is described in `IntersectionOfCylinders.pdf`. The original version of the PDF showed that generally computing a separating axis requires minimizing a convex function. No details were provided about implementing the minimizer. In an attempt to implement the query, it was clear that a deeper analysis was required. The latest version of the PDF has those details. Added a sample application to illustrate the ideas.

GTE/BuildAll\*.sln  
GTE/GTMathematics{v14,v15,v16}.vcxproj  
GTE/GTMathematics{v14,v15,v16}.vcxproj.filters  
GTE/Mathematics/IntrCylinder3Cylinder3.h  
GTE/Samples/Intersection/IntersectCylinders/IntersectCylinders\*.\*  
GTE/Samples/Intersection/IntersectCylinders/.vscode/launch.json  
GTE/Samples/Intersection/IntersectCylinders/.vscode/settings.json  
GTE/Samples/Intersection/IntersectCylinders/CMakeLists.txt  
GTE/Samples/Intersection/IntersectCylinders/CMakeSample.sh  
GTE/Samples/Intersection/IntersectCylinders/cmake-variants.json  
GTE/Samples/Intersection/CMakeLists.txt

**August 24, 2021.** The `GetCosSin` function was failing when the floating-point model was set to `/fp:fast` instead of the default model `/fp:precise` used by GTE. The function was simplified to avoid the problem. The PDF documentation (*A Robust Eigensolver for  $3 \times 3$  Symmetric Matrices*) and the source code were revised to match each other.

GTE/Mathematics/SymmetricEigensolver3x3.h

## 14 Updates to Version 5.11

**August 1, 2021.** Most of the distance subsystem of GTE was revised or rewritten, mainly to avoid the LCP solver which was a performance problem when object features were (nearly) parallel. The subsystem consists of linear algebraic objects: point, line, ray, segment, triangle, rectangle, plane, box. The `Result` objects now have constructors that initialize the members explicitly, and the member names are consistent among files. Derivation of distance queries involving aligned boxes and oriented boxes was removed by factoring out *canonical boxes*, which are aligned boxes with centers at the origin. An aligned box can be reduced to a canonical box by a translation. An oriented box can be reduced to a canonical box by a rotation and a translation. Unit tests were updated, and some classes needed unit testing.

Several bugs were discovered and fixed.

- DistPointOrientedBox.h: Template alias for DCPPointOrientedBox had AlignedBox for the last parameter.
- DistSegment3OrientedBox3.h: Had segExtent instead of -segExtent in the last ‘else’ block.
- Bug fix DistSegment3Rectangle3.h: Had segExtent instead of -segExtent in the last ‘else’ block.

GTE/Mathematics/DistLine2AlignedBox2.h  
 GTE/Mathematics/DistRay2AlignedBox2.h  
 GTE/Mathematics/DistSegment2AlignedBox2.h  
 GTE/Mathematics/DistLine2OrientedBox2.h  
 GTE/Mathematics/DistRay2OrientedBox2.h  
 GTE/Mathematics/DistSegment2OrientedBox2.h  
 GTE/Mathematics/DistLine3AlignedBox3.h  
 GTE/Mathematics/DistLine3CanonicalBox3.h  
 GTE/Mathematics/DistLine3OrientedBox3.h  
 GTE/Mathematics/DistLine3Rectangle3.h  
 GTE/Mathematics/DistLine3Triangle3.h  
 GTE/Mathematics/DistOrientedBox3OrientedBox3.h  
 GTE/Mathematics/DistPlane3AlignedBox3.h  
 GTE/Mathematics/DistPlane3CanonicalBox3.h  
 GTE/Mathematics/DistPlane3OrientedBox3.h  
 GTE/Mathematics/DistPoint3Tetrahedron3.h  
 GTE/Mathematics/DistRay3AlignedBox3.h  
 GTE/Mathematics/DistRay3CanonicalBox3.h  
 GTE/Mathematics/DistRay3OrientedBox3.h  
 GTE/Mathematics/DistRay3Rectangle3.h  
 GTE/Mathematics/DistRay3Triangle3.h  
 GTE/Mathematics/DistRectangle3AlignedBox3.h  
 GTE/Mathematics/DistRectangle3CanonicalBox3.h  
 GTE/Mathematics/DistRectangle3OrientedBox3.h  
 GTE/Mathematics/DistSegment3AlignedBox3.h  
 GTE/Mathematics/DistSegment3CanonicalBox3.h  
 GTE/Mathematics/DistSegment3OrientedBox3.h  
 GTE/Mathematics/DistSegment3Rectangle3.h  
 GTE/Mathematics/DistSegment3Triangle3.h  
 GTE/Mathematics/DistTriangle3AlignedBox3.h  
 GTE/Mathematics/DistTriangle3CanonicalBox3.h  
 GTE/Mathematics/DistTriangle3OrientedBox3.h  
 GTE/Mathematics/DistAlignedBoxAlignedBox.h  
 GTE/Mathematics/DistLineLine.h  
 GTE/Mathematics/DistLineRay.h  
 GTE/Mathematics/DistLineSegment.h  
 GTE/Mathematics/DistPointAlignedBox.h  
 GTE/Mathematics/DistPointCanonicalBox.h  
 GTE/Mathematics/DistPointHyperellipsoid.h  
 GTE/Mathematics/DistPointHyperplane.h GTE/Mathematics/DistPointLine.h  
 GTE/Mathematics/DistPointOrientedBox.h  
 GTE/Mathematics/DistPointRay.h



GTE/Mathematics/DistPointRectangle.h  
 GTE/Mathematics/DistPointSegment.h  
 GTE/Mathematics/DistPointTriangle.h  
 GTE/Mathematics/DistRayRay.h  
 GTE/Mathematics/DistRaySegment.h  
 GTE/Mathematics/DistSegmentSegment.h  
 GTE/Mathematics/CanonicalBox.h  
 GTE/Graphics/Picker.cpp  
 GTE/Mathematics/ContLozenge3.h  
 GTE/Mathematics/IntrLine3Plane3.h  
 GTE/Mathematics/IntrPlane3Capsule3.h  
 GTE/Mathematics/IntrPlane3Cylinder3.h  
 GTE/Mathematics/IntrPlane3Ellipsoid3.h  
 GTE/Mathematics/IntrPlane3OrientedBox3.h  
 GTE/Mathematics/IntrPlane3Sphere3.h  
 GTE/Mathematics/IntrSphere3Triangle3.h  
 GTE/Mathematics/Rectangle.h  
 GTE/Mathematics/SplitMeshByPlane.h  
 GTE/Samples/Distance/DistanceAlignedBoxes/DistanceAlignedBoxesWindow3.cpp  
 GTE/Samples/Distance/DistanceAligedBoxOrientedBox/DistanceAlignedBoxOrientedBoxWindow3.cpp  
 GTE/Samples/Distance/DistanceOrientedBoxes/DistanceOrientedBoxesWindow3.cpp  
 GTE/Samples/Distance/DistancePointHyperellipsoid/DistancePointHyperellipsoidConsole.cpp  
 GTE/Samples/Distance/DistanceRectangleBox/DistanceRectangleBoxWindow3.cpp  
 GTE/Samples/Distance/DistanceTriangleBox/DistanceTriangleBoxWindow3.cpp  
 GTE/Samples/Distance/DistanceSegments3/DistanceSegments3Console.h  
 GTE/Samples/Distance/DistanceSegments3/DistanceSegments3Console.cpp  
 GTE/Samples/Intersection/IntersectConvexPolyhedra/ConvexPolyhedron.h

Added `GetVertices` member function.

GTE/Mathematics/AlignedBox.h

Small modification to avoid typecasting from integer to floating point.

GTE/Mathematics/OrientedBox.h

Added `origin` member, a point on the hyperplane.

GTE/Mathematics/Hyperplane.h

The 3D point-to-plane and point-to-rectangle queries works in general dimensions. The 3D files were renamed to `DistPointHyperplane.h` and `DistPointRectangle.h`.

GTE/Mathematics/DistPoint3Plane3.h  
 GTE/Mathematics/DistPoint3Rectangle3.h

The exact rational arithmetic code for point-triangle distance was moved previously into `DistPointTriangle.h`.

[GTE/Mathematics/DistPointTriangleExact.h](#)

The exact rational arithmetic code for segment-segment distance was moved into [DistSegmentSegment.h](#).

[GTE/Mathematics/DistSegmentSegmentExact.h](#)

**July 12, 2021.** Reordered the coefficients of the fitted quadratic functions. Modified the coefficients argument to use `std::array`. This allows the array of output coefficients of [ApprQuadratic3::operator\(\)](#) to be passed directly as an input to the [QuadricSurface](#) constructor. **NOTE: The reordering will affect any of your applications that use the quadratic approximations.**

[GTE/Mathematics/ApprQuadratic2.h](#)

[GTE/Mathematics/ApprQuadratic3.h](#)

**July 9, 2021.** Added new code and sample for computing the distance in 2D between a box (aligned or oriented) and a linear component (line, ray or segment).

[GTE/BuildAll\\*.sln](#)

[GTE/GTMathematics{v14,v15,v16}.vcxproj](#)

[GTE/GTMathematics{v14,v15,v16}.vcxproj.filters](#)

[GTE/Mathematics/DistLine2AlignedBox2.h](#)

[GTE/Mathematics/DistLine2OrientedBox2.h](#)

[GTE/Mathematics/DistRay2AlignedBox2.h](#)

[GTE/Mathematics/DistRay2OrientedBox2.h](#)

[GTE/Mathematics/DistSegment2AlignedBox2.h](#)

[GTE/Mathematics/DistSegment2OrientedBox2.h](#)

[GTE/Samples/Distance/DistanceLine2Box2/DistanceLine2Box2\\*.\\*](#)

[GTE/Samples/Distance/DistanceLine2Box2/.vscode/launch.json](#)

[GTE/Samples/Distance/DistanceLine2Box2/.vscode/settings.json](#)

[GTE/Samples/Distance/DistanceLine2Box2/CMakeLists.txt](#)

[GTE/Samples/Distance/DistanceLine2Box2/CMakeSample.sh](#)

[GTE/Samples/Distance/DistanceLine2Box2/cmake-variants.json](#)

[GTE/Samples/Distance/CMakeLists.txt](#)

**June 21, 2021.** When the line parameter for the point-ray distance test is negative, the [Result.parameter](#) member was not clamped to 0.

[GTE/Mathematics/DistPointRay.h](#)

Fixed a copy-and-paste error that should have been trapped by my instantiation tool; replaced `T` by `Real`.

[GTE/Mathematics/IntrRay2Triangle2.h](#)

**June 20, 2021.** Ported from Wild Magic to GTE the test-intersection and find-intersection queries for two stationary triangles in 3D. The template type can be floating-point, but rounding errors can cause misclassifications when two triangles are nearly touching. The template type can also be an arbitrary precision type, such as [BSRational<UIntegerAP32>](#), and the intersection set (if any) is theoretically correct.

```
GTE/GTMathematics{v14,v15,v16}.vcxproj
GTE/GTMathematics{v14,v15,v16}.vcxproj.filters
GTE/Mathematics/IntrTriangle3Triangle3.h
```

**June 17, 2021.** Modified the 2D line-triangle find-intersection query to allow for [Line2](#) objects with direction vectors that are not unit length. This is necessary to support exact arithmetic in the forthcoming port of [IntrTriangle3Triangle3](#) from Wild Magic to GTE. This query projects points from 3D to 2D and calls the [IntrSegment2Triangle2](#) query.

**The modified [IntrSegment2Triangle2](#) is a breaking change.** In the previous code, the [Result.parameter\[\]](#) values were relative to the center-direction-extent form of the segment, where  $t \in [-e, e]$  for extent  $e$ . The modified code does not convert the segment to center-direction-extent form in order to avoid floating-point rounding errors when computing the unit-length direction vector. Consequently, the modified code now has [Result.parameter\[\]](#) values relative to  $[0, 1]$  where the segment is parameterized by  $p[0] + t(p[1] - p[0])$  for  $t \in [0, 1]$ .

```
GTE/Mathematics/IntrLine2Triangle2.h
GTE/Mathematics/IntrRay2Triangle2.h
GTE/Mathematics/IntrSegment2Triangle2.h
```

Cosmetic changes to make the post-line-query code the same for all find-intersection queries of the code modified in the June 14, 2021 entry.

```
GTE/Mathematics/IntrSegment3AlignedBox3.h
GTE/Mathematics/IntrSegment3Capsule3.h
GTE/Mathematics/IntrSegment3Cylinder3.h
GTE/Mathematics/IntrSegment3Ellipsoid3.h
GTE/Mathematics/IntrSegment3Sphere3.h
```

## 15 Updates to Version 5.10

**June 14, 2021.** Modified the [Result](#) structures to use consistent naming for the intersection queries between convex volumetric objects and linear components (lines, rays, segments). The code for clamping line-object results to ray-object and segment-object has also been made consistent. The `std::numeric_limits<T>::max()` in the ray-object blocks was removed as a step forward to supporting exact arithmetic using [QFNumber](#) in GTL.

```
GTE/Mathematics/IntrLine3AlignedBox3.h
GTE/Mathematics/IntrLine3Capsule3.h
GTE/Mathematics/IntrLine3Cylinder3.h
GTE/Mathematics/IntrLine3Ellipsoid3.h
GTE/Mathematics/IntrLine3OrientedBox3.h
GTE/Mathematics/IntrLine3Sphere3.h
GTE/Mathematics/IntrRay3AlignedBox3.h
GTE/Mathematics/IntrRay3Capsule3.h
GTE/Mathematics/IntrRay3Cylinder3.h
GTE/Mathematics/IntrRay3Ellipsoid3.h
```

GTE/Mathematics/IntrRay3OrientedBox3.h  
GTE/Mathematics/IntrRay3Sphere3.h  
GTE/Mathematics/IntrSegment3AlignedBox3.h  
GTE/Mathematics/IntrSegment3Capsule3.h  
GTE/Mathematics/IntrSegment3Cylinder3.h  
GTE/Mathematics/IntrSegment3Ellipsoid3.h  
GTE/Mathematics/IntrSegment3OrientedBox3.h  
GTE/Mathematics/IntrSegment3Sphere3.h

**June 9, 2021.** The modification of 21 May 2021 fixed a logic error for subdivision, but it also exposed an edge case that is overly expensive when the minimum occurs at a parabola vertex. I modified the logic in the bracketed minimum search not to subdivide. Instead, only bisection is applied.

GTE/Mathematics/Minimize1.h

Ported the code for perspective projection of an ellipsoid onto a plane from Wild Magic to GTE.

GTE/Mathematics/Projection.h

**May 27, 2021.** Added support for fitting a cylinder to a triangle mesh. I also made some cosmetic code changes for the style associated with the port to GTL.

GTE/Mathematics/ApproxCylinder3.h

The Intel C++ Compiler 19.2 warned about a signed-unsigned mismatch in two loops.

GTE/Applications/MSW/WICFileIONative.cpp

**May 24, 2021.** After installing Fedora 34 with gcc 11.1.1, several files led to compiler failures. For example, [DisjointIntervals.h](#) has a single header include of `<vector>`. A source cpp file that includes [DisjointIntervals.h](#) and then references `size_t` will fail to compile, the compiler suggesting you might have meant `std::size_t`. This implies that the `<vector>` implementation uses only `std::size_t` and does not expose access to a namespace-less `size_t`. The file [HashCombine.h](#) has a single header include of `<functional>` but has the same problem with `size_t`.

GTE/Mathematics/DisjointIntervals.h  
GTE/Mathematics/HashCombine.h  
GTE/Mathematics/Image.h  
GTE/Mathematics/MinHeap.h

## 16 Updates to Version 5.9

**May 23, 2021.** The [IncrementalDelaunay2](#) triangulation (with insertions and/or removals) uses a supertriangle approach. The construction of the insertion polygon can still include triangles sharing a supervertex, and in some cases the polygon is incorrect. [Delaunay2](#) avoids the pitfalls of the supertriangle approach by not having

one. To avoid a complete redesign, the `IncrementalDelaunay2` code was modified to create the supertriangle with the input bounding rectangle included in the initial triangulation. The insertion polygon is now guaranteed to include only Delaunay triangles but not triangles having at least one supervertex. After all insertions and removals, if you do not want the input bounding rectangle as part of the triangulation, a new member function `FinalizeTriangulation` can be called to remove all triangles sharing an input rectangle vertex. After this call, you can no longer insert or remove points; that is, the triangulation really is final. I also fixed the version number for the header file and for the 3 files in the sample application. They all had `4.8.*` when they should have had `5.8.*`.

```
GTE/Mathematics/IncrementalDelaunay2.h
GTE/Samples/Geometrics/IncrementalDelaunay2/IncrementalDelaunay2Main.cpp
GTE/Samples/Geometrics/IncrementalDelaunay2/IncrementalDelaunay2Window2.{h,cpp}
```

Microsoft Visual Studio 2019 16.9.6 allowed a comparison of a `size_t` to an `int32_t` without complaint from the code analysis tool. GCC on Linux did complain.

```
GTE/Mathematics/LDLTDecomposition.h
```

I forgot to modify the target names in two sample applications.

```
GTE/Samples/Distance/DistanceOrientedBoxConeFrustum/CMakeLists.txt
GTE/Samples/Intersection/IntersectTriangleCylinder/CMakeLists.txt
```

**May 22, 2021.** Added new code to compute the distance and pair of closest points between a box and a cone frustum.

```
GTE/BuildAll*.sln
GTE/GTMathematics{v14,v15,v16}.vcxproj
GTE/GTMathematics{v14,v15,v16}.vcxproj.filters
GTE/Mathematics/DistOrientedBox3Cone3.h
GTE/Mathematics/Cone.h
GTE/Samples/Distance/DistanceOrientedBoxConeFrustum/DistanceOrientedBoxConeFrustum*.
GTE/Samples/Distance/DistanceOrientedBoxConeFrustum/.vscode/launch.json
GTE/Samples/Distance/DistanceOrientedBoxConeFrustum/.vscode/settings.json
GTE/Samples/Distance/DistanceOrientedBoxConeFrustum/CMakeLists.txt
GTE/Samples/Distance/DistanceOrientedBoxConeFrustum/CMakeSample.sh
GTE/Samples/Distance/DistanceOrientedBoxConeFrustum/cmake-variants.json
GTE/Samples/Distance/CMakeLists.txt
```

I forgot to add the CMake files for the sample application that illustrates the test-intersection query for a triangle and a cylinder.

```
GTE/Samples/Intersection/IntersectTriangleCylinder/.vscode/launch.json
GTE/Samples/Intersection/IntersectTriangleCylinder/.vscode/settings.json
GTE/Samples/Intersection/IntersectTriangleCylinder/CMakeLists.txt
GTE/Samples/Intersection/IntersectTriangleCylinder/CMakeSample.sh
GTE/Samples/Intersection/IntersectTriangleCylinder/cmake-variants.json
GTE/Samples/Intersection/CMakeLists.txt
```

**May 21, 2021.** Fixed a bug in the subdivision logic. The logic itself was simplified to be compact and more readable.

[GTE/Mathematics/Minimize1.h](#)

**May 13, 2021.** Added an implementation of the  $LDL^T$  decomposition for positive definite matrices.

[GTE/GTMathematics{v14,v15,v16}.vcxproj](#)  
[GTE/GTMathematics{v14,v15,v16}.vcxproj.filters](#)  
[GTE/Mathematics/LDLTDecomposition.h](#)

**May 6, 2021.** The line-triangle find-intersection query needed to store the  $t$ -parameters as a pair of ordered numbers. This ensures derived classes can correctly compute interval-interval queries. The line-triangle test-intersection query determines on which side of the line the triangle vertices lie. The Boolean test for the related signed quantities was incorrectly implemented. The ray-triangle and segment-triangle queries call the line-triangle query. If that query reports an intersection, interval-interval queries are applied. It is possible that the interval queries report no-intersection, but the information was not propagated to the caller. While I was in there, I modified constructors to initialize `Result` members (to avoid the code analysis complaints by Microsoft Visual Studio 2019).

[GTE/Mathematics/IntrLine2Triangle2.h](#)  
[GTE/Mathematics/IntrRay2Triangle2.h](#)  
[GTE/Mathematics/IntrSegment2Triangle2.h](#)  
[GTE/Mathematics/IntrIntervals.h](#)

**April 30, 2021.** The Runge-Kutta 4th-order algorithm for solving the quaternion-valued differential equation  $dq/dt = \omega q/2$  uses finite-differences to estimate  $q(t + \Delta t)$  (variable name `newQuatOrient`). These must be normalized before converting them to rotation matrices and before passing them to the force and torque functions. At the end of the update call, `mQuatOrient` must also be normalized.

[GTE/Mathematics/RigidBody.h](#)

Ported the test-intersection query for a triangle and a finite cylinder from Wild Magic 5 to GTE based on user request. The WM5 code had several bugs in it which were fixed during unit testing of the GTE code. A sample application is provided.

[GTE/BuildAll\\*.sln](#)  
[GTE/GTMathematics{v14,v15,v16}.vcxproj](#)  
[GTE/GTMathematics{v14,v15,v16}.vcxproj.filters](#)  
[GTE/Mathematics/IntrTriangle3Cylinder3.h](#)  
[GTE/Samples/Intersection/IntersectTriangleCylinder/IntersectTriangleCylinder\\*.\\*](#)

## 17 Updates to Version 5.8

**April 26, 2021.** The modifications of 24 April 2021 also required modifying the extremal query file. I had tested the sample application associated with this file, and it appeared to work. Another tool showed that the file does not compile. It is not clear why this occurred in the test environment.

GTE/Mathematics/ExtremalQuery3BSP.h

Fixed a spelling error in the top-level comment of the file.

GTE/Graphics/Node.h

I investigated the [Hyperplane](#) modification of 23 April 2021, where I thought the problem might be with the QEMU/KVM virtual machine. That is not correct. The problem turned out to be that the preprocessor settings for the project needed to include [GTE\\_USE\\_ROW\\_MAJOR](#) and [GTE\\_USE\\_MAT\\_VEC](#). Once these are added, the plane construction for dimension 3 using singular value decomposition is accurate. I have kept the modification in place, because the algorithm for plane construction is trivial for dimension 3.

**April 25, 2021.** The known-problems document mentioned that [GenerateMeshUVs](#) used to work on the GPU with HLSL but then stopped working, the returned texture coordinates all NaNs. It turns out that I had introduced the bug some time ago when factoring out the GPU code to [GPUGenerateMeshUVs](#). The [GenerateMeshUVs::Vertex](#) data structure had 3 [int](#) members for use by the HLSL shader, where that shader declared a structured buffer array with [int3](#) members. The data structure had 4 [int](#) members, the last one padding, for use by the GLSL. That shader declared a structured buffer array with [ivec3](#) members, but GLSL pads each element to 16 bytes as if you had declared the members [ivec4](#). The CPU padding was conditionally compiled. The factoring removed the conditional compilation, so now the [GenerateMeshUVs::Vertex](#) is 16 bytes regardless of using HLSL or GLSL. Unfortunately, I did not modify the HLSL code to use [int4](#) instead of [int3](#). This is now fixed. The document also mentions that when running the GLSL version, the [PlanarMesh](#) call to [GetContainingTriangle](#) was failing some of the time, unable to find a containing triangle. This occurs for [GenerateMeshUVs<double>](#) but not for [GenerateMeshUVs<float>](#). The failure indicates fold-overs in the planar mesh. The double-precision arithmetic in the GLSL code appears not to be of the same precision as in that of the HLSL code.

GTE/Mathematics/GenerateMeshUV.h

GTE/MathematicsGPU/GPUGenerateMeshUV.h

GTE/Samples/Geometrics/GenerateMeshUVs/GenerateMeshUVsWindow3.{h,cpp}

**April 24, 2021.** Replaced [std::shared\\_ptr](#) by [std::unique\\_ptr](#) in the vertex, edge and triangle maps. Replaced the use of [std::weak\\_ptr<T>](#) by [T\\*](#). This improves the performance of the manifold meshes because of reduced memory management. (Thanks to Aaron Barany for these modifications.)

GTE/Mathematics/ConformalMapGenus0.h

GTE/Mathematics/ConstrainedDelaunay2.h

GTE/Mathematics/ConvexHull3.h

GTE/Mathematics/Delaunay2.h

GTE/Mathematics/ETManifoldMesh.h

GTE/Mathematics/GenerateMeshUV.h

GTE/Mathematics/IncrementalDelaunay2.h

GTE/Mathematics/MinimumVolumeBox3.h

GTE/Mathematics/PlanarMesh.h

GTE/Mathematics/TriangulateCDT.h

GTE/Mathematics/VertexCollapseMesh.h

GTE/Mathematics/VETManifoldMesh.h

**April 23, 2021.** The [Hyperplane](#) constructor whose input is a [std::array](#) of points uses singular value decomposition to build the plane through the points. The body has been replaced by a call to a function that is determined at compile time for dimension 3 and for other dimensions. This is a hack based on a bug report for the code executed on a QEMU/KVM virtual machine, which indicated the singular value decomposition was producing inaccurate results. I am unable to reproduce the problem on a non-virtual machine; the SVD works correctly for the dataset included in the bug report. I need to determine what the virtual machine is doing that causes such inaccurate results when using floating-point arithmetic.

[GTE/Mathematics/Hyperplane.h](#)

**April 16, 2021.** The Wild Magic 5 version of [IncrementalDelaunay2](#) had support for computing the containing triangle for a query point. It also contained support for accessing the Delaunay triangles (not including triangles with at least one supervertex), for accessing the indices of triangles adjacent to a specified triangle, and for accessing the convex hull polygon of the Delaunay triangles. These have now been ported to the GTE version of [IncrementalDelaunay2](#).

[GTE/Mathematics/IncrementalDelaunay2.h](#)

[GTE/Samples/Geometrics/IncrementalDelaunay2/IncrementalDelaunay2Window2.{h,cpp}](#)

**April 13, 2021.** Fixed a bug in the computation of [E1.sqrExtent](#) in the [AreaOfIntersection](#) function with [Ellipse2](#) arguments. The unit tests included one for the other [AreaOfIntersection](#) but did not include one for this function.

[GTE/Mathematics/IntrEllipse2Ellipse2.h](#)

**April 9, 2021.** When the file was copied to another project that did not have precompiled headers, it failed to compile because of [std::back\\_inserter](#). I added an include of [<iterator>](#) to fix this.

[GTE/Applications/MSW/WICFileIONative.cpp](#)

## 18 Updates to Version 5.7

**March 26, 2021.** Ported the incremental insertion and removal of points for a Delaunay 2D triangulation from Wild Magic to GTE. The Wild Magic code did not correctly handle removing points from the convex hull boundary of the triangulation. I fixed this by adding a new subsystem to correctly retriangulate the removal polygon.

[GTE/BuildAll\\*.sln](#)

[GTE/GTMathematics{v14,v15,v16}.vcxproj](#)

[GTE/GTMathematics{v14,v15,v16}.vcxproj.filters](#)

[GTE/Mathematics/IncrementalDelaunay2.h](#)

[GTE/Samples/Geometrics/IncrementalDelaunay2/IncrementalDelaunay2\\*.\\*](#)

Added constructor to `MinHeap::Result` with initialized members to avoid MSVS code analysis warnings.



GTE/Mathematics/MinHeap.h

**March 15, 2021.** The [Delaunay2](#) code was failing on a platform using a virtual machine and Microsoft Visual Studio 2015. The problem is that the compiler is optimizing away some floating-point expressions that should not be due to rounding mode. I mentioned this problem in Section 3.4 of [RAEFC Book Corrections](#). I removed the final uses of `std::fesetround` and `std::fegetround`, replacing them with [SWInterval](#) interval arithmetic support that works with the default FPU rounding mode (round to nearest ties to even).

GTE/Mathematics/APConversion.h

GTE/Mathematics/ConstrainedDelaunay2.h

GTE/Mathematics/Delaunay2.h

These modifications affect only the new [ConstrainedDelaunay2](#) and [Delaunay2](#) implementations. The older implementations do not use `cfenv` for floating-point environment changes, and they are currently tagged as *deprecated* but will exist until the full GTL distribution is available.

**March 14, 2021.** The deprecated code in [ConstrainedDelaunay2](#) (the first implementation in the header file) had a bug in [Retriangulate](#) that was introduced based on my blindly following a suggestion by the Microsoft Visual Studio code analysis tool.

GTE/Mathematics/ConstrainedDelaunay2.h

The description here is long but intended to let others know to be careful about the code analysis suggestions.

The Retriangulate function originally had a line of code to access the top of the stack,

```
auto i = stack[top--];
```

The Microsoft Visual Studio code analysis tool complained '`auto`' doesn't deduce references. A possibly unintended copy is being made and suggested modifying to a reference `auto&` (or `auto const&`). Without thinking about the message, I changed the code to

```
auto const& i = stack[top--];
```

which is an error, because now I have a reference to the `stack[top+1]` element. Later in the function,

```
stack[++top] = { i[0], isplit };
stack[++top] = { isplit, i[1] };
```

In the first line of this code, the value `top` is incremented first and then the pair is copied to the stack. The problem is that `i` is the pair to which the left-hand side of the assignment refers. The write of `i[0]` to this location overwrites itself (no problem), but the write of `isplit` to this location overwrites `i[1]` (the error). The second line of code reads `i[1]`, which was inadvertently modified to `isplit`. I have been burned several times by the faulty suggestions of the code analyzer and learned now to think about them, replacing the `auto` keyword by the actual type or ignoring them. The same problem had occurred in the new CDT code (the second implementation in the header file), but during unit testing I found and fixed the problem. I had not thought to go back to the old code to see whether it had the same problem. My solution was to replace

```
auto const& i = stack[top--];
```

by

```
std::array<size_t, 2> i = stack[top--];
```

## 19 Updates to Version 5.6

**March 8, 2021.** All but the first `mAccumulatedLength` elements are uninitialized, which causes `GetTotalLength()` to fail. The Release-build unit tests did not fail (via `NaturalSplineCurve`) using Microsoft Visual Studio because the compiler initializes the elements to zero. The compiler then optimizes away the first line of code in `GetTotalLength()` because it believes `mAccumulatedLength.back()` will return zero the first time `GetTotalLength()` is called. This hides the bug when using MSVS. Other compilers will most likely leave `mAccumulatedLength` uninitialized, in which case the bug shows up.

GTE/Mathematics/ParametricCurve.h

The `BSNumber` constructors that take integer inputs need to compute the debug-supporting `mValue` first. The previous code modifies the inputs before computing `mValue`, which causes the sign to be positive when the inputs are negative. The problem showed up only when `GTE_BINARY_SCIENTIFIC_SHOW_DOUBLE` was enabled for debugging and testing and does not affect the correctness of the actual `BSNumber`.

GTE/Mathematics/BSNumber.h

**February 11, 2021.** Added counting of maximum number of words for testing for sum of two squares and for (not yet published) `Delaunay2` that computes the triangulation using a 3D convex hull for points  $(x, y, x^2 + y^2)$ .

GTE/Tools/PrecisionCalculator/PrecisionCalculator.cpp

**February 10, 2021.** The ray-sphere and segment-sphere queries were generating incorrect results when the linear component is tangent to the sphere. This occurred because `result.parameter[1]` is uninitialized in the line-sphere query for the tangent case, and the ray-sphere and segment-sphere code uses both `result.parameter[]` values for interval-interval intersection. The `Result` nested-class constructors now have all members initialized, and `result.parameter[1]` is set to `result.parameter[0]` in the tangent case. The same issues arise with ray-ellipsoid and segment-ellipsoid queries; they were fixed in the same manner.

GTE/Mathematics/IntrLine3Sphere3.h  
GTE/Mathematics/IntrRay3Sphere3.h  
GTE/Mathematics/IntrSegment3Sphere3.h  
GTE/Mathematics/IntrLine3Ellipsoid3.h  
GTE/Mathematics/IntrRay3Ellipsoid3.h  
GTE/Mathematics/IntrSegment3Ellipsoid3.h

Added counting of maximum number of words for testing for coplanar points. Added a comment with a formula for determining the number of bytes used by `BSNumber<UIntegerFP32<N>>`. The value is  $4(N + 4)$ .

GTE/Tools/PrecisionCalculator/PrecisionCalculator.cpp

**February 2, 2021.** In `Hull3`, the incoming hull has coplanar points. When inserting the next point, the hull becomes volumetric. The incoming hull triangles are inserted into the VET mesh, but the winding orders are reversed. The triangles generated after that have the correct winding order. Fixed this.

GTE/Mathematics/ConvexHull3.h

**January 29, 2021.** Added debug support for counting the maximum number of blocks of bits used in `UIntegerFP32<N>` during application execution. The class `UIntegerAP32` already has this support.

GTE/Mathematics/UIntegerFP32.h

Added counting of maximum number of words for testing for colinear points.

GTE/Tools/PrecisionCalculator/PrecisionCalculator.cpp

**January 17, 2021.** I figured out why `MinimumVolumeBox3D` was broken. It turns out that the member function `CreateCompactMesh` has an implicit assumption that the vertices in the `VETManifoldMesh::Vertex` are ordered by the integer key. This assumption was satisfied when the vertex map was a `std::map`, but not when the vertex map was changed to a `std::unordered_map`. I restored the vertex map to be an unordered map and added code to the minimum-volume box to sort the vertices before creating the compact array of vertex adjacencies.

GTE/Mathematics/MinimumVolumeBox3.h

GTE/Mathematics/VETManifoldMesh.h

**January 15, 2021.** The sample `MinimumVolumeBox3D` was broken in that the displayed box no longer contained the convex polyhedron. I traced this back to GTE 5.4 where I replaced the `std::set` and `std::map` objects by `std::unordered_set` and `std::unordered_map` objects. For a reason that I am unable to understand, the sample runs correctly when using `std::map` for `VETManifoldMesh::VMap`, but it does not run correctly when using `std::unordered_map` for `VETManifoldMesh::VMap`. The key type in either case is the native type `int`. I restored `VMap` to use `std::map`.

GTE/Mathematics/VETManifoldMesh.h

## 20 Updates to Version 5.5

**January 14, 2021.** The `ConvexHull3` performance was absolutely awful, requiring over 1 hour to compute the hull of a 120K-vertex dataset. I reimplemented this to use incremental insertion (single-threaded) and a divide-and-conquer algorithm (multithread). On an Intel i9-10900 CPU, the incremental insertion for the 120K-vertex dataset executes in approximately 4 seconds. The divide-and-conquer algorithm using 8 threads executes in approximately 1.7 seconds. Files that depend on `ConvexHull3` were modified accordingly.

GTE/Mathematics/ConvexHull3.h

GTE/Mathematics/MinimumVolumeBox3.h

GTE/Mathematics/SeparatePoints3.h

GTE/Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow3.cpp

GTE/Samples/Geometrics/ExtremalQuery/ExtremalQueryWindow3.cpp

GTE/Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow3.cpp

Added a new file for interval arithmetic. The implementation is software based and uses `std::nextafter` for determining the intervals. This avoids the floating-point hardware state changes when setting the rounding modes, and it avoids the problem with GCC that appears not to expose the ability to modify the floating-point environment.

```
GTE/GTMathematics{v14,v15,v16}.vcxproj  
GTE/GTMathematics{v14,v15,v16}.vcxproj.filters  
GTE/Mathematics/SWInterval.h
```

Replaced `int V[3]` by `std::array<int, 3> V` in the `ETManifoldMesh::Triangle` class. A similar change had been made already to `ETManifoldMesh::Edge`.

```
GTE/Mathematics/ETManifoldMesh.h
```

**December 25, 2020.** The `DX11Engine` constructors that have a window handle input are designed for rendering to the window. These constructors create default render states that GTE wants, and these states are not all the default DX11 render states. The `DX11Engine` constructors that do not have a window handle input are designed for windowless applications using compute shaders. These constructors do not create default render states for GTE, so the default states are those of DX11. To support a windowless application that renders to an offscreen render target, and to allow that code to work whether windowed or windowless, I added creation of the default GTE render states to the compute-intended `DX11Engine` constructors.

```
GTE/Graphics/DX11/DX11Engine.cpp
```

**December 23, 2020.** Eliminated the annoying MSVS 2019 warning about `DFType` being an unscoped `enum`, suggesting that `enum class` is better. I replaced the enumeration by a list of `constexpr` values. The type `DFType` is defined to be `uint32_t`.

```
GTE/Graphics/DataFormat.h
```

## 21 Updates to Version 5.4

**December 18, 2020.** Added code to rasterize a collection of tetrahedra into a 3D grid.

```
GTE/GTMathematics{v14,v15,v16}.vcxproj  
GTE/GTMathematics{v14,v15,v16}.vcxproj.filters  
GTE/Mathematics/TetrahedraRasterizer.h
```

**December 1, 2020.** Replaced the one remaining `std::set` object by a `std::unordered_set` object.

```
GTE/Mathematics/ConstrainedDelaunay2.h
```

While porting `Delaunay2.h` from GTE to GTL, the more robust GTL unit tests for the `ToCircumcircle` function failed for nearly cocircular points. Fixed the problem in the GTE code.

GTE/Mathematics/Delaunay2.h

**November 30, 2020.** Added interfaces to allow passing a raw pointer to vertices and the number of vertices.

GTE/Mathematics/Delaunay2.h  
GTE/Mathematics/ConstrainedDelaunay2.h  
GTE/Mathematics/TriangulateCDT.h

## 22 Updates to Version 5.3

**November 16, 2020.** Added a new file to create hash functions in order to use `std::unordered_set` and `std::unordered_map` in GTL code, replacing `std::set` and `std::map` when a performance increase is desired.

GTE/Mathematics.v\*.\*  
GTE/Mathematics/HashCombine.h  
GTE/Mathematics/FeatureKey.h  
GTE/Mathematics/ETManifoldMesh.h  
GTE/Mathematics/VETManifoldMesh.h

Added new classes that do not require the user to specify the computing type. The old classes are now tagged as *deprecated* and will be removed in a later version of GTE.

GTE/Mathematics/Delaunay2.h  
GTE/Mathematics/ConstrainedDelaunay2.h  
GTE/Mathematics/TriangulateCDT.h

Classes affected by the manifold mesh and Delaunay modifications.

GTE/Mathematics/Delaunay2Mesh.h  
GTE/Mathematics/ExtremalQuery3BSP.h  
GTE/Mathematics/IntpQuadraticNonuniform.h  
GTE/Mathematics/IntpSphere2.h  
GTE/Samples/Mathematics/Interpolation2D/Interpolation2DWindow3.h

Factored `IntervalProductUp` and `IntervalProductDown` from `ConvexHull3.h` to `ProductLowerBound` and `ProductUpperBound` in `FPIInterval.h` so that the code can be shared by other computational geometry queries involving interval arithmetic.

GTE/Mathematics/ConvexHull3.h  
GTE/Mathematics/FPIInterval.h

Added a new member function `CopyFrom` that does a direct copy from `UIntegerFP<N>` to `UIntegerFP<M>` as long as `N` is no larger than `M`. This allows converting floating-point inputs to `UIntegerFP<N>` for `N`-value 2 or 4. These can then be copied on-demand into a pool of `UIntegerFP<M>` for much larger `M` that is used

to represent an expression tree that must be computed with exact arithmetic. The goal is to reduce heap memory usage when computing with arbitrary-precision arithmetic. The pool can be allocated on the heap to avoid having to greatly increase the program stack size when `M` is large.

[GTE/Mathematics/UIntegerFP32.h](#)

Fixed a bug that was introduced when performance optimizations were added to the file. The original code had allocated vectors for `mB`, `mC` and `mD`. The optimized code packed these into a single chunk of memory, but the aforementioned variables which became pointers were not set to point to the proper locations in that chunk. This was only for the clamped-spline case.

[GTE/Mathematics/NaturalSplineCurve.h](#)

**November 13, 2020.** A conditionally compiled block that was disabled did not compile when enabled because of changes to the `Vector2` constructors.

[GTE/Samples/Geometrics/Delaunay2D/Delaunay2DWindow2.cpp](#)

**November 10, 2020.** Added/updated comments about how large  $N$  must be to use `ComputeType` of `BSNumber<UIntegerFP32<N>>`. The performance is much better when you use `UIntegerFP32` rather than `UIntegerAP32` because the latter leads to significant heap management costs.

[GTE/Mathematics/Delaunay2.h](#)

[GTE/Mathematics/ConstrainedDelaunay2.h](#)

[GTE/Mathematics/TriangulateCDT.h](#)

**November 8, 2020.** When using `ComputeType` that is a floating-point type, rounding errors can cause sign misclassifications in the loop over `linkEdges` and prevent `ProcessTriangleStrip` and `ProcessCoincidentEdge` from being called. The consequence is that `partition` is an empty `std::vector` and the call to `partition.back()` causes a crash. I added a `LogAssert` call to throw an exception in this case. It is strongly recommended to use an arbitrary-precision type for `ComputeType`. Alternatively, use a try-catch block to triangulate using a floating-point type and, if an exception is thrown, repeat the call using an arbitrary-precision type. I also replaced the nondescriptive “Unexpected condition” in the `LogAssert` statements with function calls that return strings with more description.

[GTE/Mathematics/ConstrainedDelaunay2.h](#)

**November 6, 2020.** Added more members and queries to `PolygonTreeEx`. Previously, the `insideTriangles` vector stored all triangle in the polygon tree. For `TriangulateCDT` to be consistent with `TriangulateEC`, it is convenient to partition these into `interiorTriangles`, which are those triangles bounded by an outer polygon and its child inner polygons, and `exteriorTriangles`, which are those triangles bounded by an inner polygon and its child outer polygons. The point-containment query of `TriangulateEC` searches only the interior triangles. In fact, that class does not construct exterior triangles. I added point-containment queries for each type of vector member of `PolygonTreeEx` including comments about typical usage. You can create your own queries, especially if you want to use multithreading. Also, it is sometimes convenient to know which node of the polygon tree stores the containing triangle. The node index information has also been added to `PolygonTreeEx` for the various triangle vector members, and a couple of the point-containment queries use these.

GTE/Mathematics/PolygonTree.h  
GTE/Mathematics/TriangulateCDT.h

## 23 Updates to Version 5.2

**November 5, 2020.** The `ConstrainedDelaunay2` class had two bugs that needed to be fixed. The first bug was incorrect handling of adjacent triangles during retriangulation of the triangle strips containing the constrained edges. This problem shows up when the triangle strip snakes around and has a shared edge with another triangle that is not its immediate predecessor in the strip. The second bug was an incorrect computation of the pseudosquared distance function. This problem shows up when locating the closest vertex of a boundary polygon to the base polygon edge. In particular, the bug was exercised when the projections of the candidate vertices to the base edge of the polygon contained at least one projection on the segment and one projection outside the segment.

This code is approximately 13 years old and was complicated to read and debug because. In particular, it discarded the `mGraph` member from the Delaunay triangulation and instead used the compact arrays `mIndices` and `mAdjacencies`. I rewrote the `ConstrainedDelaunay2` to continue using the `mGraph` member, in the process simplifying the implementation to be readable. Many comments were added, but I plan on adding a PDF to the website describing the pitfalls of the retriangulation and how to avoid them. The original code was based on an online research paper that discussed the simplest retriangulation configuration, but had no discussion about the pitfall cases. The various file changes are described next.

Reimplemented `ConstrainedDelaunay2` according to the aforementioned comments.

GTE/Mathematics/ConstrainedDelaunay2.h

Factored out some code into a new function `UpdateIndicesAdjacencies`. This code occurred after the Delaunay triangulation to synchronize the information in `mGraph` with the compact arrays `mIndices` and `mAdjacencies`. To support `ConstrainedDelaunay2`, the factored function can be called after a user-determined set of edges have been inserted one at a time.

GTE/Mathematics/Delaunay2.h

Added two helper functions to `ETManifoldMesh::Triangle`, namely, `GetAdjacentOfEdge` and `GetOppositeVertexOfEdge`. I will continue to encapsulate common operations and add them to `ETManifoldMesh`. These operations tend to occur as in-application code, but that code should be shared.

GTE/Mathematics/ETManifoldMesh.h

The modifications to `ConstrainedDelaunay2` required a small modification to the polygon triangulation that uses constrained Delaunay triangulation. The code copies the Delaunay `mGraph` object to the local `graph` object.

GTE/Mathematics/TriangulateCDT.h

The insertions are not batched; rather, they are executed one at a time based on key strokes. The application now needs to call `UpdateIndicesAdjacencies` after each edge insertion.

GTE/Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow2.cpp

**October 26, 2020.** I redesigned and rewrote [TriangulateCDT](#) to support shared vertices, coincident vertex-edge configurations and coincident edge-edge configurations. These configurations are *not* supported by [TriangulateEC](#). To avoid repackaging polygon trees in an application using both classes, I factored out the nested [Tree](#) classes into a new class [PolygonTree](#). Objects of this class are inputs to the triangulators, and they are not modified internally. I also created a new class [PolygonTreeEx](#) that currently represents the output of [TriangulateCDT](#). Eventually, this class will become an input-output parameter for both triangulators. NOTE that [TriangulateCDT](#) does not support polygon trees where two edges intersect at an edge-interior point of both edges and that intersection point is not in the input points to the triangulator. The problem is that the constrained Delaunay triangulation works correctly when the constrained edges do not intersect other than at shared-vertex endpoints. If one were to insert two edges into the Delaunay triangulation that have an edge-interior intersection, each edge interferes with the local re-triangulation of the other edge. I plan on adding support for such edges, but the task is of significant size and will take some time.

GTE/Mathematics{v14,v15,v16}.vcxproj  
GTE/Mathematics{v14,v15,v16}.vcxproj.filters  
GTE/Mathematics/PolygonTree.h  
GTE/Mathematics/TriangulateCDT.h  
GTE/Mathematics/TriangulateEC.h  
GTE/Samples/Geometrics/TriangulationEC/TriangulationECWindow2.{h,cpp}  
GTE/Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow2.{h,cpp}

**October 26, 2020.** Added to the nested class [Triangle](#) a function that tests whether a directed edge in mesh is in the same direction as an undirected triangle edge or in the opposite direction (or not a triangle edge at all). This is a common query that is now encapsulated.

GTE/Mathematics/ETManifoldMesh.h

**October 26, 2020.** Swap chain creation in DX11 now has “flip” flags that are recommended. The [DX11Engine](#) still uses the old flags. Apparently, the internal changes to DX11 for the flip flags sometimes causes creation of a second [ID3D11Context](#) during a swap-chain [Present](#) call in order to create an [ID3D11RenderTargetView](#) and related objects. The DXGI debug layer indicates that the back buffer is unbound from the pipeline, which is not what I thought was happening with the old swap-chain creation flags. The second context appears to be create to patch the problem. However, the time of its destruction is nondeterministic. In some cases, the destruction occurs before the GTE application [mDevice](#) is destroyed, and the [FinalRelease\(mDevice\)](#) is successful. In other cases, the destruction occurs after the final release of [mDevice](#), but an exception is thrown (by the GTE code) indicating the reference count for [mDevice](#) is positive. Finally, in many cases, the second context is never created. Until I understand why this behavior occurs, I have replaced the [DX11::FinalRelease](#) calls in [DX11Engine::DestroyDevice](#) with [DX11::SafeRelease](#) calls, the latter not tracking the reference counts and not throwing exceptions.

GTE/Graphics/DX11/DX11Engine.cpp

**October 11, 2020.** The translation is now 3D, allowing for placement of the text within a 3D scene.

GTE/Graphics/TextEffect.{h,cpp}



## 24 Updates to Version 5.1

**October 11, 2020.** The [CMakeLists.txt](#) files were using [add\\_compile\\_definitions](#), which requires CMake 3.12 or later. Replaced these by [add\\_definitions](#). The modifications affected 135 files which will not be listed here.

**October 10, 2020.** Added comments that Sylvester's criterion is used to test for positive definiteness. The loop on halving the root was limited to 8 iterations, but the number has been increased to allow rational arithmetic for which an unlimited loop could be infinite. The new limit is 2048, which will not be reached for floating-point types [float](#) and [double](#). The [ApprEllipse2](#) code had a redundant test for the determinant of the entire matrix, but it has now been removed.

[GTE/Mathematics/ApprEllipse2.h](#)  
[GTE/Mathematics/ApprEllipsoid3.h](#)

**October 9, 2020.** The old code [ApprEllipse2](#) and [ApprEllipsoid3](#) for fitting points with ellipses and ellipsoids were based on a nonlinear least-squares error function that was a sum of distances from points to the objects. The comments in those files described eigendecompositions of the  $M$  matrices but were in error, and the code did not correctly implement the mathematics. Moreover, [ApprEllipsoid3](#) failed to initialize [angle\[2\]](#) before running the minimizer. The rewritten code uses a minimizer involving a 2-step gradient descent algorithm. Unit tests and end-to-end tests were added to the internal test suite to verify the algorithm and results.

[GTE/Mathematics/ApprEllipse2.h](#)  
[GTE/Mathematics/ApprEllipsoid3.h](#)

## 25 Updates to Version 5.0

**September 29, 2020.** Added support to the Linux distribution for CMake executed from a command line and for Visual Studio Code. Please read the installation and release notes on how to build the libraries and samples on Linux.

The support for building the GTE libraries are in the files listed next.

[GTE/.vscode/settings.json](#)  
[GTE/GTE.code-workspace](#)  
[GTE/CMakeLibraries.sh](#)  
[GTE/CMakeLists.txt](#)  
[GTE/cmake-variants.json](#)  
[GTE/Applications/CMakeLists.txt](#)  
[GTE/Applications/cmake-variants.json](#)  
[GTE/Graphics/CMakeLists.txt](#)  
[GTE/Graphics/cmake-variants.json](#)  
[GTE/Mathematics/CMakeLists.txt](#)  
[GTE/Mathematics/cmake-variants.json](#)  
[GTE/MathematicsGPU/CMakeLists.txt](#)  
[GTE/MathematicsGPU/cmake-variants.json](#)

The CMake and Visual Studio Code support are listed next. The libraries must be built first before building any samples.

```
GTE/Samples/CMakeLists.txt
GTE/Samples/CMakeSamples.sh
GTE/Samples/<subfolder>/CMakeLists.txt
GTE/Samples/<subfolder>/CMakeSamples.sh
GTE/Samples/<subfolder>/<appfolder>/vscode/launch.json
GTE/Samples/<subfolder>/<appfolder>/vscode/settings.json
GTE/Samples/<subfolder>/<appfolder>/<appfolder>.code-workspace
GTE/Samples/<subfolder>/<appfolder>/cmake-variants.json
GTE/Samples/<subfolder>/<appfolder>/CMakeLists.txt
GTE/Samples/<subfolder>/<appfolder>/CMakeSample.sh
```

The sample subfolders are [Distance](#), [Geometrics](#), [Graphics](#), [Imagics](#), [Intersection](#), [Mathematics](#), [Physics](#) and [Scene-Graphs](#). The number of application folders is quite large and not listed here.

The shared-library executables in the Linux distribution were crashing on exit from the [main](#) program. Using gdb and the core dump, the problem appeared to be in the destruction of global objects in the [gtapplications](#) shared library. The singleton [TheWindowSystem](#) was actually created 3 times because of the way shared libraries are linked and loaded. I had added `-rdynamic` to the [makesample.gte](#) link line (suggested by a poster at stackoverflow). This eliminated the multiple creations of [TheWindowSystem](#). Unfortunately, on-exit crashes still occurred, this time in the destruction of global objects in the [gtgraphics](#) shared library. The only global objects are several class-static members. To diagnose with a visual debugger, I decided to add Visual Studio Code support. With this environment, the on-exit crashes no longer occur. The CMake output files are cryptic, and I am not skilled enough to figure out what differences occur between CMake and my makefiles regarding linking and loading of shared libraries. Visual Studio Code and CMake work fine, so I am abandoning my simple Unix makefile approach.

```
GTE/makeapplications.gte
GTE/makegraphics.gte
GTE/makemathematicsgpu.gte
GTE/makelibraries.sh
GTE/Samples/makeallsamples.gte
GTE/Samples/makesamples.gte
GTE/Samples/makesample.gte
```

Moved the [GTE/Mathematics/GPU](#) folder to [GTE/MathematicsGPU](#) to support the new CMake and Visual Studio Code project organization on Linux. All the associated project source files had to be modified so the header includes access the new location. Some application files had to be modified.

```
GTE/GTMathematicsGPU.{v14,v15,v16}.{vcxproj,vcxproj.filters}
GTE/Samples/Geometrics/GenerateMeshUVs/GenerateMeshUVsWindows3.cpp
GTE/Samples/Physics/BlownGlass/BlownGlassWindows3.h
GTE/Samples/Physics/Fluids2D/Fluids2DWindows2.h
GTE/Samples/Physics/Fluids3D/Fluids2DWindows3.h
```

Visual Studio Code with g++ on Ubuntu 18.04.5 LTS complained about potentially uninitialized variables.

They are initialized, but the compiler cannot determine this from the code. I set default values to avoid the warning.

[GTE/Samples/Geometrics/GenerateMeshUVs/GenerateMeshUVsWindow3.cpp](#)

Visual Studio Code with g++ on Ubuntu 18.04.5 LTS complained about potentially uninitialized variables. The vector components referred to are not initialized in some circumstances, but the program logic avoids using them in those circumstances. I initialized the vectors to zero to avoid the warning.

[GTE/Mathematics/DistPointHyperellipsoid.h](#)

**September 25, 2020.** The find-intersection query for moving spheres and oriented boxes calls the base-class protected query for moving spheres and aligned boxes. That call requires the center point to be in the first octant and makes adjustments accordingly. The find-intersection for the oriented boxes did not make this adjustment. I moved the transforming of the center point into the base-class query to fix the problem. The visual test harness for this code is the sample application MovingSpheresBoxes, where I apparently never moved the sphere into a position that exercised the bug.

[GTE/Mathematics/IntrAlignedBox3Sphere3.h](#)

**September 18, 2020.** Deprecated the class [UniqueVerticesTriangles](#). Added a replacement, [UniqueVerticesSimplices](#) that works in any dimension 2 or larger. The class has been used for removing duplicated and unused vertices from triangle meshes and for generating meshes from a vertex-only based representation to one using an indexed representation. The generalized code applies to dimension 2 and will be used for computational geometry algorithms involving polygons (Boolean operations on polygons, for example). The deprecation is in the C++ 14 sense: the class is tagged with [\[\[deprecated\]\]](#). It will be removed sometime in the near future.

[GTE/Mathematics/UniqueVerticesSimplices.h](#)  
[GTE/Mathematics/UniqueVerticesTriangles.h](#)  
[GTE/Mathematics/IntrConvexMesh3Plane3.h](#)  
[GTE/Mathematics/MinimumVolumeBox3.h](#)  
[GTE/Mathematics/SurfaceExtractorMC.h](#)

**September 17, 2020.** The [BSPPolygon2::Finalize](#) function passed [\\*this](#) as a non-const parameter and [this→mEArray](#) as a const parameter to the [BSPTree2](#) constructor, which should have been a clue that the BSP implementation is badly done. A test data set was included in a bug report, and it led to an infinite loop in the [BSPTree2](#) code because [mEArray](#) was modified via the [\\*this](#) object. A copy of [mEArray](#) is now passed as the second parameter of the [BSPTree2](#) constructor.

The constructor also has a switch statement that classifies the intersection type of two edges. In the cases [TRANSVERSE.POSITIVE](#) and [TRANSVERSE.NEGATIVE](#), it is possible that floating-point rounding error can cause the intersection point to be one of the segment endpoints. This must be trapped and handled separately. Before the change, the test data set triggered an assertion in [SplitEdge](#) for the user reporting the problem. I was unable to reproduce this, but compiled expressions using floating-point arithmetic can lead to different low-level code depending on the compiler, and the rounding behavior can vary. This is not just a matter of the low-level expression tree of operations, it can also be a matter of what precision registers are used and whether downcasts occur from a high-precision register (say, 80-bit) to a low-precision register (say, 64-bit).

GTE/Mathematics/BSPPolygon2.h

**September 17, 2020.** Removed the compiler define for `GTE_THROW_ON_UINTEGERFP32_OUT_OF_RANGE` and exposed the one line of code controlled by it in `SetNumBits`. An exception needs to be thrown if the bit request exceeds the number of bits provided by the class so that a caller can trap this with a try-catch block.

## 26 Updates to Version 4.9

**September 15, 2020.** Reverted the path variable `GTE4_PATH` to `GTE_PATH`.

GTE/Applications/Application.h  
GTE/Applications/Environment.h  
GTE/Applications/Environment.cpp

**September 14, 2020.** Initialized some `std::array` objects to avoid warnings by gcc 10.2.1 on Fedora 32 for potentially uninitialized variables. The variables are initialized, but the compiler cannot determine this solely from the code.

GTE/Mathematics/IntpQuadraticNonuniform2.h

Bypassed a couple of `TriangleKey<true>` constructor calls to avoid a warning by gcc 7.5.0 on Ubuntu 18.04.5 LTS regarding assumptions on strict overflow.

GTE/Samples/Imagics/AdaptiveSkeletonClimbing3.h

**September 11, 2020.** Updated the C#/C++ managed code projects to call the new interfaces for `MinimumVolumeBox3`.

GTE/Samples/CSharpCppManaged/CppLibrary/MinimumVolumeBox.{h,cpp}  
GTE/Samples/CSharpCppManaged/ManagedLibrary/MinimumVolumeBox.{h,cpp}  
GTE/Samples/CSharpCppManaged/CSharpApplication/Program.cs

**September 11, 2020.** The `TIQuery` code had logic:

```
if (fmid <= zero) { block0 } else if (fmid == zero) { block1 }
```

so block1 is dead code. The logic was modified to

```
if (fmid < zero) { block0 } else if (fmid == zero) { block1 }
```

**September 8, 2020.** Added `operator+=`, `operator-=`, `operator*=` and `operator/=` functions to support `Vector<N,T>` where `T` is `FPInterval<T>` or `APIInterval<T>`.

GTE/Mathematics/APIInterval.h  
GTE/Mathematics/FPInterval.h

**September 7, 2020.** Removed a couple of commented lines that were part of the debugging and testing of the code. The virtual minimizer functions needed to be in protected scope.

GTE/Mathematics/MinimumVolumeBox3.h

## 27 Updates to Version 4.8

**September 3, 2020.** The clang compiler complained about missing `istream` and `ostream` symbols. Added header includes for these.

GTE/Mathematics/BSNumber.h

The edge type was `EdgeKey<false>` (unordered edge) but needed to be `EdgeKey<true>` (ordered edge) because the polygon needs to have ordered vertices.

GTE/Mathematics/BSPPolygon2.h

In revising the code from GTE3 to GTE4, the `LogAssert(binfo...)` calls in `ProcessInterior` should have been removed. Moreover, the `-2` flag was inadvertently changed to `2`, which is a valid index for the geometry. These calls have been removed.

GTE/Mathematics/ConstrainedDelaunay2.h

The function `GetBoundaryPolygons` had a call `edgePairs.erase(vStart)` that removed all edge pairs involving `vStart`, which is incorrect behavior. A block of code was added to remove only the edge from `vStart` to `vNext`.

GTE/Mathematics/ETManifoldMesh.h

**September 1, 2020.** The convex hull classes `ConvexHull2` and `ConvexHull3` performed all geometric queries using rational arithmetic when the `ComputeType` is an arbitrary precision class. I replaced the queries with ones that use floating-point interval arithmetic to determine signs of expressions, falling back to rational arithmetic only when the interval arithmetic cannot determine the exact sign. The `ComputeType` need no longer be specified. The class determines the number of bits of precision required to compute the hull. I will be making similar changes in other computational geometry code, replacing `PrimalQuery2` and `PrimalQuery3` by classes that use interval arithmetic with fallback to rational arithmetic.

GTE/Mathematics/ConvexHull2.h

GTE/Mathematics/ConvexHull3.h

GTE/Mathematics/SeparatePoints2.h

GTE/Mathematics/SeparatePoints3.h

GTE/Mathematics/MinimumAreaBox2.h

GTE/Mathematics/MinimumVolumeBox3.h

GTE/Samples/Geometrics/ConvexHull2D/ConvexHull2DWindow2.{h,cpp}

GTE/Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow3.cpp

GTE/Samples/Geometrics/ExtremalQuery/ExtremalQueryWindow3.cpp

**August 22, 2020.** Fixed a bug in the `operator*` member function of `BSPrecision`. The word counting for `BSRational` just copied the results from that of `BSNumber`. Instead, the computations for `BSRational` use the same algorithm as that of `BSNumber`, but copying does not do that.

GTE/Mathematics/BSPrecision.h

**August 14, 2020.** Microsoft Visual Studio 2019 now incorporates a new C++ Standard Library, *Apache-2.0 WITH LLVM-exception*; previous versions used the library provided by Dinkumware. The comparison operators of `FeatureKey` used the `std::array` comparisons. Profiling code that includes `ETManifoldMesh`, which uses `EdgeKey` and `TriangleKey` in `std::map` objects showed that these operators are much slower in Debug builds than the Dinkumware version. I replaced the comparisons with simple ones to remove the slowdown.

GTE/Mathematics/FeatureKey.h

Sadly, running applications that use my rational arithmetic library with classes `BSNumber` and `BSRational` also have significant slowdowns in Debug builds. I am considering rolling reduced versions of `std::array` and `std::vector` that are included only in Debug builds.

**August 14, 2020.** Restored the `Timer` class, which is a simple and convenient high-resolution timer for applications.

GTE/Mathematics/Timer.h

## 28 Updates to Version 4.7

**August 11, 2020.** Removed the tools projects from the build-all solutions. These can be built separately when needed.

GTE/BuildAll.\*.sln  
GTE/BuildAllDX11.\*.sln  
GTE/BuildAllGL45.\*.sln

Added an implementation of the Remez algorithm for minimax polynomial approximations to functions. Added robust and fast approximations to rotation matrices; see `RotationEstimate.h`. A tool was added that generates the minimax polynomial coefficients for the rotation matrix approximations.

GTE/Mathematics.{v14,v15,v16}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/RemezAlgorithm.h  
GTE/Mathematics/RotationEstimate.h  
GTE/Tools/RotationApproximation/\*

**July 21, 2020.** The `SetSign` function needed to update the `mValue` (debugging support).

GTE/Mathematics/BSRational.h

**July 20, 2020.** The classes `Matrix2x2` and `Matrix3x3` are not used by the header files, so the corresponding include statements were replaced to get access to `Vector2` and `Vector3`.

```
GTE/Mathematics/ApprHeightLine2.h
GTE/Mathematics/ApprHeightPlane3.h
```

## 29 Updates to Version 4.6

**June 6, 2020.** Refactored `WICFileIO`, adding a new class `WICFileIONative` that allows load/save operations without having to use any GTE class. Class `WICFileIO` is now an example of how to load/save `Texture2` objects using only the services from `WICFileIONative`. I did not provide a Linux version of `WICFileIONative` but will do so at a later date.

```
GTE/GTApplications*.{v14,v16,v16}.vcproj*
GTE/Applications/WICFileIO.h
GTE/Applications/MSW/WICFileIO.{h,cpp}
GTE/Applications/MSW/WICFileIONative.{h,cpp}
```

**June 2, 2020.** Added a templated `Set` function, similar to the already present `Get` functions, for convenience of the user not to have to constantly add `reinterpret_cast` of pointers passed to `SetData`.

```
GTE/Graphics/Resource.h
```

**May 30, 2020.** The code did not compile when using `Real` set to `BSRational<UIntegerAP32>` because of the presence of some integer quantities in the arithmetic equations for the coefficients of the  $h$ -polynomial. I added typecasts of those to `Real`.

```
GTE/Mathematics/DistLine3Circle3.h
```

**May 28, 2020.** Added a test in `CopyGpuToGpu` to determine whether the entire resource is to be copied or only a subresource. The old code always called `CopySubresource`. The new code will call `CopyResource` when appropriate.

```
GTE/Graphics/DX11/DX11Buffer.cpp
```

**May 3, 2020.** The code blocks with the point-triangle distance queries were not copying the barycentric coordinates from the point-triangle query result to the segment-triangle query result. The last block where the segment endpoint for the negative extent is closest to the triangle had set the segment-triangle query result member `result.segmentParameter` to the positive extent, but it should have been the negative extent.

```
GTE/Mathematics/DistSegment3Triangle3.h
```

**April 23, 2020.** Added another `Rotate` function to transform 3-tuple vectors by a quaternion. The old and the new functions now also have conditional compilation based on whether or not `GTE_USE_MAT_VEC` is defined. The default for all projects is that this preprocessor symbol is defined.

GTE/Mathematics/Quaternion.h

**April 16, 2020.** Fixed a bug in the `Convert` function that converts one `BSNumber` to another one with a specified precision. The bug arose when the output number did not satisfy the invariant that the nonzero `UInteger` part is a positive odd number. A shift-right operation needed to be applied. The unit tests were updated with a case related to this. A new function `IsValid` has been added to `BSNumber` that, when exposed via a conditional define, verifies any constructed `BSNumber` satisfies the invariant.

GTE/Mathematics/BSNumber.h

## 30 Updates to Version 4.5

**April 13, 2020.** Rewrote the class `UniqueVerticesTriangles`. The class allows you to convert triangle soup to indexed triangles, removing duplicate vertices from the soup. It was later extended to remove duplicate vertices from indexed triangles. The revision adds the ability to remove unused vertices as well as duplicate vertices, which is desirable in applications wanting a compact representation of meshes.

GTE/Mathematics/UniqueVerticesTriangles.h

GTE/Mathematics/IntrConvexMesh3Plane3.h

GTE/Mathematics/SurfaceExtractorMC.h

Factored out the enumeration of `IDXGIOutput` objects for an adapter to a public static function `DXGIOutput::Enumerate`. This avoids repeated enumeration each time a `DXGIAdapter` constructor is called. The GTEngine code never uses these objects, but if your application needs them, you can access the adapter by `DX11Engine::GetAdapter` and then call the static function `DXGIOutput::Enumerate`.

GTE/Graphics/DX11/DXGIAdapter.cpp

GTE/Graphics/DX11/DXGIOutput.{h,cpp}

Added a new template function to `DX11.h` named `SafeAddRef`. Replaced the COM `AddRef` and `Release` calls by those to `DX11::SafeAddRef` and `DX11::SafeRelease`, even if it is known the pointers are not null. This supports debugging reference counting by allowing additional code to be added in one place (the `DX11` class) to log the counts.

GTE/Graphics/DX11/DX11.h

GTE/Graphics/DX11/DXGIAdapter.cpp

GTE/Graphics/DX11/DXGIOutput.cpp

GTE/Graphics/DX11/DX11Engine.cpp

GTE/Graphics/DX11/DX11GeometryShader.cpp

GTE/Graphics/DX11/DX11GraphicsObject.cpp

GTE/Graphics/DX11/DX11Texture1.cpp

GTE/Graphics/DX11/DX11Texture1Array.cpp

GTE/Graphics/DX11/DX11Texture2.cpp

GTE/Graphics/DX11/DX11Texture2Array.cpp

GTE/Graphics/DX11/DX11Texture3.cpp



GTE/Graphics/DX11/DX11TextureCube.cpp  
GTE/Graphics/DX11/DX11TextureCubeArray.cpp  
GTE/Graphics/DX11/DX11TextureRT.cpp  
GTE/Graphics/DX11/DX11VertexShader.cpp  
GTE/Graphics/DX11/HLSLShaderFactory.cpp

**April 12, 2020.** Fixed a COM reference counting problem with the DXGI adapters and outputs.

GTE/Graphics/DX11/DXGIAdapter.cpp  
GTE/Graphics/DX11/DXGIOutput.cpp  
GTE/Graphics/DX11/DX11Engine.{h,cpp}

Added a template `GetNumReferences` for reading the reference count from a COM object.

GTE/Graphics/DX11/DX11.h

Revised the logic for creation of the `DX11Engine` object. If the application sets `parameters.deviceCreationFlags` to `D3D11_CREATE_DEVICE_DEBUG`, the DX11 debug layer will crash when the adapter is specified as a non-null pointer (obtained via `DXGIAdapter::Enumerate`). The debug layer will work only when a null adapter pointer is passed to `D3D11CreateDevice` in addition to the flags parameter set to `D3D11_CREATE_DEVICE_DEBUG`. If you want the debug layer, you cannot simultaneously select the GPU adapter.

GTE/Applications/MSW/WindowSystem.cpp

**April 8, 2020.** Added new files to support exact-arithmetic find-intersection queries for planes and convex polyhedra.

GTE/GTMathematics.{v14,v15,v15}.{sln,vcxproj,vcxproj.filters}  
GTE/Mathematics/ConvexMesh3.h  
GTE/Mathematics/IntrConvexMesh3Plane3.h  
GTE/Samples/Intersection/IntersectPlaneConvexPolyhedron/IntersectPlaneConvexPolyhedron\*.\*

Added constructors to handle triangles stored as `std::vector` of `std::array<int, 3>`. The original constructors take `std::vector` of `int`, where the precondition is that the number of indices is a multiple of 3.

GTE/Mathematics/UniqueVerticesTriangles.h

**April 4, 2020.** Added `noexcept` to the move constructors and the move operators.

GTE/Mathematics/UIntegerAP32.h  
GTE/Mathematics/UIntegerFP32.h  
GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSRational.h

Removed unnecessary `gte` namespace scoper.

GTE/Mathematics/APIInterval.h

**March 25, 2020.** Modified the [Font](#) constructor to be protected because this class is supposed to be an abstract base class.

GTE/Graphics/Font.h

**March 24, 2020.** Added a function [GetMostPowerful](#) that enumerates the available GPU adapters and selects a discrete GPU if one exists or Intel Integrated Graphics if it exists. With current hardware, in the unlikely event that Intel Integrated Graphics does not exist, Microsoft WARP is selected.

GTE/Graphics/DX11/DXGIAdapter.{h,cpp}  
GTE/Applications/MSW/WindowSystem.cpp

Added a function to copy the back buffer to a texture. For now this is available only for the DirectX 11 engine. I will add support later for the OpenGL 4.5 engine.

GTE/Graphics/DX11/DX11Engine.{h,cpp}

**March 15, 2020.** Modified the creation of the [DX11Engine](#) object for the application library. The old code passed a null adapter to allow the DXGI system to select the GPU. If an enumeration of adapters were to be performed first, DXGI selects the first adapter in the enumeration. On a Microsoft Surface Book with Intel Integrated Graphics and a discrete NVIDIA graphics chip, the Intel graphics shows up first. The new code will select a discrete adapter if available. If such an adapter is not on the system, it will then select Intel graphics. If this does not exist (and the computer is a dinosaur), Microsoft WARP is chosen.

GTE/Applications/MSW/WindowSystem.cpp

**March 13, 2020.** Added new function [GetBoundaryPolygons](#) that computes the connected components of boundary edges for the mesh. The comments for that function indicate how branch points of the vertex adjacency graph of the boundary edges are handled.

GTE/Mathematics/ETManifoldMesh.h

**March 9, 2020.** Added new functions [CreateCompactGraph](#), [GetComponentsConsistentChirality](#) and [MakeConsistentChirality](#) that support updating the mesh so that each connected component has triangles of the same winding order.

GTE/Mathematics/ETManifoldMesh.h

**March 8, 2020.** Added [FeatureKey](#), [EdgeKey](#), [TriangleKey](#) and [TetrahedronKey](#) custom visualizers.

GTE/gtengine.vis

**February 25, 2020.** Apparently, the creation of a rectangle mesh using the [Mesh](#) and [RectangleMesh](#) classes was a work in progress that was accidentally checked in. The construction of the mesh was incorrect. Restored the old code.

GTE/Graphics/MeshFactory.cpp

**February 21, 2020.** Added a `LogWarning` call in the last block of function `Sub`. This case cannot occur by design, but it in fact did occur during experiments for rounding algorithms of arbitrary-precision numbers (while writing the RAEFGC book). I had failed to write down the example of failure and did not analyze the call stack to see how this could have happened. If this block is reached, please report it; the `BSNumber` inputs to `operator+` or `operator-` need to be reported as part of the bug report. In the event this case does occur, the code returns the correct answer of zero.

GTE/Mathematics/UIntegerALU32.h

**February 17, 2020.** Fixed the last comment in `operator<` to “One or both numbers are zero.”

GTE/Mathematics/UIntegerALU32.h

**February 12, 2020.** Unit tests of `IEEEBinary16` in GTL exposed a couple of problems. The conversion of a 32-bit normal floating-point number to a 16-bit subnormal floating-point number was incorrect. The `std::asinh(IEEEBinary16)` wrapper function called `asin` instead of `asinh`.

GTE/Mathematics/IEEEBinary16.h

Modified code to match that of GTL. The `Classification` enumeration is now `enum class Classification` to conform to C++ core suggestions by Visual Studio. Added some clarifying comments. Implemented the TODO blocks regarding NaNs.

GTE/Mathematics/IEEEBinary.h

**February 5, 2020.** Added bisection algorithms that use floating-point or arbitrary-precision arithmetic, the latter with a user-specified precision.

GTE/GTMathematics.{v14,v15,v16}.{vcxproj,vcxproj.filters}  
GTE/Mathematics/RootsBisection1.h  
GTE/Mathematics/RootsBisection2.h

**February 1, 2020.** The wrong constructor was called when `USE_COVARIANCE_W_DIRECTION` was enabled. Modified the code to use the correct constructor.

GTE/Samples/Mathematics/FitCylinder/FitCylinderWindow3.cpp

Added debug blocks of code to places where the `BSNumber` is modified and the new debug member `mValue` needs to be updated.

GTE/Mathematics/BSNumber.h

The conversion from `BSRational` to `BSRational` of a specified precision had a bug that the unit tests did not catch. The unit tests all involved rational numbers that had repeating binary patterns. For a number that has a finite bit pattern, the code needs to detect this and properly format the bit pattern for output.

GTE/Mathematics/BSRational.h

**January 13, 2020.** Fixed comments in the file (removed the Gte prefix from the file names).

GTE/Mathematics/GaussNewtonMinimizer.h  
GTE/Mathematics/LevenbergMarquardtMinimizer.h

## 31 Updates to Version 4.4

**January 12, 2020.** The main reason for the update is to support Intel C++ compilers with version 17, 18 and 19.

**January 11, 2020.** Added the ported tools [GenerateApproximations](#), [GenerateOpenGLWrapper](#) and [PrecisionCalculator](#) to the build-all solutions.

GTE/BuildAll.{v14,v15,v16}.sln  
GTE/BuildAllDX11.{v14,v15,v16}.sln  
GTE/BuildAllGL45.{v14,v15,v16}.sln

Ported the [GenerateOpenGLWrapper](#) tool from GTEngine 3 to GTEngine 4. The GTEngine 3 version has some manually modified lines of code in [GL45.cpp](#). The tool was updated to generate those lines automatically.

GTE/Tools/GenerateOpenGLWrapper/GenerateOpenGLWrapper.{v14,v15,v16}.{vcxproj,vcxproj.filters}  
GTE/Tools/GenerateOpenGLWrapper/GenerateOpenGLWrapper.cpp  
GTE/Tools/GenerateOpenGLWrapper/GL45.h  
GTE/Tools/GenerateOpenGLWrapper/Initialize.txt  
GTE/Tools/GenerateOpenGLWrapper/Version.txt  
GTE/Graphics/GL45/GL45.{h,cpp}

Ported the [GenerateApproximations](#) tool from GTEngine 3 to GTEngine 4.

GTE/Tools/GenerateApproximations/GenerateApproximations.{v14,v15,v16}.{vcxproj,sln}  
GTE/Tools/GenerateApproximations/FitASin.h  
GTE/Tools/GenerateApproximations/FitATan.h  
GTE/Tools/GenerateApproximations/FitCos.h  
GTE/Tools/GenerateApproximations/FitExp2.h  
GTE/Tools/GenerateApproximations/FitInvSqrt.h  
GTE/Tools/GenerateApproximations/FitLog2.h  
GTE/Tools/GenerateApproximations/FitReciprocal.h  
GTE/Tools/GenerateApproximations/FitSin.h  
GTE/Tools/GenerateApproximations/FitSqrt.h  
GTE/Tools/GenerateApproximations/FitTan.h  
GTE/Tools/GenerateApproximations/GenerateApproximations.cpp

Ported the [PrecisionCalculator](#) tool from GTEngine 3 to GTEngine 4.

GTE/Tools/PrecisionCalculator/PrecisionCalculator.{v14,v15,v16}.{vcxproj,vcxproj.filters,sln}  
GTE/Tools/GenerateOpenGLWrapper/PrecisionCalculator.cpp

At some point in time the inputs to some member functions were [int](#) but were later changed to [uint32\\_t](#). This makes inequality comparisons to zero irrelevant.

GTE/Graphics/IndexBuffer.cpp  
GTE/Graphics/Particles.cpp

The Intel Compiler 17 complained that Codeint `wmain(int, wchar_t*[])` is an incorrect signature, which it is not. The tool does not use command-line parameters, so the signature was modified to `int wmain()`.

GTE/Tools/BitmapFontCreator/BitmapFontCreator.cpp

The Intel Compiler 17 generated errors for `CopyGpuToGpu(parameters)`, claiming these hide the virtual function `CopyGpuToGpu()`. The Intel Compiler 19 did not have this problem (nor does Microsoft Visual Studio or g++). These functions are not implemented yet, so I renamed them to `CopyLevelGpuToGpu(parameters)` for now.

GTE/Graphics/GL45/GL45Texture.h  
GTE/Graphics/GL45/GL45TextureArray.h

The Intel Compiler 17 generated errors for `OnUpdate(parameters)`, claiming these hide the virtual function `OnUpdate()`. The Intel Compiler 19 did not have this problem (nor does Microsoft Visual Studio or g++). The update function with parameters is protected, so I renamed them to `OnUpdateSingle(parameters)`.

GTE/Mathematics/PdeFilter2.h  
GTE/Mathematics/CurvatureFlow2.h  
GTE/Mathematics/GaussianBlur2.h  
GTE/Mathematics/GradientAnisotropic2.h  
GTE/Mathematics/PdeFilter3.h  
GTE/Mathematics/CurvatureFlow3.h  
GTE/Mathematics/GaussianBlur3.h  
GTE/Mathematics/GradientAnisotropic3.h

The `Plane3` constructor calls involved a triple of points, which means the constructor with the `std::array` input is used. The code was written as `Plane3<Real>{p0,p1,p1}`, but the Intel Compiler 17 complained. The code was modified to `Plane3<Real>({p0,p1,p2})`. It is not clear why all the other compilers allowed the original code, which looks like an initializer-list constructor call.

GTE/Mathematics/SeparatingPoints3.h

The Intel Compiler 17 warned about hiding the base-class members for the `Parameters` constructor, where the inputs used the same names as the base class. The input names were modified.

GTE/Samples/Imagics/GpuGaussianBlur2Window2.h  
GTE/Samples/Imagics/GpuGaussianBlur3Window2.h

**January 8, 2020.** The Intel compilers complained about the signature to `main` in all the samples. I had `int main(int, char const*[])` but the standard format is `int main(int, char*[])` or `int main(int, char**)`. I modified all such `main` calls to have no parameters, which is a long list of files not mentioned here. A couple of the samples use command-line parameters, so the `main` functions for those were modified to use `char*`.

The initializer-list constructors for classes were not handled properly by MSVS 2013. For example, to create a `Vector2<Real>` object using an initializer list, the syntax is `Vector2<Real>{x, y}`. However, MSVS 2013 did not allow this, requiring instead the syntax `Vector2<Real>({x, y})`. The Intel compiler had problems with some occurrences of the latter. They also has problems with some assignment statements that led to construction via initializer lists. Now that MSVS 2013 is no longer supported, syntax without parentheses is now used. While modifying these, some calls to `BoundingSphere::SetCenter` were found that passed an initializer list of 4 elements, because the input of that function used to be `Vector4`. Now the input is `Vector3`, which has an initializer-list constructor that allows more than 3 elements (the ones after the first three are ignored). The `SetCenter` calls were modified to have initializer lists of 3 elements.

```
GTE/Mathematics/AdaptiveSkeletonClimbing3.h
GTE/Graphics/CullingPlane.h
GTE/Mathematics/Ellipse3.h
GTE/Mathematics/QFNumber.h
GTE/Mathematics/SeparatePoints3.h
GTE/Mathematics/Transform.h
GTE/Mathematics/TriangulateCDT.h
GTE/Mathematics/TriangulateEC.h
GTE/Mathematics/Vector2.h
GTE/Mathematics/Vector3.h
GTE/Graphics/SamplerState.cpp
GTE/Graphics/BlendState.cpp
GTE/Graphics/MeshFactory.cpp
GTE/Graphics/BspNode.cpp
GTE/Graphics/PickRecord.cpp
GTE/Graphics/Node.cpp
GTE/Graphics/Material.cpp
GTE/Graphics/Lighting.cpp
GTE/Graphics/LightCameraGeometry.cpp
GTE/Samples/Distance/DistanceAlignedBoxes/DistanceAlignedBoxesWindow3.cpp
GTE/Samples/Distance/DistanceAlignedBoxOrientedBox/DistanceAlignedBoxOrientedBoxWindow3.cpp
GTE/Samples/Distance/DistanceOrientedBoxes/DistanceOrientedBoxesWindow3.cpp
GTE/Samples/Distance/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow3.cpp
GTE/Samples/Distance/DistanceRectangleBox/DistanceRectangleBoxWindow3.cpp
GTE/Samples/Distance/DistanceTriangleBox/DistanceTriangleBoxWindow3.cpp
GTE/Samples/Geometries/Delaunay3D/Delaunay3DWindow3.cpp
GTE/Samples/Intersection/IntersectBoxCone/IntersectBoxConeWindow3.cpp
GTE/Samples/Intersection/IntersectBoxCylinder/IntersectBoxCylinderWindow3.cpp
GTE/Samples/Intersection/IntersectBoxSphere/IntersectBoxSphereWindow3.cpp
GTE/Samples/Intersection/IntersectSphereCone/IntersectSphereConeWindow3.cpp
GTE/Samples/Physics/HelixTubeSurface/HelixTubeSurfaceWindow3.cpp
GTE/Samples/SceneGraphs/BlendedAnimations/BlendedAnimationsWindow3.cpp
GTE/Samples/SceneGraphs/Picking/PickingWindow3.cpp
```

The inputs to some constructor calls used names `number` and `encoding`, which are the union-member names of the base class. The Intel compilers warned about this, so the constructor input names were modified.

```
GTE/Mathematics/IEEEBinary16.h
```

The `SetMember` and `GetMember` functions are supposed to return Boolean values, but the last blocks of the implementations were missing the return statements.

```
GTE/Mathematics/TextureBuffer.h
```

Intel Compiler 17 does not support the template alias helper `remove_cv_t`, so I replaced it with something simpler in my arbitrary-precision code.

```
GTE/Mathematics/Math.h
```

## 32 Updates to Version 4.3

January 4, 2020. Ported the managed code projects for GTEngine 4.x.

```
GTE/Samples/CSharpManaged_MSVS2019/CppLibrary/CppLibrary.v16.vcxproj
GTE/Samples/CSharpManaged_MSVS2019/CppLibrary/CppLibrary.v16.vcxproj.filters
GTE/Samples/CSharpManaged_MSVS2019/CppLibrary/CppLibrary.h
GTE/Samples/CSharpManaged_MSVS2019/CppLibrary/MinimumVolumeBox.h
GTE/Samples/CSharpManaged_MSVS2019/CppLibrary/MinimumVolumeBox.cpp
GTE/Samples/CSharpManaged_MSVS2019/CSharpApplication/CSharpApplication.v16.sln
GTE/Samples/CSharpManaged_MSVS2019/CSharpApplication/CSharpApplication.v16.csproj
GTE/Samples/CSharpManaged_MSVS2019/CSharpApplication/Program.cs
GTE/Samples/CSharpManaged_MSVS2019/CSharpApplication/App.config
GTE/Samples/CSharpManaged_MSVS2019/CSharpApplication/Properties/AssemblyInfo.cs
GTE/Samples/CSharpManaged_MSVS2019/ManagedLibrary/ManagedLibrary.v16.sln
GTE/Samples/CSharpManaged_MSVS2019/ManagedLibrary/ManagedLibrary.v16.vcxproj
GTE/Samples/CSharpManaged_MSVS2019/ManagedLibrary/ManagedLibrary.v16.vcxproj.filters
GTE/Samples/CSharpManaged_MSVS2019/ManagedLibrary/ManagedObject.h
GTE/Samples/CSharpManaged_MSVS2019/ManagedLibrary/MinimumVolumeBox.h
GTE/Samples/CSharpManaged_MSVS2019/ManagedLibrary/MinimumVolumeBox.cpp
GTE/Samples/CSharpManaged_MSVS2019/ManagedLibrary/AssemblyInfo.cpp
```

```
GTE/Samples/CSharpManaged_MSVS2017/CppLibrary/CppLibrary.v15.vcxproj
GTE/Samples/CSharpManaged_MSVS2017/CppLibrary/CppLibrary.v15.vcxproj.filters
GTE/Samples/CSharpManaged_MSVS2017/CppLibrary/CppLibrary.h
GTE/Samples/CSharpManaged_MSVS2017/CppLibrary/MinimumVolumeBox.h
GTE/Samples/CSharpManaged_MSVS2017/CppLibrary/MinimumVolumeBox.cpp
GTE/Samples/CSharpManaged_MSVS2017/CSharpApplication/CSharpApplication.v15.sln
GTE/Samples/CSharpManaged_MSVS2017/CSharpApplication/CSharpApplication.v15.csproj
GTE/Samples/CSharpManaged_MSVS2017/CSharpApplication/Program.cs
GTE/Samples/CSharpManaged_MSVS2017/CSharpApplication/App.config
GTE/Samples/CSharpManaged_MSVS2017/CSharpApplication/Properties/AssemblyInfo.cs
GTE/Samples/CSharpManaged_MSVS2017/ManagedLibrary/ManagedLibrary.v15.sln
GTE/Samples/CSharpManaged_MSVS2017/ManagedLibrary/ManagedLibrary.v15.vcxproj
GTE/Samples/CSharpManaged_MSVS2017/ManagedLibrary/ManagedLibrary.v15.vcxproj.filters
GTE/Samples/CSharpManaged_MSVS2017/ManagedLibrary/ManagedObject.h
GTE/Samples/CSharpManaged_MSVS2017/ManagedLibrary/MinimumVolumeBox.h
GTE/Samples/CSharpManaged_MSVS2017/ManagedLibrary/MinimumVolumeBox.cpp
GTE/Samples/CSharpManaged_MSVS2017/ManagedLibrary/AssemblyInfo.cpp
```

```
GTE/Samples/CSharpManaged_MSVS2015/CppLibrary/CppLibrary.v14.vcxproj
GTE/Samples/CSharpManaged_MSVS2015/CppLibrary/CppLibrary.v14.vcxproj.filters
GTE/Samples/CSharpManaged_MSVS2015/CppLibrary/CppLibrary.h
GTE/Samples/CSharpManaged_MSVS2015/CppLibrary/MinimumVolumeBox.h
GTE/Samples/CSharpManaged_MSVS2015/CppLibrary/MinimumVolumeBox.cpp
GTE/Samples/CSharpManaged_MSVS2015/CSharpApplication/CSharpApplication.v14.sln
GTE/Samples/CSharpManaged_MSVS2015/CSharpApplication/CSharpApplication.v14.csproj
GTE/Samples/CSharpManaged_MSVS2015/CSharpApplication/Program.cs
GTE/Samples/CSharpManaged_MSVS2015/CSharpApplication/App.config
GTE/Samples/CSharpManaged_MSVS2015/CSharpApplication/Properties/AssemblyInfo.cs
GTE/Samples/CSharpManaged_MSVS2015/ManagedLibrary/ManagedLibrary.v14.sln
GTE/Samples/CSharpManaged_MSVS2015/ManagedLibrary/ManagedLibrary.v14.vcxproj
GTE/Samples/CSharpManaged_MSVS2015/ManagedLibrary/ManagedLibrary.v14.vcxproj.filters
GTE/Samples/CSharpManaged_MSVS2015/ManagedLibrary/ManagedObject.h
GTE/Samples/CSharpManaged_MSVS2015/ManagedLibrary/MinimumVolumeBox.h
GTE/Samples/CSharpManaged_MSVS2015/ManagedLibrary/MinimumVolumeBox.cpp
GTE/Samples/CSharpManaged_MSVS2015/ManagedLibrary/AssemblyInfo.cpp
```

## 33 Updates to Version 4.2

December 28, 2019. Replaced the `std::memset` calls by `std::fill` calls.

[GTE/Mathematics/NURBSSurface.h](#)

GTE/Mathematics/NURBSVolume.h

**December 27, 2019.** Added a least-squares algorithm for fitting two parallel lines to points in the plane, where the points presumably lie on the lines. A document *Least Squares Fitting of Parallel Lines to Points in 2D* has been uploaded to the website to describe the algorithm.

GTE/Mathematics/ApprParallelLines2.h

The multiplication and division by the natural logarithm of 2 were swapped in the exponent and logarithm estimation files.

GTE/Mathematics/ExpEstimate.h  
GTE/Mathematics/LogEstimate.h

## 34 Updates to Version 4.1

**December 5, 2019.** The minor version was modified to 2 (for GTE 4.2). Fixed the comment in the post-build soft-link setting.

GTE/makeapplications.gte  
GTE/makegraphics.gte  
GTE/makemathematicsgpu.gte

Removed a call `rnd(mte)` that was not used.

GTE/Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow2.cpp

Added an include of `<algorithm>` because the class accesses `std::max` (compiler error occurs now with MSVS 2019 16.4.0).

GTE/Mathematics/RootsPolynomial.h

Fixed a bug in the `Evaluate` function.

GTE/Mathematics/ApprPolynomial4.h

The `GTGraphicsGL45` library had a dependency on the `GTApplicationsGL45` library via the class `GLXEngine` when used for compute shaders; the constructor has to create an X-window that is not exposed to the caller. I removed that dependency.

GTE/Graphics/GL45/GLX/GLXEngine.cpp

Removed an include of `Applications/Environment.h` that caused the `Graphics` library to have a dependency on the `GTApplications*` libraries. The `AreaLightEffect` does not use an `Environment` object.



GTE/Graphics/AreaLightEffect.h

**December 4, 2019.** Fixed out-of-range indices in the GLSL reflection code. Modified the reflection functions to use enumerations for indexing rather than raw pointer incrementing.

GTE/Graphics/GL45/GLSLReflection.cpp

**November 23, 2019.** Replaced the `std::fabs` call with a sign test to allow using Gaussian elimination with `QFNumber` without yet having to implement `std::fabs` for `QFNumber`

GTE/Mathematics/GaussianElimination.h

**November 22, 2019.** Added functions `GetTokens`, `GetTextTokens` and `GetAdvancedTextTokens` as convenience functions for extracting tokens from a string.

GTE/Mathematics/StringUtility.h

**November 4, 2019.** The design of `QFNumber` requires explicitly passing the  $d$ -variable to constructors. This is problematic in implementations using generic template code for a `Real` type, because  $d$  is not available internally. The class `LCPSolver` uses generic 0 and 1 in copies and assignments. Constructors were added to allow passing the values of 0 and 1 for the specific  $d$ -value of the quadratic field numbers involved in the computations.

GTE/Mathematics/LCPSolver.h

**November 3, 2019.** Reformatted some comments and added more specific ideas about representations for infinities and NaNs of `BSNumber`.

GTE/Mathematics/BSNumber.h GTE/Mathematics/BSRational.h

**October 23, 2019.** Modified the `Result` nested class to provide more information about the returned result. This includes an `LCPSolverShared<Real>::Result` member rather than the previous `bool queryIsSuccessful` member.

GTE/Mathematics/IntrAlignedBox3Cylinder3.h

**October 17, 2019.** Fixed some comments. Removed the `Gte` file prefix in the `ToTetrahedron` calls. Fixed the counts for `N` for `BSRational`; they are much smaller than previously reported (incorrect counting in `BSPrecision`).

GTE/Mathematics/PrimalQuery3.h

Added `std::enable_if` to use division operations only if the arithmetic system allows it.

GTE/Mathematics/APIInterval.h

**October 9, 2019.** Renamed class `Interval` and file `Interval.h` to `FPIInterval` and `FPIInterval.h` to emphasize these apply to native floating-point types `float` and `double`. Added class `APIInterval` and file `APIInterval.h` for interval arithmetic using arbitrary-precision types. These types do not need the rounding modes set as the floating-point types do.

GTE/Mathematics/Interval.h  
GTE/Mathematics/FPIInterval.h  
GTE/Mathematics/APIInterval.h  
GTE/GTMathematics.\*.vcxproj  
GTE/GTMathematics.\*.vcxproj.filters

Added support for conversion from text-string numbers to `BSNumber` and `BSRational` objects. This supports inputs of precision larger than native integer and floating-point types.

GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSRational.h

**September 27, 2019.** Changed the member names from `GetMin` and `GetMax` to the more descriptive `GetMinOfSqrt` and `GetMaxOfSqrt`. Removed the minimum-closest parameter of the estimators. Added member functions to return a single estimate rather than a bounding interval.

GTE/Mathematics/APConversion.h

**September 26, 2019.** Fixed a bug in `UIntegerALU32::Sub`. The last statement that sets the number of bits after locating the leading 1-bit to allow reducing the size of the bits array fails when `self` has no 1-bits (the `block` value is -1, which causes an out-of-range lookup). Added a test for this case and set the number of bits explicitly to zero. Modified the `SetNumBits` functions in `UIntegerAP32` and `UIntegerFP32` to test whether the input is nonnegative and adjust accordingly.

GTE/Mathematics/UIntegerALU32.h  
GTE/Mathematics/UIntegerAP32.h  
GTE/Mathematics/UIntegerFP32.h

Added helper conversion functions that are used in the `APPrecision` class to avoid exposing `BSNumber` objects. One conversion computes a `BSRational` to a specified precision from another `BSRational`. The other conversion computes a `float` or `double` from a `BSRational`; the precision is that of the output floating-point type.

GTE/Mathematics/BSRational.h

Modified `EstimateSqrt` and `EstimateApB` to generate iterates at twice the precision specified by the user. This avoids the quadratic growth in number of bits that causes significant performance loss during Newton's method. Modified `EstimateAmB` to use a better algorithm for estimating the linear combination of two square roots by a `BSRational`.

GTE/Mathematics/APConversion.h

**September 25, 2019.** Updated the code to handle both `BSNumber` and `BSRational` simultaneously. The formulas were incorrect for bit counting, but fortunately they overcounted. The implementation was fixed and the construction of the formulas is described in the Geometric Computing book.

`GTE/Mathematics/BSPrecision.h`

Changed `typedef` statements to `using` statements.

`GTE/Mathematics/IEEEBinary.h`

Cleaned up white space and modified some comments. Removed the bodies of four of the comparisons, replacing them by the logical equivalences to equality and less-than comparison.

`GTE/Mathematics/QFNumber.h`

**September 11, 2019.** Removed the friend declarations for `UnitTestBSNumber` because now the unit tests have access to the private members via public member accessors.

`GTE/Mathematics/UIntegerAP32.h`

`GTE/Mathematics/UIntegerFP32.h`

**September 10, 2019.** Added an implementation of interval arithmetic.

`GTE/GTMathematics.*.vcxproj`

`GTE/GTMathematics.*.vcxproj.filters`

`GTE/Mathematics/Interval.h`

**September 5, 2019.** Renamed the template parameter `UIntegerType` to `UInteger` for consistency of naming. The geometry book uses the latter name for the type.

`GTE/Mathematics/BSNumber.h`

`GTE/Mathematics/BSRational.h`

`GTE/Mathematics/UIntegerAP32.h`

**September 4, 2019.** Replaced the `Convert` function with a new version. The old version was specifically for `float` and `double`. The new version allows you to specify the precision of a conversion to `BSNumber`, which can then be used for conversions to `float` and `double`.

`GTE/Mathematics/BSRational.h`

Added a `Convert` function that allows you to specify the precision of a conversion from a `BSNumber` to another `BSNumber`. Added a non-const `GetUInteger` function.

`GTE/Mathematics/BSNumber.h`

**September 3, 2019.** Added `RoundUp` function to support conversion from `BSRational` to a `BSNumber` of a specified precision.

GTE/Mathematics/UIntegerALU32.h

The `GetMaxSize` functions are now static because they do not depend on a particular object.

GTE/Mathematics/UIntegerAP32.h  
GTE/Mathematics/UIntegerFP32.h

Added two more interface functions in the comments about `UIntegerType`.

GTE/Mathematics/BSNumber.h

Fixed comment where the multiplication operator occurred instead of the power operator.

GTE/Mathematics/BSRational.h

The constructors with the `int32_t` parameter and the function `SetNumBits` are intended to be used only internally (in the class `UIntegerALU32`). However, the constructors are public and there is a chance of a mismatch if a signed integer is passed to a constructor rather than an unsigned integer. To avoid this, the constructor with the `int32_t` parameter was removed. Also, the `SetNumBits` function has an input whose type needed to be `int32_t`. Finally, added a new function `GetMaxSize` that returns the maximum 32-bit integer for `UIntegerAP32` and returns N for `UIntegerFP32`.

GTE/Mathematics/UIntegerALU32.h  
GTE/Mathematics/UIntegerAP32.h  
GTE/Mathematics/UIntegerFP32.h

Added functions to set all bits (up through maximum size) to zero.

GTE/Mathematics/UIntegerAP32.h  
GTE/Mathematics/UIntegerFP32.h

Added an include of `<cfenv>` to allow access to the floating-point environment.

GTE/Mathematics/Math.h

## 35 Updates to Version 4.0

**August 29, 2019.** I introduced a bug when `HeightInRange` was added to the `Cone` class. The comparison needed to be for  $h^2$ , not  $h$ .

GTE/Mathematics/ContCone.h

**August 26, 2019.** The classes were missing some public-internal member functions and `std::frexp` that had been added to the GTEngine 3.x classes. Moved the public-internal member functions to public section with the other accessors.

GTE/Mathematics/BSNumber.h  
GTE/Mathematics/BSRational.h

**August 16, 2019.** Added the ability to specify sorting of eigenvalues and eigenvectors in the noniterative solver `NISymmetricEigensolver3x3`. The sorting code was factored out of the iterative solver `SymmetricEigensolver3x3` so it can be shared by both classes.

GTE/Mathematics/SymmetricEigensolver3x3.h

**August 15, 2019.** The relative paths to the libraries were hard-coded in the strings for the solution files. They needed to be the pattern `_GT4_RELATIVE_PATH_`. Added post-build copies of the executables to the appropriate subfolders of `GTE/Executables`.

GTE/Tools/GenerateProject/ProjectTemplate.{v14,v15,v16}.cpp  
GTE/Tools/GenerateProject/GenerateProject.{v14,v15,v16}.vcxproj

## 36 Updates to Version 3.30

**January 9, 2020.** Added the changes to the `Result` structure that was already made for the GTEngine 4 track.

IntrAlignedBox3Cylinder3.h

## 37 Updates to Version 3.29

**December 28, 2019.** Replaced the `std::memset` calls by `std::fill` calls.

NURBSSurface.h  
NURBSVolume.h

**December 27, 2019.** Added a least-squares algorithm for fitting two parallel lines to points in the plane, where the points presumably lie on the lines. A document *Least Squares Fitting of Parallel Lines to Points in 2D* has been uploaded to the website to describe the algorithm.

ApprParallelLines2.h

The multiplication and division by the natural logarithm of 2 were swapped in the exponent and logarithm estimation files.

ExpEstimate.h  
LogEstimate.h

## 38 Updates to Version 3.28

**December 5, 2019.** The minor version was modified to 29 (for GTE 3.29). Fixed the comment in the post-build soft-link setting.

makeengine.gte  
makeengine\_werror.gte

Modified the `GLXEngine` constructor for compute shaders to access X11 directly rather than through `TheWindowSystem`. Although not relevant for GTEngine 3, it is relevant for GTE 4 where the graphics and application libraries have been separated.

GLXEngine.cpp

Removed a call `rnd(mte)` that was not used.

Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.cpp

Added an include of `<algorithm>` because the class accesses `std::max` (compiler error occurs now with MSVS 2019 16.4.0).

RootsPolynomial.h

Fixed a bug in the `Evaluate` function.

ApprPolynomial4.h

**December 4, 2019.** Fixed out-of-range indices in the GLSL reflection code. Modified the reflection functions to use enumerations for indexing rather than raw pointer incrementing.

GLSLReflection.cpp

Fixed a bug in `UIntegerALU32::Sub`. The last statement that sets the number of bits after locating the leading 1-bit to allow reducing the size of the bits array fails when `self` has no 1-bits (the `block` value is -1, which causes an out-of-range lookup). Added a test for this case and set the number of bits explicitly to zero. Modified the `SetNumBits` functions in `UIntegerAP32` and `UIntegerFP32` to test whether the input is nonnegative and adjust accordingly.

UIntegerALU32.h  
UIntegerAP32.{h,cpp}  
UIntegerFP32.h

The constructors with the `int32_t` parameter and the function `SetNumBits` are intended to be used only internally (in the class `UIntegerALU32`). However, the constructors are public and there is a chance of a

mismatch if a signed integer is passed to a constructor rather than an unsigned integer. To avoid this, the constructor with the `int32_t` parameter was removed. Also, the `SetNumBits` function has an input whose type needed to be `int32_t`. Finally, added a new function `GetMaxSize` that returns the maximum 32-bit integer for `UIntegerAP32` and returns `N` for `UIntegerFP32`.

`UIntegerALU32.h`  
`UIntegerAP32.{h,cpp}`  
`UIntegerFP32.h`

Added functions `GetMaxSize`. Added functions `SetAllBitsToZero` to set all bits (up through maximum size) to zero.

`UIntegerAP32.h`  
`UIntegerFP32.h`

## 39 Updates to Version 3.27

**August 29, 2019.** I introduced a bug when `HeightInRange` was added to the `Cone` class. The comparison needed to be for  $h^2$ , not  $h$ .

`ContCone.h`

**August 16, 2019.** Added the ability to specify sorting of eigenvalues and eigenvectors in the noniterative solver `NISymmetricEigensolver3x3`. The sorting code was factored out of the iterative solver `SymmetricEigensolver3x3` so it can be shared by both classes.

`SymmetricEigensolver3x3.h`

## 40 Updates to Version 3.26

**August 8, 2019.** A bug was introduced in the virtual `Fit` function that is used only in the RANSAC code. Also, the assignment operator used to copy the candidate model to the best-fit model did not work and required another virtual function `CopyParameters`, which had to be implemented in all the derived classes. The fixes were made and unit tests were added to verify RANSAC is working as designed.

`ApprQuery.h`  
`ApprGaussian2.h`  
`ApprGaussian3.h`  
`ApprHeightLine2.h`  
`ApprHeightPlane3.h`  
`ApprOrthogonalLine2.h`  
`ApprOrthogonalLine3.h`  
`ApprOrthogonalPlane3.h`

ApprPolynomial2.h  
ApprPolynomial3.h  
ApprPolynomial4.h  
ApprPolynomialSpecial2.h  
ApprPolynomialSpecial3.h  
ApprPolynomialSpecial4.h

## 41 Updates to Version 3.25

**August 1, 2019.** Added an include of the `cstring` header to access the definition for `std::memcpy`.

UnsymmetricEigenvalues.h

**July 31, 2019.** Replaced the C-style arrays by `std::array`-based members.

EulerAngles.h

Added two new member functions to class `Font`. Updated `BitmapFontCreator` and added new fonts to the graphics system.

GTEngine.\*.vcxproj\*  
Font.{h,cpp}  
Tools/BitmapFontCreator/BitMapFontCreator.cpp  
GTGraphicsShared.h  
FontArialW400H18.{h,cpp}  
FontArialW400H12.{h,cpp}  
FontArialW400H14.{h,cpp}  
FontArialW400H16.{h,cpp}  
FontArialW700H12.{h,cpp}  
FontArialW700H14.{h,cpp}  
FontArialW700H16.{h,cpp}  
FontArialW700H18.{h,cpp}

Replace occurrences of 0 by `nullptr` in calls to `GetAdjDet`.

IntelSSE.h

Initialized all the members of `Result` at the beginning of the query code.

IntrArc2Arc2.h  
IntrSegment2Arc.h

Exposed the epsilon and tolerance parameters. Removed the `LogAssert` about `tv` being in the correct interval, replacing the code by clamping `tv` to the interval.



Minimize{1,N}.h

At the request of a user, added a working-data structure to improve performance by avoiding multiple `std::vector` objects.

NaturalSplineCurve.h

At the request of a user, modified the class to track some more information and to have a specialized find-neighbors query when the maximum number of neighbors is 1.

NearestNeighborQuery.h

Added the ability to derive from `OverlayEffect`. Added a shader parameter to specify the z-depth to allow multiple overlays to be ordered on the screen.

OverlayEffect.{h,cpp}

Added support for multithreaded picking of triangle primitives.

Picker.{h,cpp}

Added more information when `SetOffset` or `SetNumActiveElements` triggers an assertion. The assertion is now changed to a warning.

Resource.cpp

Added the ability to create vectors with all 1-valued components.

Vector.h

Added a `Load` function that takes an `HMODULE` object to locate resources within the application.

WICFileIO.{h,cpp}

**July 30, 2019.** Redesigned `ApprQuery` to replace the Curiously Recurring Template pattern by a simple virtual function system. Eliminated the need to implement two nearly equal versions of the fitters.

ApprQuery.h  
ApprGaussian{2,3}.h  
ApprHeightLine2.h  
ApprHeightPlane3.h  
ApprOrthogonalLine{2,3}.h  
ApprOrthogonalPlane3.h  
ApprPolynomial{2,3,4}.h  
ApprPolynomialSpecial{2,3,4}.h

Added comments about the matrices automatically initialized to zero by the `Matrix` constructor. Reformatted the code.

`ApprQuadratic{2,3}.h`

Replace the C-style array of endpoints by `std::array`-based members.

`Arc2.h`

Added an adapter function `Evaluate` that takes an input of type `Real*` and reinterprets it to use the evaluation function that takes an input of type `Vector<Real,N>`.

`ParametricCurve.h`

Added a function `operator bool()` and a member `mConstructed` to notify the caller whether or not the object was created successfully. If the linear system solver fails, the object is not constructed. Added a function `Evaluate` that allows you to compute derivatives as well as the position (which was already supported by `GetPosition`).

`BSplineCurveFit.h`

Added an adapter functions to compute the bounding object containing points whose input is `std::vector`.

`ContCircle2.h`

`ContSphere3.h`

`ContOrientedBox{2,3}.h`

Added a conditional define to allow the `LogAssert` call to occur in `GetTangent`. The assertion is disabled by default.

`ConvexHull2.h`

Restored the old algorithm code that used constrained quadratic minimization. This will be used in the upcoming GTL distribution.

`DistPointTriangle3.h`

Added `std::ostringstream` code to format the `HRESULT` as a hexadecimal number for better readability.

`DX11Include.h`

Added new file for some simple string utilities, including converting between narrow and wide strings.

`StringUtility.h`

Added `const` to `GetVariable`. Set the default constructor and destructor using the new C++ mechanism.

`Environment.{h,cpp}`

**July 29, 2019.** Renamed the `operator()` functions to `FitUsingLengths` and added an epsilon parameter used to terminate the iterations. Added an implementation `FitUsingSquaredLengths` that is bounded in time and involves solving a linear system. It is much faster than `FitUsingLengths`. The new algorithm is described in the least-squares fitting PDF at the website.

`ApprCircle2.h`  
`ApprSphere3.h`

**July 10, 2019.** Implemented `std::ldexp` for `BSNumber` and `BSRational`. Added internal-public member functions to support this.

`BSNumber.h`  
`BSRational.h`

**June 22, 2019.** Reimplemented the intersection code for line/ray/segment and cone based on the cone redesign. Added extensive unit tests that cover all nonbranching blocks in the code to verify correctness. The new implementations support arbitrary precision arithmetic. The line-cone PDF document was rewritten to describe the new code.

`IntrLine3Cone3.h`  
`IntrRay3Cone3.h`  
`IntrSegment3Cone3.h`

**June 22, 2019.** Added code that allows intersection of intervals of any of the types  $[t_0, t_1]$ ,  $[t_0, +\infty)$  or  $(-\infty, t_1]$ . Boolean inputs are used to specify the type of semiinfinite intervals passed to the queries.

`IntrIntervals.h`

Revised the cone primitive so that `std::numeric_limits<Real>::max()` no longer represents infinite height. Instead, the setting of height extremes is now controlled by the constructors and new member functions `MakeInfiniteCone`, `MakeInfiniteTruncatedCone`, `MakeFiniteCone` and `MakeConeFrustum`. Internally, the maximum height is represented by  $-1$  and used by new member functions `IsFinite` and `IsInfinite` to report whether the maximum height of the cone is finite or infinite. A new member function `HeightInRange` allows you to test whether a specified height is in the height range of the cone. These changes allow for geometric operations on cones when the underlying type is arbitrary precision `BSNumber` and `BSRational` that do not have representations of infinities.

`Cone.h`

Modified the containment query to use the new `HeightInRange` and to avoid using `Length` so that arbitrary precision `BSNumber` and `BSRational` can be used for exact containment queries.

ContCone.h

Modifications based on the cone redesign.

IntrAlignedBox3Cones.h  
IntrOrientedBox3Cone3.h  
IntrSphere3Cone3.h  
Samples/Mathematics/IntersectBoxCone/IntersectBoxConeWindow.cpp  
Samples/Mathematics/IntersectSphereCone/IntersectSphereConeWindow.cpp

Fixed a comment.

IntrBSplineUniform.h

**June 13, 2019.** A C-style array was declared with 3 elements when it should have been 2.

IntrHalfspace3Segment3.h

The **B** vector was uninitialized but needed to be set to zero. This was the behavior when the code was written, but apparently the array-based vector class used to initialize its members to zero, which it currently does not do.

ApprParaboloid3.h

Removed the use of `std::numeric_limits<max>` to allow the code to be used with rational arithmetic such as **BSNumber** and **BSRational**. The code comments explain the change in semantics.

IntrIntervals.h

Added a new file that replaces **GteQuadraticField.h**. The new class **QFElement** implements the necessary arithmetic interfaces to be used as-is in the mathematics code of GTEngine. The **QuadraticField** class had wrappers to allow sharing of the *d*-value of the field. I removed the sharing, allowing each quadratic field element to have its own copy.

GTMathematics.h  
QFElement.h  
IntrSphere3Triangle3.h  
QuadraticField.h

**June 4, 2019.** Changes in the trackball mechanism broke the application because the world box and world triangle were not computed correctly for the intersection queries. I missed this during end-to-end testing. The goal of the sample is to illustrate that the intersection queries work, and the previous sample code was way too complicated for this purpose. Now I use the same paradigm as in other object-object intersection samples. The triangle does not move. The box can be translated and rotated in its local coordinate system.

Samples/Mathematics/IntersectTriangleBox/IntersectBoxTriangle.{h,cpp}

**June 2, 2019.** Fixed a bug I recently introduced. The `DrawPixel` functor was setting the pixels to 0 but needed to be `0xFF000000` to produce opaque pixels.

`Samples/Physics/SimplePendulum/SimplePendulum.cpp`

Removed the single-step mode because the time step was extremely small. Modified the time step to be the same whether debug or release configuration.

`Samples/Physics/SimplePendulumFriction/SimplePendulumFrictionWindow.{h,cpp}`

Added `LogReporter` support to be consistent with other sample applications.

`Samples/Imagics/AdaptiveSkeletonClimbing3/AdaptiveSkeletonClimbing3.cpp`

The assertions for matrix-times-vector and vector-times-matrix were incorrect. They were not caught by unit tests that exposed the assertions.

`GMatrix.h`

**May 30, 2019.** The increase in spot angle had a copy-and-paste error that led to decreasing the spot angle. The lighting constant buffer is shared by the vertex and pixel shaders for a specific light type and a specific geometry type. The key processing was modified to ensure that the relevant lighting member is incremented or decremented only once.

`Samples/Graphics/Lights/LightsWindow.cpp`

Some of the projects had a data-file folder but the contents were files from the Wild Magic 5 distribution. Modified these to contain the files that the current application uses. Other projects did not have data-file folders, so I added them. And the annoying bug in Visual Studio (multiple major versions) that causes HLSL files to be moved out of my shader-file folders showed up again. I set the HLSL files to “Does not participate in build.”

`Samples/Graphics/Terrain/Terrain*.vcxproj*`

Removed class-static data that is never used.

`Font.h`

**May 29, 2019.** Removed unused variables.

`Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp`

**May 19, 2019.** The class was missing implementations of three inline functions.

`Controller.h`

**May 18, 2019.** Added a test for the Hygon Dhyana processor.

CPUQueryInstructions.cpp

**May 17, 2019.** The implementation of `GetIndex` was missing.

TextureCubeArray.h

**May 16, 2019.** The members were declared as `float` instead of `Real`.

GradientAnisotropic2.h

Renamed function input variable from `position` to `velocity`.

MassSpringSurface.h

**May 7, 2019.** Corrected the comments.

ApprPolynomialSpecial{3,4}.h

ContEllipse2.h

ContEllipsoid3.h

**May 6, 2019.** The `Vector3` members had hard-coded `float` which needed to be `Real`.

Torus3.h

A relative path for `GteCubicRootsQR.h` was used rather than the global path.

QuarticRootsQR.h

**May 4, 2019.** Restored the default null pointer parameters to the `Inverse` functions.

Matrix2x2.h

Matrix3x3.h

**May 3, 2019.** Removed `GteWrapper.h` and `GteWrapper.cpp` from the engine. These provided `Memcpy`, a wrapper to deal with the Microsoft security versions of memory copies. Replaced `Memcpy` by `memcpy` in other files.

GTEngine.\*.vcxproj\*

GTLowLevel.h

GaussianElimination.h

GenerateMeshUV.h

LinearSystem.h

MinimizeN.h  
 SingularValueDecomposition.h  
 SymmetricEigensolver.h  
 UnsymmetricEigenvalues.h  
 DX11Buffer.cpp  
 DX11Texture.cpp  
 HLSLShader.cpp  
 HLSLShaderFactory.cpp  
 HLSLShaderVariable.cpp  
 Font.cpp  
 MarchingCubes.cpp  
 Samples/Geometries/ConvexHull3D/ConvexHull3DWindow.cpp  
 Samples/Geometries/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.cpp

Replaced `memcpy` by `std::memcpy`.

GaussianElimination.h  
 GenerateMeshUV.h  
 LinearSystem.h  
 MinimizeN.h  
 SingularValueDecomposition.h  
 SymmetricEigensolver.h  
 UnsymmetricEigenvalues.h  
 DX11Buffer.cpp  
 DX11Texture.cpp  
 HLSLShader.cpp  
 HLSLShaderFactory.cpp  
 HLSLShaderVariable.cpp  
 Font.cpp  
 CPUQueryInstructions.cpp  
 Samples/Geometries/ConvexHull3D/ConvexHull3DWindow.cpp  
 Samples/Geometries/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp  
 Samples/Geometries/SplitMeshByPlane/SplitMeshByPlaneWindow.cpp  
 Samples/Geometries/VertexCollapseMesh/VertexCollapseMeshWindow.cpp  
 Samples/Graphics/Castle/LoadData.cpp  
 Samples/Graphics/CubeMaps/CubeMapsWindow.cpp  
 Samples/Graphics/GeometryShaders/GeometryShadersWindow.cpp  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp  
 Samples/Graphics/TextureArrays/TextureArraysWindow.cpp  
 Samples/Graphics/TextureUpdating/TextureUpdatingWindow.cpp  
 Samples/Imagics/AdaptiveSkeletonClimbing2/AdaptiveSkeletonClimbing2Window.cpp  
 Samples/Imagics/ExtractLevelCurves/ExtractLevelCurvesWindow.cpp  
 Samples/Imagics/ExtractLevelSurfaces/ExtractLevelSurfacesWindow.cpp  
 Samples/Imagics/ExtractRidges/ExtractRidges.cpp  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.cpp  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp  
 Samples/Mathematics/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow.cpp

Samples/Mathematics/MovingSphereBox/MovingSphereBoxWindow.cpp  
Samples/Mathematics/NURBSSphere/NURBSSphereWindow.cpp  
Samples/Physics/BouncingBall/DeformableBall.cpp

Replaced `memset` by `std::memset`.

BasisFunction.h  
BSplineCurveFit.h  
BSplineSurfaceFit.h  
GaussianElimination.h  
AkimaUniform2.h  
AkimaUniform3.h  
LinearSystem.h  
NURBSSurface.h  
NURBSVolume.h  
SingularValueDecomposition.h  
SymmetricEigensolver.h  
MassSpringArbitrary.h  
DX11InputLayout.cpp  
GL4InputLayout.cpp  
WGLEngine.cpp  
ConstantBuffer.cpp  
TextureBuffer.cpp  
CPUQueryInstructions.cpp  
Fluid2InitializeSource.cpp  
Fluid2InitializeState.cpp  
Fluid3InitializeSource.cpp  
Fluid3InitializeState.cpp

Samples/Graphics/StructuredBuffers/StructuredBuffersWindow.cpp  
Samples/Graphics/TextureUpdating/TextureUpdatingWindow.cpp  
Samples/Imagics/BSplineInterpolation/BSplineInterpolation.cpp  
Samples/Imagics/GpuGaussianBlur3/GpuGaussianBlur3Window.cpp  
Samples/Imagics/VideoStreams/VideoStreamsWindow.cpp  
Samples/Mathematics/GeodesicHeightFields/GeodesicHeightFieldsWindow.cpp  
Samples/Mathematics/MovingSphereBox/MovingSphereBoxWindow.cpp  
Samples/Mathematics/NURBSSphere/NURBSSphereWindow.cpp  
Samples/Mathematics/PartialSums/PartialSums.cpp  
Samples/Mathematics/ShortestPath/GpuShortestPath.cpp  
Samples/Physics/BallHill/BallHillWindow.cpp  
Samples/Physics/FoucaultPendulum/FoucaultPendulumWindow.cpp  
Samples/Physics/SimplePendulum/SimplePendulum.cpp

**May 2, 2019.** Replaced `GTEngine.h` by only those headers necessary to compile the application. The remaining reasons vary with sample application. Eliminated explicit references to `GTE_USE_MAT_VEC`. Eliminated



explicit references to [GTE\\_DEV\\_OPENGL](#). Eliminated explicit references to [ProgramFactory::PF\\_\\*](#) enumerates. Split the HLSL files that contained both a vertex shader into files, each containing a single shader. Renamed the GLSL shader files.

```
Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.*.vcxproj*
Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.cpp
Samples/Basics/AppendConsumeBuffers/Shaders/AppendConsume.{glsl,hlsl}
Samples/Basics/AppendConsumeBuffers/Shaders/AppendConsume.cs.{glsl,hlsl}
Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.*.vcxproj*
Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.cpp
Samples/Basics/IEEEFloatingPoint/Shaders/TestSubnormals.{glsl,hlsl}
Samples/Basics/IEEEFloatingPoint/Shaders/TestSubnormals.cs.{glsl,hlsl}
Samples/Geometries/CLODPolyline/CLODPolylineWindow.{h,cpp}
Samples/Geometries/ConformalMapping/ConformalMappingWindow.{h,cpp}
Samples/Geometries/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow.{h,cpp}
Samples/Geometries/ConvexHull2D/ConvexHull2DWindow.{h,cpp}
Samples/Geometries/ConvexHull3D/ConvexHull3DWindow.{h,cpp}
Samples/Geometries/Delaunay2D/Delaunay2DWindow.{h,cpp}
Samples/Geometries/Delaunay3D/Delaunay3DWindow.{h,cpp}
Samples/Geometries/DisjointIntervalsRectangles/DisjointIntervalsRectangles.cpp
Samples/Geometries/GenerateMeshUVs/GenerateMeshUVsWindow.{h,cpp}
Samples/Geometries/MinimalCycleBasis/MinimalCycleBasisWindow.{h,cpp}
Samples/Geometries/MinimumAreaBox2D/MinimumAreaBox2DWindow.{h,cpp}
Samples/Geometries/MinimumAreaCircle2D/MinimumAreaCircle2DWindow.{h,cpp}
Samples/Geometries/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.{h,cpp}
Samples/Geometries/MinimumVolumeSphere3D/MinimumVolumeSphere3DWindow.{h,cpp}
Samples/Geometries/PolygonBooleanOperations/PolygonBooleanOperationsWindow.{h,cpp}
Samples/Geometries/SplitMeshByPlane/SplitMeshByPlaneWindow.{h,cpp}
Samples/Geometries/TriangulateCDT/TriangulateCDTWindow.{h,cpp}
Samples/Geometries/TriangulateEC/TriangulateECWindow.{h,cpp}
Samples/Geometries/VertexCollapseMesh/VertexCollapseMeshWindow.{h,cpp}
Samples/Graphics/AreaLights/AreaLights.*.vcxproj*
Samples/Graphics/AreaLights/AreaLightEffect.{h,cpp}
Samples/Graphics/AreaLights/AreaLightsWindow.{h,cpp}
Samples/Graphics/AreaLights/Shaders/AreaLight.hlsl
Samples/Graphics/AreaLights/Shaders/AreaLight{VS,PS}.glsl
Samples/Graphics/AreaLights/Shaders/AreaLight.{vs,ps}.{hlsl,glsl}
Samples/Graphics/BillboardNodes/BillboardNodesWindow.{h,cpp}
Samples/Graphics/BlendedAnimations/BlendedAnimationsWindow.{h,cpp}
Samples/Graphics/BlendedTerrain/BlendedTerrain.*.vcxproj*
Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.{h,cpp}
Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.{h,cpp}
Samples/Graphics/BlendedTerrain/Shaders/BlendedTerrain.hlsl
Samples/Graphics/BlendedTerrain/Shaders/BlendedTerrain{VS,PS}.glsl
Samples/Graphics/BlendedTerrain/Shaders/BlendedTerrain.{vs,ps}.{hlsl,glsl}
Samples/Graphics/BlownGlass/BlownGlass.*.vcxproj*
Samples/Graphics/BlownGlass/BlownGlassWindow.{h,cpp}
Samples/Graphics/BlownGlass/Shaders/VolumeRender.hlsl
```

Samples/Graphics/BlownGlass/Shaders/VolumeRender{VS,PS}.glsl  
 Samples/Graphics/BlownGlass/Shaders/VolumeRender.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/BspNodes/BspNodesWindow.{h,cpp}  
 Samples/Graphics/BufferUpdating/BufferUpdatingWindow.{h,cpp}  
 Samples/Graphics/BumpMaps/BumpMaps\*.vcxproj\*  
 Samples/Graphics/BumpMaps/SimpleBumpMapEffect.cpp  
 Samples/Graphics/BumpMaps/BumpMapsWindow.{h,cpp}  
 Samples/Graphics/BumpMaps/Shaders/SimpleBumpMap.hlsl  
 Samples/Graphics/BumpMaps/Shaders/SimpleBumpMap{VS,PS}.glsl  
 Samples/Graphics/BumpMaps/Shaders/SimpleBumpMap.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/CameraAndLightNodes/CameraAndLightNodesWindow.{h,cpp}  
 Samples/Graphics/Castle/CastleWindow.{h,cpp}  
 Samples/Graphics/Castle/CreateMeshes.cpp  
 Samples/Graphics/Castle/TexturePNT1Effect.cpp  
 Samples/Graphics/CubeMaps/CubeMaps\*.vcxproj\*  
 Samples/Graphics/CubeMaps/CubeMapEffect.cpp  
 Samples/Graphics/CubeMaps/CubeMapsWindow.{h,cpp}  
 Samples/Graphics/CubeMaps/Shaders/CubeMap.hlsl  
 Samples/Graphics/CubeMaps/Shaders/CubeMap{VS,PS}.glsl  
 Samples/Graphics/CubeMaps/Shaders/CubeMap.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/GeometryShaders/GeometryShaders\*.vcxproj\*  
 Samples/Graphics/GeometryShaders/GeometryShadersWindow.{h,cpp}  
 Samples/Graphics/GeometryShaders/RandomSquares.hlsl  
 Samples/Graphics/GeometryShaders/RandomSquaresIndirect.hlsl  
 Samples/Graphics/GeometryShaders/RandomSquaresDirect{VS,GS}.glsl  
 Samples/Graphics/GeometryShaders/RandomSquaresIndirect{VS,GS}.glsl  
 Samples/Graphics/GeometryShaders/RandomSquaresPS.glsl  
 Samples/Graphics/GeometryShaders/RandomSquaresDirect.{vs,gs,ps}.{hlsl,glsl}  
 Samples/Graphics/GeometryShaders/RandomSquaresIndirect.{vs,gs,ps}.{hlsl,glsl}  
 Samples/Graphics/GlossMaps/GlossMaps\*.vcxproj\*  
 Samples/Graphics/GlossMaps/GlossMapEffect.{h,cpp}  
 Samples/Graphics/GlossMaps/GlossMapsWindow.{h,cpp}  
 Samples/Graphics/GlossMaps/Shaders/GlossMap.hlsl  
 Samples/Graphics/GlossMaps/Shaders/GlossMap.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/IKControllers/IKControllersWindow.{h,cpp}  
 Samples/Graphics/Lights/LightsWindow.{h,cpp}  
 Samples/Graphics/LightTexture/LightTextureWindow.{h,cpp}  
 Samples/Graphics/MorphControllers/MorphControllersWindow.{h,cpp}  
 Samples/Graphics/MorphFaces/MorphFaces\*.vcxproj\*  
 Samples/Graphics/MorphFaces/CubicInterpolator.h  
 Samples/Graphics/MorphFaces/MorphFacesWindow.{h,cpp}  
 Samples/Graphics/MorphFaces/Shaders/Texture2PNT{VS,PS}.glsl  
 Samples/Graphics/MorphFaces/Shaders/Texture2PNT.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargets\*.vcxproj\*  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.{h,cpp}  
 Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargets.hlsl  
 Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargets{Vertex,Pixel}.glsl  
 Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargets.{vs,ps}.{hlsl,glsl}

Samples/Graphics/ParticleControllers/ParticleControllersWindow.{h,cpp}  
 Samples/Graphics/Picking/PickingWindow.{h,cpp}  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersection.\*.vcxproj\*  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersectionWindow.{h,cpp}  
 Samples/Graphics/PlaneMeshIntersection/Shaders/DrawIntersections.{hlsl,glsl}  
 Samples/Graphics/PlaneMeshIntersection/Shaders/PlaneMeshIntersection.hlsl  
 Samples/Graphics/PlaneMeshIntersection/Shaders/PlaneMeshIntersection{Vertex,Pixel}.glsl  
 Samples/Graphics/PlaneMeshIntersection/Shaders/DrawIntersections.cs.{hlsl,glsl}  
 Samples/Graphics/PlaneMeshIntersection/Shaders/PlaneMeshIntersection.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/PointControllers/PointControllersWindow.{h,cpp}  
 Samples/Graphics/ProjectedTextures/ProjectedTextures.\*.vcxproj\*  
 Samples/Graphics/ProjectedTextures/ProjectedTexturesWindow.{h,cpp}  
 Samples/Graphics/ProjectedTextures/Shaders/ProjectedTextureEffect.cpp  
 Samples/Graphics/ProjectedTextures/Shaders/ProjectedTexture.hlsl  
 Samples/Graphics/ProjectedTextures/Shaders/ProjectedTexture{VS,PS}.glsl  
 Samples/Graphics/ProjectedTextures/Shaders/ProjectedTexture.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/SphereMaps/SphereMaps.\*.vcxproj\*  
 Samples/Graphics/SphereMaps/SphereMapsWindow.{h,cpp}  
 Samples/Graphics/SphereMaps/Shaders/SphereMapEffect.cpp  
 Samples/Graphics/SphereMaps/Shaders/SphereMap.hlsl  
 Samples/Graphics/SphereMaps/Shaders/SphereMap{VS,PS}.glsl  
 Samples/Graphics/SphereMaps/Shaders/SphereMap.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/StructuredBuffers/StructuredBuffers.\*.vcxproj\*  
 Samples/Graphics/StructuredBuffers/StructuredBuffersWindow.{h,cpp}  
 Samples/Graphics/StructuredBuffers/Shaders/StructuredBuffers.hlsl  
 Samples/Graphics/StructuredBuffers/Shaders/StructuredBuffers{VS,PS}.glsl  
 Samples/Graphics/StructuredBuffers/Shaders/StructuredBuffers.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/Terrain/Terrain.\*.vcxproj\*  
 Samples/Graphics/Terrain/TerrainWindow.{h,cpp}  
 Samples/Graphics/Terrain/Shaders/TerrainEffect.cpp  
 Samples/Graphics/Terrain/Shaders/Terrain.hlsl  
 Samples/Graphics/Terrain/Shaders/Terrain{VS,PS}.glsl  
 Samples/Graphics/Terrain/Shaders/Terrain.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/TextureArrays/TextureArrays.\*.vcxproj\*  
 Samples/Graphics/TextureArrays/TextureArraysWindow.{h,cpp}  
 Samples/Graphics/TextureArrays/Shaders/TextureArrays.hlsl  
 Samples/Graphics/TextureArrays/Shaders/TextureArrays{Vertex,Pixel}.glsl  
 Samples/Graphics/TextureArrays/Shaders/TextureArrays.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/TextureUpdating/TextureUpdatingWindow.{h,cpp}  
 Samples/Graphics/Texturing/TexturingWindow.{h,cpp}  
 Samples/Graphics/VertexColoring/VertexColoringWindow.{h,cpp}  
 Samples/Graphics/VertexTextures/VertexTextures.\*.vcxproj\*  
 Samples/Graphics/VertexTextures/VertexTexturesWindow.{h,cpp}  
 Samples/Graphics/VertexTextures/Shaders/DisplacementEffect.{h,cpp}  
 Samples/Graphics/VertexTextures/Shaders/Displacement.hlsl  
 Samples/Graphics/VertexTextures/Shaders/Displacement{VS,PS}.glsl  
 Samples/Graphics/VertexTextures/Shaders/Displacement.{vs,ps}.{hlsl,glsl}  
 Samples/Graphics/WireMesh/WireMesh.\*.vcxproj\*

Samples/Graphics/WireMesh/WireMeshWindow.{h,cpp}  
 Samples/Graphics/WireMesh/Shaders/WireMesh.hlsl  
 Samples/Graphics/WireMesh/Shaders/WireMesh{VS,PS,GS}.glsl  
 Samples/Graphics/WireMesh/Shaders/WireMesh.{vs,ps,gs}.{hlsl,glsl}  
 Samples/Imagics/AdaptiveSkeletonClimbing2/AdaptiveSkeletonClimbing2.cpp  
 Samples/Imagics/AdaptiveSkeletonClimbing3/AdaptiveSkeletonClimbing3.cpp  
 Samples/Imagics/BSplineInterpolation/BSplineInterpolation.cpp  
 Samples/Imagics/Convolution/Convolution.\*.vcxproj\*  
 Samples/Imagics/Convolution/ConvolutionWindows.{h,cpp}  
 Samples/Imagics/Convolution/Shaders/Convolve\*.{hlsl,glsl}  
 Samples/Imagics/Convolution/Shaders/Convolve\*.cs.{hlsl,glsl}  
 Samples/Imagics/ExtractLevelCurves/ExtractLevelCurvesWindow.{h,cpp}  
 Samples/Imagics/ExtractLevelSurfaces/ExtractLevelSurfacesWindow.{h,cpp}  
 Samples/Imagics/ExtractRidges/ExtractRidges.cpp  
 Samples/Imagics/GaussianBlurring/GaussianBlurring.\*.vcxproj\*  
 Samples/Imagics/GaussianBlurring/GaussianBlurringWindow.{h,cpp}  
 Samples/Imagics/GaussianBlurring/Shaders/GaussianBlur3x3.{hlsl,glsl}  
 Samples/Imagics/GaussianBlurring/Shaders/GaussianBlur3x3.cs.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur2/GpuGaussianBlur2.\*.vcxproj\*  
 Samples/Imagics/GpuGaussianBlur2/GpuGaussianBlur2Window.{h,cpp}  
 Samples/Imagics/GpuGaussianBlur2/Shaders/BoundaryDirichlet.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur2/Shaders/BoundaryNeumann.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur2/Shaders/GaussianBlur.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur2/Shaders/BoundaryDirichlet.cs.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur2/Shaders/BoundaryNeumann.cs.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur2/Shaders/GaussianBlur.cs.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/GpuGaussianBlur3.\*.vcxproj\*  
 Samples/Imagics/GpuGaussianBlur3/GpuGaussianBlur3Window.{h,cpp}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/BoundaryDirichlet.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/DrawImage.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/BoundaryNeumann.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/GaussianBlur.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/BoundaryDirichlet.cs.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/BoundaryNeumann.cs.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/DrawImage.ps.{hlsl,glsl}  
 Samples/Imagics/GpuGaussianBlur3/Shaders/GaussianBlur.cs.{hlsl,glsl}  
 Samples/Imagics/MedianFiltering/MedianFiltering.\*.vcxproj\*  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.{h,cpp}  
 Samples/Imagics/MedianFiltering/Shaders/Median3x3.{hlsl,glsl}  
 Samples/Imagics/MedianFiltering/Shaders/Median5x5.{hlsl,glsl}  
 Samples/Imagics/MedianFiltering/Shaders/MedianBySort.{hlsl,glsl}  
 Samples/Imagics/MedianFiltering/Shaders/MedianShared.hlsl  
 Samples/Imagics/MedianFiltering/Shaders/Median3x3.cs.{hlsl,glsl}  
 Samples/Imagics/MedianFiltering/Shaders/Median5x5.cs.{hlsl,glsl}  
 Samples/Imagics/MedianFiltering/Shaders/MedianBySort.cs.{hlsl,glsl}  
 Samples/Imagics/MedianFiltering/Shaders/MedianShared.cs.hlsl  
 Samples/Imagics/SurfaceExtraction/SurfaceExtraction.\*.vcxproj\*  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.{h,cpp}

Samples/Imagics/SurfaceExtraction/Shaders/DrawSurfaceIndirect.hlsl  
 Samples/Imagics/SurfaceExtraction/Shaders/DrawSurfaceIndirect{VS,GS,PS}.glsl  
 Samples/Imagics/SurfaceExtraction/Shaders/ExtractSurface.{hlsl,glsl}  
 Samples/Imagics/SurfaceExtraction/Shaders/ExtractSurfaceIndirect.{hlsl,glsl}  
 Samples/Imagics/SurfaceExtraction/Shaders/DrawSurfaceIndirect.vs,gs,ps.hlsl  
 Samples/Imagics/SurfaceExtraction/Shaders/DrawSurfaceIndirect.{vs,gs,ps}.glsl  
 Samples/Imagics/SurfaceExtraction/Shaders/ExtractSurface.cs.{hlsl,glsl}  
 Samples/Imagics/SurfaceExtraction/Shaders/ExtractSurfaceIndirect.cs.{hlsl,glsl}  
 Samples/Imagics/VideoStreams/VideoStreamsWindow.{h,cpp}  
 Samples/Mathematics/AllPairsTriangles/AllPairsTriangles\*.vcxproj\*  
 Samples/Mathematics/AllPairsTriangles/AllPairsTrianglesWindow.{h,cpp}  
 Samples/Mathematics/AllPairsTriangles/TriangleIntersection.h  
 Samples/Mathematics/AllPairsTriangles/Shaders/DrawUsingVertexID.hlsl  
 Samples/Mathematics/AllPairsTriangles/Shaders/DrawUsingVertexID{VS,PS}.glsl  
 Samples/Mathematics/AllPairsTriangles/Shaders/InitializeColors.{hlsl,glsl}  
 Samples/Mathematics/AllPairsTriangles/Shaders/TriangleIntersection.{hlsl,glsl}  
 Samples/Mathematics/AllPairsTriangles/Shaders/VertexColorIndexed.hlsl  
 Samples/Mathematics/AllPairsTriangles/Shaders/VertexColorIndexed{VS,PS}.glsl  
 Samples/Mathematics/AllPairsTriangles/Shaders/DrawUsingVertexID.{vs,ps}.hlsl,glsl  
 Samples/Mathematics/AllPairsTriangles/Shaders/InitializeColors.cs.{hlsl,glsl}  
 Samples/Mathematics/AllPairsTriangles/Shaders/TriangleIntersection.cs.{hlsl,glsl}  
 Samples/Mathematics/AllPairsTriangles/Shaders/VertexColorIndexed.{vs,ps}.hlsl,glsl  
 Samples/Mathematics/ApproximateEllipseByArcs/ApproximateEllipseByArcs.{h,cpp}  
 Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.{h,cpp}  
 Samples/Mathematics/BSplineCurveReduction/BSplineCurveReductionWindow.{h,cpp}  
 Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.{h,cpp}  
 Samples/Mathematics/DistanceAlignedBoxes/DistanceAlignedBoxesWindow.{h,cpp}  
 Samples/Mathematics/DistanceAlignedBoxOrientedBox/DistanceAlignedBoxOrientedBoxWindow.{h,cpp}  
 Samples/Mathematics/DistanceOrientedBoxes/DistanceOrientedBoxesWindow.{h,cpp}  
 Samples/Mathematics/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow.{h,cpp}  
 Samples/Mathematics/DistancePointHyperellipsoid/DistancePointHyperellipsoid.cpp  
 Samples/Mathematics/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow.{h,cpp}  
 Samples/Mathematics/DistanceRectangleBox/DistanceRectangleBoxWindow.{h,cpp}  
 Samples/Mathematics/DistanceSegments3/DistanceSegments3\*.vcxproj\*  
 Samples/Mathematics/DistanceSegments3/DistanceSegments3.cpp  
 Samples/Mathematics/DistanceSegments3/Shaders/DistanceSeg3Seg3.{hlsl,glsl}  
 Samples/Mathematics/DistanceSegments3/Shaders/DistanceSeg3Seg3.cs.{hlsl,glsl}  
 Samples/Mathematics/DistanceTriangleBox/DistanceTriangleBoxWindow.{h,cpp}  
 Samples/Mathematics/FitCone/FitConeWindow.{h,cpp}  
 Samples/Mathematics/FitCylinder/FitCylinderWindow.{h,cpp}  
 Samples/Mathematics/FitTorus/FitTorusWindow.{h,cpp}  
 Samples/Mathematics/GeodesicEllipsoid/GeodesicEllipsoidWindow.{h,cpp}  
 Samples/Mathematics/GeodesicHeightField/GeodesicHeightFieldWindow.{h,cpp}  
 Samples/Mathematics/Interpolation2D/Interpolation2DWindow.{h,cpp}  
 Samples/Mathematics/IntersectBoxCone/IntersectBoxConeWindow.{h,cpp}  
 Samples/Mathematics/IntersectBoxCylinder/IntersectBoxCylinderWindow.{h,cpp}  
 Samples/Mathematics/IntersectBoxSphere/IntersectBoxSphereWindow.{h,cpp}  
 Samples/Mathematics/IntersectConvexPolyhedra/IntersectConvexPolyhedraWindow.{h,cpp}



Samples/Mathematics/IntersectInfiniteCylinders/IntersectInfiniteCylindersWindow.{h,cpp}  
 Samples/Mathematics/IntersectSphereCone/IntersectSphereConeWindow.{h,cpp}  
 Samples/Mathematics/IntersectTriangleBox/IntersectTriangleBoxWindow.{h,cpp}  
 Samples/Mathematics/IntersectTriangles2D/IntersectTriangles2DWindow.{h,cpp}  
 Samples/Mathematics/MovingCircleRectangle/MovingCircleRectangleWindow.{h,cpp}  
 Samples/Mathematics/MovingSphereBox/MovingSphereBoxWindow.{h,cpp}  
 Samples/Mathematics/NURBSCircle/NURBSCircleWindow.{h,cpp}  
 Samples/Mathematics/NURBSCurveExample/NURBSCurveExampleWindow.{h,cpp}  
 Samples/Mathematics/NURBSSphere/NURBSSphereWindow.{h,cpp}  
 Samples/Mathematics/PartialSums/PartialSums\*.vcxproj\*  
 Samples/Mathematics/PartialSums/PartialSums.cpp  
 Samples/Mathematics/PartialSums/Shaders/PartialSums.{hlsl,glsl}  
 Samples/Mathematics/PartialSums/Shaders/PartialSums.cs.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/PlaneEstimation\*.vcxproj\*  
 Samples/Mathematics/PlaneEstimation/PlaneEstimationWindow.{h,cpp}  
 Samples/Mathematics/PlaneEstimation/Shaders/EvaluateBezier.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/Shaders/PlaneEstimation.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/Shaders/PlaneVisualize.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/Shaders/PositionVisualize.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/Shaders/EvaluateBezier.cs.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/Shaders/PlaneEstimation.cs.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/Shaders/PlaneVisualize.ps.{hlsl,glsl}  
 Samples/Mathematics/PlaneEstimation/Shaders/PositionVisualize.ps.{hlsl,glsl}  
 Samples/Mathematics/RootFinding/RootFinding\*.vcxproj\*  
 Samples/Mathematics/RootFinding/RootFinding.cpp  
 Samples/Mathematics/RootFinding/Shaders/RootFinder.{hlsl,glsl}  
 Samples/Mathematics/RootFinding/Shaders/RootFinder.cs.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/ShortestPath\*.vcxproj\*  
 Samples/Mathematics/ShortestPath/ShortestPathWindow.{h,cpp}  
 Samples/Mathematics/ShortestPath/CpuShortestPath.{h,cpp}  
 Samples/Mathematics/ShortestPath/GpuShortestPath.{h,cpp}  
 Samples/Mathematics/ShortestPath/Shaders/InitializeDiagToCol.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/InitializeDiagToRow.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/PartialSumsDiagToCol.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/PartialSumsDiagToRow.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/UpdateShader.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/WeightsShader.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/InitializeDiagToCol.cs.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/InitializeDiagToRow.cs.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/PartialSumsDiagToCol.cs.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/PartialSumsDiagToRow.cs.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/UpdateShader.cs.{hlsl,glsl}  
 Samples/Mathematics/ShortestPath/Shaders/WeightsShader.cs.{hlsl,glsl}  
 Samples/Mathematics/SymmetricEigensolver3x3/SymmetricEigensolver3x3.cpp  
 Samples/Mathematics/ThinPlateSplines/ThinPlateSplines.cpp  
 Samples/Physics/BallHill/BallHillWindow.{h,cpp}  
 Samples/Physics/BallRubberBand/BallRubberBandWindow.{h,cpp}  
 Samples/Physics/BouncingBall/BouncingBallWindow.{h,cpp}

Samples/Physics/Cloth/ClothWindow.{h,cpp}  
 Samples/Physics/DoublePendulum/DoublePendulumWindow.{h,cpp}  
 Samples/Physics/ExtremalQuery/ExtremalQueryWindow.{h,cpp}  
 Samples/Physics/FlowingSkirt/FlowingSkirtWindow.{h,cpp}  
 Samples/Physics/Fluids2D/Fluids2D\*.vcxproj\*  
 Samples/Physics/Fluids2D/Fluids2DWindow.{h,cpp}  
 Samples/Physics/Fluids2D/Shaders/DrawDensity.{hlsl,glsl}  
 Samples/Physics/Fluids2D/Shaders/DrawDensity.ps.{hlsl,glsl}  
 Samples/Physics/Fluids3D/Fluids3D\*.vcxproj\*  
 Samples/Physics/Fluids3D/Fluids3DWindow.{h,cpp}  
 Samples/Physics/Fluids3D/Shaders/VolumeRender.hlsl  
 Samples/Physics/Fluids3D/Shaders/VolumeRenderVS.glsl  
 Samples/Physics/Fluids3D/Shaders/VolumeRenderPS.glsl  
 Samples/Physics/Fluids3D/Shaders/VolumeRender.vs.{hlsl,glsl}  
 Samples/Physics/Fluids3D/Shaders/VolumeRender.ps.{hlsl,glsl}  
 Samples/Physics/FoucaultPendulum/FoucaultPendulumWindow.{h,cpp}  
 Samples/Physics/FreeFormDeformation/FreeFormDeformationWindow.{h,cpp}  
 Samples/Physics/FreeTopFixedTip/FreeTopFixedTipWindow.{h,cpp}  
 Samples/Physics/GelatinBlob/GelatinBlobWindow.{h,cpp}  
 Samples/Physics/GelatinCube/GelatinCubeWindow.{h,cpp}  
 Samples/Physics/HelixTubeSurface/HelixTubeSurfaceWindow.{h,cpp}  
 Samples/Physics/IntersectingBoxes/IntersectingBoxesWindow.{h,cpp}  
 Samples/Physics/IntersectingRectangles/IntersectingRectanglesWindow.{h,cpp}  
 Samples/Physics/KeplerPolarForm/KeplerPolarFormWindow.{h,cpp}  
 Samples/Physics/MassPulleySpring/MassPulleySpringWindow.{h,cpp}  
 Samples/Physics/MassSprings3D/MassSprings3D\*.vcxproj\*  
 Samples/Physics/MassSprings3D/MassSprings3DWindow.{h,cpp}  
 Samples/Physics/MassSprings3D/CpuMassSpringVolume.{h,cpp}  
 Samples/Physics/MassSprings3D/GpuMassSpringVolume.{h,cpp}  
 Samples/Physics/MassSprings3D/Shaders/DrawUsingVertexID.hlsl  
 Samples/Physics/MassSprings3D/Shaders/DrawUsingVertexID{VS,PS}.glsl  
 Samples/Physics/MassSprings3D/Shaders/RungeKutta.hlsl  
 Samples/Physics/MassSprings3D/Shaders/RungeKutta{1a,1b,2a,2b,3a,3b,4a,4b}.glsl  
 Samples/Physics/MassSprings3D/Shaders/DrawUsingVertexID.{vs,ps}.{hlsl,glsl}  
 Samples/Physics/MassSprings3D/Shaders/RungeKutta.cs.hlsl  
 Samples/Physics/MassSprings3D/Shaders/RungeKutta{1a,1b,2a,2b,3a,3b,4a,4b}.cs.hlsl  
 Samples/Physics/MassSprings3D/Shaders/RungeKutta{1a,1b,2a,2b,3a,3b,4a,4b}.cs.glsl  
 Samples/Physics/Rope/RopeWindow.{h,cpp}  
 Samples/Physics/SimplePendulum/SimplePendulum.cpp  
 Samples/Physics/SimplePendulumFriction/SimplePendulumFrictionWindow.{h,cpp}  
 Tools/GenerateApproximations/GenerateApproximations.cpp  
 Tools/GenerateApproximations/FitASin.h  
 Tools/GenerateApproximations/FitATan.h  
 Tools/GenerateApproximations/FitCos.h  
 Tools/GenerateApproximations/FitExp2.h  
 Tools/GenerateApproximations/FitInvSqrt.h  
 Tools/GenerateApproximations/FitLog2.h  
 Tools/GenerateApproximations/FitReciprocal.h

Tools/GenerateApproximations/FitSin.h  
Tools/GenerateApproximations/FitSqrt.h  
Tools/GenerateApproximations/FitTan.h  
Tools/PrecisionCalculator/PrecisionCalculator.cpp

Here are some notes about fixes to some bugs that were discovered during testing after the aforementioned changes.

- The [BumpMaps](#) sample show incorrect results when OpenGL is used and the torus is textured rather than bump mapped. The problem is that the GLSL [location](#) values for [SimpleBumpMap.vs.glsl](#) are hard-coded for the vertex data structure used in bump mapping. The channels in order are position, normal, light direction, base texture coordinate and normal texture coordinate. When the 'b' key is pressed to toggle to texturing only, the GLSL shader embedded in [Texture2Effect](#) has hard-coded [location](#) values for a vertex with position and texture coordinate, which conflicts with the vertex used in bump mapping. I rewrote the code to have two torii, one for bump mapping and one for texturing. Longer term, I need to modify the GLSL processing code to allow the [location](#) to use DX-like semantics which are replaced by actual locations based on the attached vertex buffer.
- The [GeometryShaders](#) sample triggers an assertion when using DX11-Debug and [USE\\_DRAW\\_DIRECT](#) commented out. The assertion code occurs in the DX11 block but needed to be in the OpenGL block. Also fixed [Shader](#) for OpenGL to deal with vendor-specific ordering of structured buffer layout information.
- The [AllPairsTriangles](#) sample was not rendering correctly in the debug or release configurations using OpenGL and when [USE\\_CPU\\_FIND\\_INTERSECTIONS](#) is active. The vertex format was a position as a 3-tuple of [float](#) and a color index of type [unsigned int](#). Thinking the 3-tuple is expanded to a 4-tuple in GLSL, I modified the CPU position to be a 4-tuple, but the rendering was still not correct. The color index is type [DF\\_R32\\_UINT](#), and I verified that the OpenGL vertex array object corresponding to the color index is [GL\\_UINT](#). I then modified the vertex format to be a 4-tuple of [float](#) with vertex ([x](#), [y](#), [z](#), [colorIndex](#)), and I modified the shaders accordingly. The rendering is now correct. I do not know whether I am incorrectly setting up the buffers or whether the graphics driver has a bug.
- The [ApproximateEllipseByArcs](#) for debug or release OpenGL configurations showed a black screen. This is a result of two calls to [mEngine->DisplayColorBuffer\(0\)](#), one in the [Window2::OnDisplay](#) call and one after the message drawing in [ApproximateEllipseByArcs::OnDisplay](#). I added an override of the virtual [DrawScreenOverlay](#) and moved the message drawing to it so that only one swap buffers occurs.
- I modified the [DistanceSegment3](#) project CPU code and shader code to make the struct packing simpler. The random number generation for the segment components was replaced by reading from input files. This allows for reproducibility of the results when using different compilers. I added the output data as comments in the code.
- Fixed the trackball motion in [IntersectTriangleBox](#) by replacing the old code (that was broken by a previous update to the trackball design) with new code that is a lot simpler.
- Fixed a compiler error in [MassSprings3D](#). The CPU-based mass-spring code had an input [ProgramFactory&](#) that had been changed to a smart-pointer type in the GPU-based code.

Eliminated the explicit use of [GTE\\_DEV\\_OPENGL](#) conditional compilation.



DirectionalLightTextureEffect.cpp  
OverlayEffect.cpp  
PointLightTextureEffect.cpp  
TextEffect.cpp  
Texture2Effect.cpp  
Texture3Effect.cpp  
Fluid2UpdateState.cpp  
Fluid3UpdateState.cpp

Added a `Set` function that has a texture-sampler pair. This is designed to avoid having explicit `GTE_DEV_OPENGL` conditional compilation in the sample applications. I also fixed a problem with the structured buffer layouts when compiling for OpenGL. The GL reports the members of the layout, but the order can vary for different OpenGL implementations. For example, the ordering might be by member offset or it might be by member name in alphabetical order. I modified the OpenGL-based `Shader` constructor to sort each layout by member offset.

`Shader.{h,cpp}`

Added `DoTransform` functions to transform a vector  $v$  by a matrix  $M$  according to whether the user has selected the convention `GTE_USE_MAT_VEC` (function returns  $Mv$ ) or `GTE_USE_VEC_MAT` (function returns  $vM$ ). Added `SetBasis` and `GetBasis` functions to treat the columns of a matrix as a basis when `GTE_USE_MAT_VEC` is active or to treat the rows of a matrix as a basis when `GTE_USE_VEC_MAT` is active. This allows the sample applications to hide the conditional compilation for transforming.

`Matrix2x2.h`  
`Matrix3x3.h`  
`Matrix4x4.h`

Fixed a compiler error when `GTE_USE_VEC_MAT` was enabled.

`Trackball.cpp`

**April 13, 2019.** Exposed the include of `fstream` in the header file so that callers of `CreateFromFiles` do not have to include explicitly that header. Before the change, `fstream` was exposed indirectly by `GTGraphicsDX11.h` but not `GTGraphicsGL4.h`.

`ProgramFactory.{h,cpp}`

Modified the top-level headers to encapsulate better the graphics, window and application layers. The goal is to replace `GTEngine.h` in the sample applications by only those header files needed for compilation, avoiding the slow compile times for the BuildAll solutions in Microsoft Visual Studio. Also, a goal is to avoid exposing explicitly the symbol `GTE_DEV_OPENGL` for conditional compilation in the applications. The initial test case is `AppendConsumeBuffers` which had a significant amount of explicit conditional compilation for DX11, WGL, GLX when creating the graphics engine and program factory and for loading the shader file. Made all the parameters default values for the `WGLEngine` and `GLXEngine` constructors that take the `useDepth24Stencil8` inputs. This allows for generic engine construction without exposing explicitly the `GTE_DEV_OPENGL` or `__LINUX__`

preprocessor symbols. The generic definitions for [DefaultEngine](#), [DefaultProgramFactory](#) and [DefaultShaderName](#) live in [GTGraphics.h](#). Added an include of [GTGraphics.h](#) because any application deriving from [Window3](#) will need a graphics engine.

```
GTEngine.{v12,v14,v15,v16}.{vcxproj,vcxproj.filters}  
GTGraphicsShared.h  
GTApplication.h  
GTEngine.h  
GTGraphics.h  
WGLEngine.h  
GLXEngine.h  
Window3.h
```

Added the GLX-based Linux files to the project but disabled them from compiling in any Windows-based compilation. This is convenient for searching through Visual Studio and for editing GLX-based files without having to drag them from Windows Explorer into the Visual Studio IDE.

```
GTEngine.{v12,v14,v15,v16}.{vcxproj,vcxproj.filters}
```

Added makefiles with the [-Werror](#) flag set. This allows me to compile on a Linux box and have the compiler terminate as soon as a warning occurs (which I then fix). Too many warnings have been missed when the compiler does not stop.

```
GTEngine/makeengine_werror.gte  
GTEngine/Samples/makesample_werror.gte  
GTEngine/Samples/makesamples_werror.gte  
GTEngine/Samples/makeallsamples_werror.gte
```

## 42 Updates to Version 3.24

**April 29, 2019.** MSVS 2019 default settings for cpp and h files is to use hard-coded tabs rather than spaces. I forgot to modify this to use-spaces after installing MSVS 2019. Some files had hard-coded tabs that were removed.

```
DisjointIntervals.h  
TCBSplineCurve.h  
Samples/DX11/LowLevel/LowLevel.cpp  
Samples/DX11/LowLevelStream/LowLevelStream.cpp  
Samples/Mathematics/IntersectConvexPolyhedra/ConvexPolyhedron.h  
Samples/Mathematics/IntersectConvexPolyhedra/MTMesh.h  
Samples/Mathematics/IntersectConvexPolyhedra/UnorderedSet.h  
Tools/GenerateProjects/GenerateProjects.cpp  
Tools/GenerateProjects/ProjectTemplate.v16.{h,cpp}
```

After end-to-end testing of the sample applications, I moved several projects from the `Geometrics` folder to the `Mathematics` folder but forgot to modify the `mEnvironment` path setting.

```
Samples/Mathematics/AllPairsTriangles/AllPairsTrianglesWindow.cpp
Samples/Mathematics/DistanceSegments3/DistanceSegments3.cpp
Samples/Mathematics/ShortestPath/ShortestPathWindow.cpp
```

## 43 Updates to Version 3.23

**April 12, 2019.** Created projects and solutions for Microsoft Visual Studio 2019.

This is a list too large to include here.

Added support for generating MSVS 2019 sample projects and solutions

```
Tools/GenerateProjects/GenerateProjects.cpp
ProjectTemplate.v16.{h,cpp}
```

Updated the comments about Microsoft Visual Studio versions. GTEngine has projects for MSVS 2013, 2015, 2017 and 2019.

```
GTEngineDEF.h
```

The `main` programs had a `void` return. No-permissive mode for C++ requires the return value to be `int`.

```
Samples/DX11/LowLevel/LowLevel.cpp
Samples/DX11/LowLevelStream/LowLevelStream.cpp
```

Made changes in no-permissive mode to avoid MSVS 2019 complaints.

```
Tools/BitmapFontCreator/BitmapFontCreator.cpp
```

The function `GetInterval` is not expected to fail, but the code is written as if it could. To avoid potentially unused variable warnings, set `xmin` and `xmax` to zero in the failure case.

```
DisjointIntervals.h
```

Removed the `minIndex` variable from the `Refine` function. It is effectively unused and was included for debugging purposes.

```
RiemannianGeodesic.h
```

Removed unused variable `found` in function `AssignDirichletMaskBorder`.

PdeFilter1.h

Modified the logic of `GetKeyInfo` to avoid a gcc warning about potentially uninitialized `key` and `dt`. The code is correct, but the compiler cannot determine this metaknowledge.

TCBSplineCurve.h

When the function values at the interval endpoints have the same sign, the root finder returns 0 as the number of iterations indicating it is unknown whether the interval has a root. To avoid warnings about potentially uninitialized values, the `root` value is set anyway (to an interval endpoint). The local variable `gmin` in `Bisect` of the line-circle distance query was there for debugging. It has been removed.

RootBisection.h

DistLine3Circle3.h

The `House` function declared `V` as a `std::array` but did not initialize its elements to zero, which might lead to a result that is uninitialized in all but its first element.

CubicRootsQR.h

QuarticRootsQR.h

**April 10, 2019.** Reorganized the sample applications so that they live in the folders suggested by the engine code they illustrate.

GTBuildAll.{v12,v14,v15}.sln

Moved to Geometrics from Mathematics.

- CLODPolyline
- DisjointIntervalsRectangles
- GenerateMeshUVs
- PolygonBooleanOperations
- SplitMeshByPlane

Moved to Geometrics from Imagics.

- ConformalMapping

Moved to Mathematics from Geometrics.

- AllPairsTriangles
- DistanceAlignedBoxes
- DistanceAlignedBoxOrientedBox
- DistanceOrientedBoxes
- DistancePointConvexPolyhedron
- DistancePointHyperellipsoid
- DistanceRectangleBox
- DistanceSegments3

```

DistanceTriangleBox
IntersectBoxCone
IntersectBoxCylinder
IntersectBoxSphere
IntersectConvexPolyhedra
IntersectSphereCone
IntersectTriangleBox
IntersectTriangles2D
ShortestPath

```

Ported the WM5 sample [IntersectInfiniteCylinders](#).

```

GTBuildAll.{v12,v14,v15}.sln
Samples/Mathematics/IntersectInfiniteCylinders/IntersectInfiniteCylinders.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/IntersectInfiniteCylinders/IntersectInfiniteCylinders.cpp

```

Ported the WM5 sample [ThinPlateSplines](#).

```

GTBuildAll.{v12,v14,v15}.sln
Samples/Mathematics/ThinPlateSplines/ThinPlateSplines.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/ThinPlateSplines/ThinPlateSplines.cpp

```

Ported the WM5 sample [IntersectConvexPolyhedra](#). The sample has its own triangle mesh data structures, but I left them mainly intact just to get the sample running. The GTEngine version of the sample needs to be rewritten to use GTEngine mesh data structures and to merge the sample's [ConvexPolyhedron](#) class with GTEngine's [ConvexPolyhedron3](#) class.

```

GTBuildAll.{v12,v14,v15}.sln
Samples/Mathematics/IntersectConvexPolyhedra/IntersectConvexPolyhedra.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/IntersectConvexPolyhedra/IntersectConvexPolyhedra.{h,cpp}
Samples/Mathematics/IntersectConvexPolyhedra/ConvexPolyhedron.h
Samples/Mathematics/IntersectConvexPolyhedra/MTEdge.h
Samples/Mathematics/IntersectConvexPolyhedra/MTMesh.h
Samples/Mathematics/IntersectConvexPolyhedra/MTVertex.h
Samples/Mathematics/IntersectConvexPolyhedra/MTTriangle.h
Samples/Mathematics/IntersectConvexPolyhedra/UnorderedSet.h

```

Changed the [mRoot](#) object from a [Node](#) to a [Spatial](#). This allows attaching a [Visual](#) object to the tracking device. Before this modification, you had to create a [Node](#) parent of a [Visual](#) and attach the parent to the tracking device.

```

TrackingObject.{h,cpp}

```

**April 9, 2019.** Ported the WM5 sample [DistancePointEllipseEllipsoid](#). This project had the distance queries implemented for point-ellipse, point-ellipsoid, and point-hyperellipsoid. The queries already exist in [Dist-PointHyperellipsoid.h](#), so the ported project has some code that acts as a unit test to verify the query results. The project was also renamed.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
Samples/Mathematics/DistancePointHyperellipsoid/DistancePointHyperellipsoid.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/DistancePointHyperellipsoid/DistancePointHyperellipsoid.cpp

```

Refactored the WM5 sample [ClodPolyline](#) that implemented continuous level of detail of a polyline in 3 dimensions using vertex collapses. The new engine class is [CLODPolyline](#) and supports  $n$ -dimensional polylines. The sample application itself was ported but renamed.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTMathematics.h
CLODPolyline.h
Samples/Geometrics/CLODPolyline/CLODPolyline.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Geometrics/CLODPolyline/CLODPolylineWindow.{h,cpp}

```

**April 8, 2019.** Refactored the WM5 sample [ClipMesh](#) that implemented splitting a mesh by a plane. The new engine class is [SplitPlaneByMesh](#). The sample application itself was ported but renamed.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTMathematics.h
SplitMeshByPlane.h
Samples/Geometrics/SplitPlaneByMesh/SplitPlaneByMesh.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Geometrics/SplitPlaneByMesh/SplitPlaneByMeshWindow.{h,cpp}

```

Refactored the WM5 sample [Boolean2D](#) that implemented Boolean operations on polygons in 2D using BSP trees. The new engine class is [BSPPolygon2](#) and has nested classes that were in separate files in the WM5 sample. The sample application itself was ported but renamed.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTMathematics.h
BSPPolygon2.h
Samples/Geometrics/PolygonBooleanOperations/PolygonBooleanOperations.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Geometrics/PolygonBooleanOperations/PolygonBooleanOperationsWindow.{h,cpp}

```

**April 5, 2019.** Ported the remaining WM5 curves/surfaces/volumes code to GTEngine. Modified the signature for [Evaluate](#) both for parametric curves and parametric surfaces. The quadric surface code uses exact rational arithmetic, and it was convenient to add constructors to [BSRational](#) that take numerators and denominators that are integers (signed or unsigned, 32-bit or 64-bit). Collapsed the two constructors for [Polynomial1](#) into one constructor with default parameters. Reformatted all the curves/surfaces/volumes code for the new format where template function bodies occur inside the class declaration.

```

PolynomialCurve.h
QuadricSurface.h

```

```

GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTMathematics.h
BasisFunction.h
BezierCurve.h
BSplineCurve.h
BSplineCurveFit.h
BSplineSurface.h
BSplineSurfaceFit.h
BSplineVolume.h
BSRational.h
DarbouxFrame.h
FrenetFrame.h
IndexAttribute.h
Mesh.h
NaturalSplineCurve.h
NURBSCurve.h
NURBSSurface.h
NURBSVolume.h
ParametricCurve.h
ParametricSurface.h
Polynomial1.h
RectangleMesh.h
RectanglePatchMesh.h
RevolutionMesh.h
TCBSplineCurve.h
TubeMesh.h
VertexAttribute.h

```

## 44 Updates to Version 3.22

**April 4, 2019.** Fixed compiler error in permissive mode on Ubuntu 18.04, gcc 7.3.0, where a standard header file needed to be included.

```

MinimumAreaCircle2.h
MinimumVolumeSphere3.h

```

Reformatted the file by moving function bodies into the class.

```

BandedMatrix.h

```

**March 26, 2019.** Refactored the WM5 sample [BooleanIntervalRectangle](#) to create engine classes [DisjointIntervals](#) and [DisjointRectangles](#) that encapsulate Boolean operations on intervals  $[x_0, x_1)$  and on rectangles  $[x_0, x_1) \times [y_0, y_1)$ . The sample application itself was ported but renamed.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}

```

GTMathematics.h  
 DisjointIntervals.h  
 DisjointRectangles.h  
 Samples/Mathematics/DisjointIntervalsRectangles/DisjointIntervalsRectangles.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
 Samples/Mathematics/DisjointIntervalsRectangles/DisjointIntervalsRectangles.{h,cpp}

**March 23, 2019.** Ported the WM5 class [BSplineReduction](#). Ported the sample application [BSplineFitContinuous](#) (with a renaming).

GTBuildAll.{v12,v14,v15}.sln  
 GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
 GTMathematics.h  
 BSplineReduction.h  
 Samples/Mathematics/BSplineCurveReduction/BSplineCurveReduction.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
 Samples/Mathematics/BSplineCurveReduction/BSplineCurveReductionWindow.{h,cpp}

**March 22, 2019.** Ported the WM5 class [EllipsoidGeodesic](#). Ported the sample application [GeodesicPaths](#) (with a renaming).

GTBuildAll.{v12,v14,v15}.sln  
 GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
 GTMathematics.h  
 EllipsoidGeodesic.h  
 Samples/Mathematics/GeodesicEllipsoid/GeodesicEllipsoid.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
 Samples/Mathematics/GeodesicEllipsoid/GeodesicEllipsoidWindow.{h,cpp}

Ported the WM5 classes [RiemannianGeodesic](#) and [BSplineGeodesic](#). Ported the sample application [GeodesicHeightField](#).

GTBuildAll.{v12,v14,v15}.sln  
 GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
 GTMathematics.h  
 RiemannianGeodesic.h  
 BSplineGeodesic.h  
 Samples/Mathematics/GeodesicHeightField/GeodesicHeightField.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
 Samples/Mathematics/GeodesicHeightField/GeodesicHeightFieldWindow.{h,cpp}  
 Samples/Mathematics/GeodesicHeightField/Data/ControlPoints.txt

Ported the WM5 class [Lozenge3](#) and queries [ContLozenge3](#) to GTEngine.

GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
 GTMathematics.h  
 Lozenge3.h  
 ContLozenge3.h

**March 21, 2019.** Ported the WM5 sample application [GpuGaussianBlur3](#) to GTEngine. Added new images to the application data.



```

GTBuildAll.{v12,v14,v15}.sln
Samples/Imagics/GpuGaussianBlur3/GpuGaussianBlur3.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/GpuGaussianBlur3/GpuGaussianBlur3Window.{h,cpp}
Samples/Imagics/GpuGaussianBlur3/Shaders/GaussianBlur.{hlsl,glsl}
Samples/Imagics/GpuGaussianBlur3/Shaders/BoundaryDirichlet.{hlsl,glsl}
Samples/Imagics/GpuGaussianBlur3/Shaders/BoundaryNeumann.{hlsl,glsl}
Samples/Imagics/GpuGaussianBlur3/Shaders/DrawImage.{hlsl,glsl}
Samples/Data/Head_U16_X128_Y128_Z64.binary
Samples/Data/Head_U16_S128x128_T8x8.binary
Samples/Data/Head_U8_S128x128_T8x8.binary

```

Changed the loaded 3D image to be the newly resized 3D x-ray crystallography data set.

```

Samples/Imagics/BSplineInterpolation/BSplineInterpolation.cpp

```

**March 20, 2019.** Ported the WM5 sample application [GpuGaussianBlur2](#) to GTEngine.

```

GTBuildAll.{v12,v14,v15}.sln
Samples/Imagics/GpuGaussianBlur2/GpuGaussianBlur2.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/GpuGaussianBlur2/GpuGaussianBlur2Window.{h,cpp}
Samples/Imagics/GpuGaussianBlur2/Shaders/GaussianBlur.{hlsl,glsl}
Samples/Imagics/GpuGaussianBlur2/Shaders/BoundaryDirichlet.{hlsl,glsl}
Samples/Imagics/GpuGaussianBlur2/Shaders/BoundaryNeumann.{hlsl,glsl}

```

The comments in [WICFileIO](#) indicated only a couple of texture formats are supported. There are quite a few of them, so the comments were updated to reflect this.

```

GTEngine/Include/Applications/MSW/WICFileIO.h

```

**March 19, 2019.** Refactored the WM5 sample [AdaptiveSkeletonClimbing3](#) to create an engine class [AdaptiveSkeletonClimbing3](#) that encapsulates the surface extraction. The sample application itself was ported.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTImagics.h
AdaptiveSkeletonClimbing3.h
Samples/Imagics/AdaptiveSkeletonClimbing3/AdaptiveSkeletonClimbing3.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/AdaptiveSkeletonClimbing3/AdaptiveSkeletonClimbing3.cpp

```

Ported the WM5 sample [ExtractRidges](#) to GTEngine.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
Samples/Imagics/ExtractRidges/ExtractRidges.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/ExtractRidges/ExtractRidges.cpp

```

**March 18, 2019.** Refactored the WM5 sample [AdaptiveSkeletonClimbing2](#) to create an engine class [AdaptiveSkeletonClimbing2](#) that encapsulates the curve extraction. The sample application itself was ported.

```
GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTImagics.h
AdaptiveSkeletonClimbing2.h
Samples/Imagics/AdaptiveSkeletonClimbing2/AdaptiveSkeletonClimbing2.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/AdaptiveSkeletonClimbing2/AdaptiveSkeletonClimbing2.cpp
```

Ported the WM5 classes [FastMarch](#), [FastMarch2](#) and [FastMarch3](#) to GTEngine. These classes are used for sophisticated image segmentation based on level set and fast marching methods.

```
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTImagics.h
FastMarch.h
FastMarch2.h
FastMarch3.h
```

Ported the WM5 classes [MeshCurvature](#) and [ConformalMap](#) to GTEngine. The latter class is now named [ConformalMapGenus0](#) to make it clear the topology of the input and output meshes are that of a sphere. The WM5 sample application for conformal mappings was also ported.

```
GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTMathematics.h
ConformalMapGenus0.h
MeshCurvature.h
Samples/Imagics/ConformalMapping/ConformalMapping.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/ConformalMapping/ConformalMappingWindow.{h,cpp}
Samples/Data/Brain_V4098_T8192.binary
```

Factored out common code in [Trackball](#) and [Trackcylinder](#) to a new base class [TrackObject](#). WM5 had the ability for the trackball to modify the local rotation of any node in a scene, but that capability had not been ported to GTEngine. This capability has now been added to the GTEngine code.

```
Trackball.{h,cpp}
Trackcylinder.{h,cpp}
TrackObject.{h,cpp}
```

**March 12, 2019.** Ported the WM5 PDE-based filters to GTEngine.

```
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTImagics.h
CurvatureFlow2.h
CurvatureFlow3.h
```

```

FastGaussianBlur1.h
FastGaussianBlur2.h
FastGaussianBlur3.h
GaussianBlur2.h
GaussianBlur3.h
GradientAnisotropic2.h
GradientAnisotropic3.h
PdeFilter.h
PdeFilter1.h
PdeFilter2.h
PdeFilter3.h

```

**March 11, 2019.** Ported the WM5 [ExtractSurfaceCubes](#) and [ExtractSurfaceTetra](#) classes to GTE [SurfaceExtractorCubes](#) and [SurfaceExtractorTetrahedra](#). The classes are now templated on image type that must be signed or unsigned integers using 1, 2 or 4 bytes. An abstract base class was added for sharing code, [SurfaceExtractor](#). A new sample application was added to illustrate and test the ported code.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTImagics.h
SurfaceExtractor.h
SurfaceExtractorCubes.h
SurfaceExtractorTetrahedra.h
Samples/Imagics/ExtractLevelSurfaces/ExtractLevelSurfaces.{v12,v14,v15}.sln,vcxproj,vcxproj.filters}
Samples/Imagics/ExtractLevelSurfaces/ExtractLevelSurfacesWindow.{h,cpp}
Samples/Data/Molecule_U8_X100_Y100_Z120.binary

```

**March 8, 2019.** Renaming old surface extractor to one that indicates Marching Cubes is used. This allows porting the other flavors of surface extraction from Wild Magic 5 to GTEngine.

```

GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTImagics.h
SurfaceExtractor.h
SurfaceExtractorMC.h
Samples/Physics/BouncingBall/DeformableBall.cpp

```

**March 8, 2019.** Ported the WM5 [ExtractCurveSquares](#) and [ExtractCurveTriangles](#) classes to GTE [CurveExtractorSquares](#) and [CurveExtractorTriangles](#) (the names to be consistent with the already existing class [SurfaceExtractor](#)). The classes are now templated on image type that must be signed or unsigned integers using 1, 2 or 4 bytes. An abstract base class was added for sharing code, [CurveExtractor](#). A new sample application was added to illustrate and test the ported code. Also, the file organization in the Imagics folder of the Visual Studio projects was modified to add subfolders Extraction, Images and Utilities.

```

GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTImagics.h
CurveExtractor.h

```

CurveExtractorSquares.h  
 CurveExtractorTriangles.h  
 Samples/Imagics/ExtractLevelCurves/ExtractLevelCurves.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
 Samples/Imagics/ExtractLevelCurves/ExtractLevelCurvesWindow.{h,cpp}  
 Samples/Data/Head\_U16\_X256\_Y256.binary  
 Samples/Data/Head\_U16\_X256\_Y256.png  
 Samples/Data/Head\_U8\_X256\_Y256.binary

**March 7, 2019.** Added specialized type trait `std::is_signed` for `BSNumber` and `BSRational`.

BSNumber.h  
 BSRational.h

**March 6, 2019.** Fixed compile breaks when `GTE_IMAGICS_ASSERT_ON_INVALID_INDEX` was enabled. The internal tests trapped problems for `Image` but not for `Image2` and `Image3`; fixed those tests. Reformatted the files for the new coding rules and fixed an incorrect comment in `Image`.

Image.h  
 Image2.h  
 Image3.h

**March 6, 2019.** Converted the graphics class `BoundingSphere` to a template class in order to support the pending port of the Wild Magic 5 collision detection system. The ported code will be templated and support `float` and `double`. The idea is to separate the physics code from the graphics system data structures. The class `CullingPlane` had to be converted to a template class because `BoundingSphere` uses that class.

GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
 BoundingSphere.h  
 CullingPlane.h  
 Culler.{h,cpp}  
 Spatial.h  
 Visual.h  
 BoundingSphere.cpp  
 CullingPlane.cpp

**March 6, 2019.** Ported from Wild Magic 5 to GTEngine the test-intersection and find-intersection queries for stationary 2D triangles. Added a sample application to illustrate usage and for testing.

GTBuildAll.{v12,v14,v15}.sln  
 GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
 GTMathematics.h  
 IntrTriangle2Triangle2.h  
 Samples/Geometrics/IntersectTriangles2D/IntersectTriangles2D.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
 Samples/Geometrics/IntersectTriangles2D/IntersectTriangles2DWindow.{h,cpp}

## 45 Updates to Version 3.21

**March 4, 2019.** Modified the sphere-cone test-intersection query to handle four types of cones: infinite, infinite truncated, finite and frusta. Added a sample application that was used for testing. The [Intersection-SphereCone.pdf](#) document has been updated to describe the algorithms.

```
GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
Cone.h
IntrSphere3Cone3.h
Samples/Geometrics/IntersectSphereCone/IntersectSphereCone.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Geometrics/IntersectSphereCone/IntersectSphereConeWindow.{h,cpp}
```

The [Window::OnCharPress](#) calls are replaced by the functions [Window2::OnCharPress](#) or [Window3::OnCharPress](#). The [Window2](#) class does not override [OnCharPress](#), so there is no changes in the behavior of applications that use [Window2](#). However, the [Window3](#) class overrides [Window::OnCharPress](#) to allow the derived application to control key-generated translation and rotation speed.

```
Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.cpp
Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow.cpp
Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow.cpp
Samples/Geometrics/Delaunay3D/Delaunay3DWindow.cpp
Samples/Geometrics/DistanceAlignedBoxes/DistanceAlignedBoxesWindow.cpp
Samples/Geometrics/DistanceAlignedBoxOrientedBox/DistanceAlignedBoxOrientedBoxWindow.cpp
Samples/Geometrics/DistanceOrientedBoxes/DistanceOrientedBoxesWindow.cpp
Samples/Geometrics/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow.cpp
Samples/Geometrics/IntersectBoxCylinder/IntersectBoxCylinderWindow.cpp
Samples/Geometrics/IntersectBoxSphere/IntersectBoxSphereWindow.cpp
Samples/Geometrics/IntersectRectangleBox/IntersectRectangleBoxWindow.cpp
Samples/Geometrics/IntersectTriangleBox/IntersectTriangleBoxWindow.cpp
Samples/Geometrics/MinimumAreaCircle2D/MinimumAreaCircle2DWindow.cpp
Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3DWindow.cpp
Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow.cpp
Samples/Geometrics/TriangulationEC/TriangulationECWindow.cpp
Samples/Graphics/BillboardNodes/BillboardNodesWindow.cpp
Samples/Graphics/BlendedAnimations/BlendedAnimationsWindow.cpp
Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp
Samples/Graphics/BumpMaps/BumpMapsWindow.cpp
Samples/Graphics/Lights/LightsWindow.cpp
Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp
Samples/Graphics/TextureUpdating/TextureUpdatingWindow.cpp
Samples/Graphics/VertexCollapseMesh/VertexCollapseMeshWindow.cpp
Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp
Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.cpp
Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.cpp
Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp
Samples/Mathematics/Interpolation2D/Interpolation2DWindow.cpp
```

Samples/Physics/Cloth/ClothWindow.cpp  
Samples/Physics/Fluids3D/Fluids3DWindow.cpp  
Samples/Physics/MassSprings3D/MassSprings3DWindow.cpp  
Samples/Physics/Rope/RopeWindow.cpp

**February 14, 2019.** Modified the interfaces to use `Vector3<Real>` rather than `Vector4<Real>`. This is in preparation for porting the Wild Magic 5 collision detection system to GTEngine.

BoundingSphere.{h,cpp}  
Picker.cpp

**February 13, 2019.** Wrote a new document for clipping a convex polygon against a hyperplane. The implementation is a new file that replaces an old file for 3D only but can be used as well for 2D.

GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
GTMathematics.h  
IntrConvexPolygonHyperplane.h  
IntrConvexPolygonPlane.h  
IntrTriangle3OrientedBox3.h

**February 12, 2019.** Moved the experimental `GTGraphicsDX12.h` to an unpublished development folder. The DX12 engine is not yet fully featured.

GTGraphicsDX12.h  
GTEngine.h

**February 6, 2019.** Ported the Wild Magic 5 `IKController`, `IKJoint` and `IKGoal` classes to GTEngine. The joint and goal classes are now nested structures inside `IKController` that are managed by the controller itself. A sample application has been added to GTEngine.

GTBuildAll.{v12,v14,v15}.sln  
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
GTGraphics.h  
IKController.{h,cpp}  
Samples/Graphics/IKControllers/IKControllers.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/IKControllers/IKControllersWindow.{h,cpp}

**February 5, 2019.** Ported the Wild Magic 5 `Particles` and `ParticleController` classes to GTEngine. A sample application has been added to GTEngine.

GTBuildAll.{v12,v14,v15}.sln  
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
GTGraphics.h  
Particles.{h,cpp}  
ParticleController.{h,cpp}

```
Samples/Graphics/ParticleControllers/ParticleControllers.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/ParticleControllers/BloodCellController.{h,cpp}
Samples/Graphics/ParticleControllers/ParticleControllersWindow.{h,cpp}
```

**February 3, 2019.** Ported the Wild Magic 5 [PointController](#) class to GTEngine. A sample application has been added to GTEngine.

```
GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTGraphics.h
PointController.{h,cpp}
Samples/Graphics/PointControllers/PointControllers.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/PointControllers/PointControllersWindow.{h,cpp}
```

**February 2, 2019.** Ported the Wild Magic 5 [MorphController](#) class to GTEngine. A sample application has been added to GTEngine.

```
GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTGraphics.h
MorphController.{h,cpp}
Samples/Graphics/MorphControllers/MorphControllers.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/MorphControllers/MorphControllersWindow.{h,cpp}
```

**January 31, 2019.** Ported the Wild Magic 5 terrain system to GTEngine. The ported code has a [Terrain](#) class with a private nested class [Page](#). WM5 terrain forced the user to store data in files, and internally the terrain system loaded those files. The GTEngine terrain eliminates that constraint, and now the user passes arrays of heights to initialize the terrain. This allows heights to be procedurally generated during execution. The terrain API had been simplified. A sample application has been added to GTEngine that duplicates the one in WM5.

```
GTBuildAll.{v12,v14,v15}.sln
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTGraphics.h
Terrain.{h,cpp}
Samples/Graphics/Terrain/Terrain.{v12,v14,v15}.sln
Samples/Graphics/Terrain/Terrain.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/Terrain/TerrainWindow.{h,cpp}
Samples/Graphics/Terrain/TerrainEffect.{h,cpp}
Samples/Graphics/Terrain/Shaders/BaseMulDetailFogExpSqr.hlsl
Samples/Graphics/Terrain/Shaders/BaseMulDetailFogExpSqrVS.glsl
Samples/Graphics/Terrain/Shaders/BaseMulDetailFogExpSqrPS.glsl
```

The DX11/HLSL engine properly maps channels of a position-normal-tcoord vertex to the inputs of [Texture2Effect](#) vertex shaders (using semantics). The GL4/GLSL engine does not properly map the channels because the [location](#) for texture coordinates is listed as 1 in the GLSL code but the normal vector occurs in location 1 for PNT1 objects. Added a class to patch this and allow the GL4/GLSL version of Castle

to display the textures correctly. The GL4 engine will be revised in GTL to include a better system for mapping vertex formats to GLSL shaders.

```
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
Castle.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
CastleWindow.h  
CreateMeshes.cpp  
TexturePNT1Effect.{h,cpp}
```

After creating the index buffer in [CreateRectangle](#), the test for a null pointer (low-probability failure to allocate the index buffer) used the vertex buffer pointer rather than the index buffer.

```
MeshFactory.cpp
```

**January 22, 2019.** The projects were missing the [ContAlignedBox.h](#) file.

```
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
```

## 46 Updates to Version 3.20

**January 17, 2019.** Added new files. Two type traits were created in [GteMath.h](#), one is [is\\_arbitrary\\_precision](#) to support conditional compilation via [enable\\_if](#) for selection between floating-point or arbitrary precision arithmetic ([BSNumber](#), [BSRational](#)). The other is [has\\_division\\_operator](#) to support conditional compilation via [enable\\_if](#) for selection between [BSNumber](#) (has no division operator) and [BSRational](#) (has division operator). The implementations for [float](#), [double](#) and [long double](#) are in [GteMath.h](#). The files [GteBSNumber.h](#) and [GteBSRational.h](#) have implementations for their respective classes. The file [GteArbitraryPrecision.h](#) includes all the headers to support GTEngine arbitrary precision arithmetic. The file [GteQuadraticField.h](#) supports arithmetic for numbers of the form  $x + y\sqrt{d}$ , where  $x$ ,  $y$  and  $d$  are real or rational with  $d > 0$ . When rational, the class supports exact arithmetic for geometric queries involving square roots (vector normalization, roots of quadratic polynomials) until the very end when the output of the queries need floating-point-valued results.

```
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
GTMathematics.h  
Math.h  
BSNumber.h  
BSRational.h  
ArbitraryPrecision.h  
QuadraticField.h
```

**January 16, 2019.** Added new files that implement finding the first time of contact and the corresponding contact point between a sphere and a triangle, both moving with constant linear velocity. A sample application was added for testing the code.

```
GTBuildAll.{v12,v14,v15}.sln  
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
```



GTMathematics.h  
GteIntrSphere3Triangle3.h  
Samples/Mathematics/MovingSphereTriangle/MovingSphereTriangle.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
Samples/Mathematics/MovingSphereTriangle/MovingSphereTriangleWindow.{h,cpp}

**January 11, 2019.** The test-intersection query for two 2D line segments had a bug when the segments are on the same line. The `result.intersect` member was set to `true` always when it should have been set to `iiResult.intersect`.

IntrSegment2Segment2.h

## 47 Updates to Version 3.19

**January 9, 2019.** Added new files for representing nonmanifold triangle meshes.

GTLowLevel.h  
GTMathematics.h  
SharedPtrCompare.h  
WeakPtrCompare.h  
ETNonmanifoldMesh.{h,cpp}  
VETNonmanifoldMesh.{h,cpp}

**December 11, 2018.** `Quaternion<Real>` was derived from `Vector<4, Real>` in order to share the unary and binary operators for linear algebraic operations and to share `Dot`, `Length` and `Normalize` for geometric operations. Unfortunately, implicit conversions hide the fact that there is a conflict between quaternion multiplication `Quaternion<Real>::operator*` and multiplication operators `Vector<4, Real>::operator*`. Similar conflicts exist for the negation unary operator. The vector-based operations return `Vector<4, Real>` objects, and the multiplications resolve to the component-wise multiplication of vectors instead of the group-algebraic multiplication of quaternions. Expressions such as `2.0 * q0 * q1` and `-q0 * q1` do not compile to the mathematical expressions one expects. For example, `2.0 * q0 * q1` is parsed as `(2.0 * q0) * q1`. The product `2.0 * q0` is compiled to use the vector-scalar multiplication (which is what we want) and returns a vector object, say `v`. The compiler then has to generate code for `v * q1`, which unfortunately resolves to the component-wise vector product rather than the quaternion product. Also for example, `-q0 * q1` is parsed so that `-q0` is computed by the vector unary negation and returns a vector object, say `v`. Once again the compiler uses the component-wise vector product for `v * q1` rather than quaternion multiplication. As a result, I removed the dependency of `Quaternion<Real>` on `Vector<4, Real>` as a base class. Added unary and binary operators for linear algebraic operations. Added `Dot`, `Length` and `Normalize` functions for geometric operations.

Quaternion.h

Reformatted the files, revised the SLERP comments and added `SlerpRPH` to the `Quaternion` class because the `SLERP` estimation class has a function to estimate `SlerpRPH`.

Quaternion.h  
SlerpEstimate.h

Removed unused variables. The compiler complaints about unused variables occurred only after the `Quaternion` changes. The constructor for the quaternion class was modified from an empty body to `Quaternion() = default`, so my guess is that this change caused the compiler to realize that the variables were unused.

Samples/Geometrics/DistanceAlignedBoxes/DistanceAlignedBoxesWindow.cpp  
Samples/Geometrics/DistanceAlignedBoxOrientedBox/DistanceAlignedBoxOrientedBoxWindow.cpp  
Samples/Geometrics/DistanceOrientedBoxes/DistanceOrientedBoxesWindow.cpp  
Samples/Geometrics/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow.cpp  
Samples/Geometrics/DistanceRectangleBox/DistanceRectangleBoxWindow.cpp  
Samples/Geometrics/DistanceTriangleBox/DistanceTriangleBoxWindow.cpp  
Samples/Geometrics/IntersectBoxCone/IntersectBoxConeWindow.cpp  
Samples/Geometrics/IntersectBoxCylinder/IntersectBoxCylinderWindow.cpp  
Samples/Geometrics/IntersectBoxSphere/IntersectBoxSphereWindow.cpp

**December 6, 2018.** Reformatted the file in preparation for porting to GTL.

Polynomial1.h

## 48 Updates to Version 3.18

**November 30, 2018.** Added test for point-in-cone (in any dimension 2 or larger).

ContCone.h  
GTMathematics.h

**November 30, 2018.** In the `Samples` folder, renamed the top-level folder `CSharpCppManaged` to `CSharpCppManaged.MSVS2017`. Renamed the project files and filter files with appropriate modifications to the XML to include the v14 version number of MSVS 2017. Added similar wrappers for MSVS 2013 in the top-level folder `CSharpCppManaged.MSVS2013` and in the top-level folder `CSharpCppManaged.MSVS2015` for MSVS 2015.

**November 29, 2018.** Extended the test-intersection queries to support aligned boxes as well as oriented boxes and to support cone frusta as well as infinite cones. Modified the sample application to test all cases. The `Cone<N,Real>` class was modified to contain `minHeight` and `maxHeight` members (the previous version had only a maximum height with the assumption that the minimum height is zero).

Cone3.h  
IntrAlignedBox3Cone3.h  
IntrOrientedBox3Cone3.h  
IntrLine3Cone3.h  
Samples/Geometrics/IntersectBoxCone/IntersectBoxConeWindow.{h,cpp}

Reformatted the files so the member functions occur within the header. Added comments that refer to a new PDF document which contains the algorithm details for test-intersection and find-intersection queries between linear components and boxes.

IntrLine3AlignedBox3.h  
IntrLine3OrientedBox3.h  
IntrRay3AlignedBox3.h  
IntrRay3OrientedBox3.h  
IntrSegment3AlignedBox3.h  
IntrSegment3OrientedBox3.h

## 49 Updates to Version 3.17

**October 30, 2018.** I used to have sections ordered alphabetically by the names of the subfolders described in the comments. Two phase name lookups for template matching by the MSVS 2017 compiler had no problems with the ordering, but the Linux g++ compiler does. This occurred when trying to match `std::sqrt(...)` and other math functions when the inputs are based on `BSNumber` or `BSRational`. The *Arithmetic* section has been moved before all other headers, and the `UInteger*` files have been moved before the `BS*` files.

GTMathematics.h

**October 30, 2018.** Modified the cone fitting code to allow the user to specify whether the cone input is the initial guess or whether to compute the cone initial guess internally. The least-squares fitting document has been updated to describe the algorithm for computing the initial guess. A new sample application has been added to illustrate.

ApprCone3.h  
GTBuildAll.{v12,v14,v15}.sln  
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
Samples/Mathematics/FitCone/FitCone.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
Samples/Mathematics/FitCone/FitConeWindow.{h,cpp}

**October 30, 2018.** Modified the torus fitting code to allow the user to specify whether the torus input is the initial guess or whether to compute the torus initial guess internally. A new sample application has been added to illustrate. Linux g++ on Ubuntu 16.04 complained again about ambiguous lookup of `std::sqrt` when the input is `BSRational`. I had to modify the order of the header includes in `GTMathematics.h` to avoid this problem when compiling `FitTorusWindow`. It appears two-phase name lookup for template matching has the unpleasant consequence of forcing order dependence of header files.

ApprTorus3.h  
GTBuildAll.{v12,v14,v15}.sln  
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
GTMathematics.h  
Samples/Mathematics/FitTorus/FitTorus.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}  
Samples/Mathematics/FitTorus/FitTorusWindow.{h,cpp}

**October 28, 2018.** When using `ComputeType` of `float` or `double`, floating-point rounding errors can cause the `UpdateSupport` functions to fail to find a bounding circle/sphere. There was a trap in the code for this failure, but the handler was choosing the bounding sphere from an array of spheres computed in the function,

but it used an out-of-range-index. Now the [UpdateSupport](#) functions report an error condition. When the top-level logic for point processing finds an error, it computes a bounding circle/sphere using the algorithm in [GetContainer](#) of [GteContCircle2.h](#) or [GteContSphere3.h](#). This circle/sphere is generally not minimal. The [operator\(\)](#) reports success or failure. On failure you can always try to call the function again because the random shuffle is most likely to be different from the previous one. A change in ordering of points might lead to a successful construction. To be certain that you will always obtain the minimal bound, you really need to use an exact rational type for [ComputeType](#).

[MinimumAreaCircle2.h](#)  
[MinimumAreaSphere3.h](#)

**October 22, 2018.** Added implementations for NURBS curves that represent quarter, half or full circles and NURBS surfaces that represent eighth, half or full spheres. Added a sample applications to illustrate. Reformatted the base NURBS classes and replace the arrays [BasisFunctionInput](#) by individual items in order to allow the derived classes to construct the base classes.

[GTBuildAll.{v12,v14,v15}.sln](#)  
[GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}](#)  
[GTMathematics.h](#)  
[NURBSCurve.h](#)  
[NURBSSurface.h](#)  
[NURBSVolume.h](#)  
[NURBSCircle.h](#)  
[NURBSSphere.h](#)  
[Samples/Mathematics/NURBSCircle/NURBSCircle.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}](#)  
[Samples/Mathematics/NURBSCircle/NURBSCircleWindow.{h,cpp}](#) [Samples/Mathematics/NURBSSphere/NURBSSphere.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}](#)  
[Samples/Mathematics/NURBSSphere/NURBSSphereWindow.{h,cpp}](#)

**October 26, 2018.** Factored the  $G(W)$  function so that the summations involving only sample point components can be precomputed. This leads to a massive performance increase when evaluating  $G$  over a dense set of vectors  $W$  on the unit hemisphere.

[ApprCylinder3.h](#)

Added member functions for drawing thick lines, rectangles, circles and ellipses.

[Window2.{h,cpp}](#)

**October 20, 2018.** [DXEngine](#) tries to create a device for feature levels in the order 11.1, 11.0, 10.1, 10.0, 9.3, 9.2 and 9.1. The member [featureLevel](#) of the DX11 version of [Window::Parameter](#) was intended to be the least capable feature level attempted during the creation. The default was 11.0, which means if you have a graphics card that supports DX10 but not DX11, the device creation fails and the application aborts (with a [LogError](#) dialog indicating the failure). To execute with DX10, you needed to set the [featureLevel](#) to something less capable than 11.0. I had modified the device creation in [DXEngine](#) some time ago to create a device by iterating over the feature levels, and if one is found it sets the shader model accordingly for the [D3DCompile](#)

call during shader compilation. Because of this design for device creation, there is no need for the `featureLevel` member or for clamping the search to a limited number of feature levels. This member and the support that uses it has been removed.

Include/Applications/MSW/DX11/GteWindow.h  
Source/Applications/MSW/DX11/GteWindow.cpp  
Source/Applications/MSW/DX11/GteWindowSystem.cpp  
Include/Applications/Graphics/DX11/GteDX11Engine.h  
Source/Applications/Graphics/DX11/GteDX11Engine.cpp  
Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.cpp  
Samples/Mathematics/PartialSums/PartialSums.cpp  
Samples/Mathematics/RootFinding/RootFinding.cpp  
Samples/DX11/RawBuffers/RawBuffers.cpp

## 50 Updates to Version 3.16

**October 19, 2018.** With `/permissive-` in Microsoft Visual Studio 2017 (and with `no-permissive` on Linux), the two-phase name lookup for template functions was failing because of the order of the header file inclusion. The order must be `GteUIntegerAP32.h`, `GteBSRational.h` and `GteRootsPolynomial.h` in order for the compiler to find a match for `std::sqrt` and other math function calls in `RootsPolynomial` that take inputs from `BSRational`.

ApprTorus3.h

**October 17, 2018.** An MSVS 2017 internal compiler error occurs for the `SCPolynomial` member function definitions when the `/permissive-` option is used. I moved the definitions to the point of declaration in the subclass to eliminate the error. I also set the `/permissive-` option in the engine project (only for MSVS 2017, the previous compilers do not recognize the option).

GTEngine.v15.vcxproj  
DistCircle3Circle3.h

**October 16, 2018.** The `GetContainer` functions did not initialize the radius of the output circle or sphere. The default constructors set the radius to 1, so if the points are all a distance less than 1 from their average, the bounding circle or sphere is larger than need be. I added to `GetContainer` initialization of the radius to 0.

ContCircle2.h  
ContSphere3.h

Added more comments to the file to describe the differences between representation of vectors by a basis, representation of points by an affine basis and Cartesian coordinates of points.

ConvertCoordinates.h

**October 9, 2018.** Renamed some variables to use the same names as in the PDF that describes the noniterative solver. Added more comments to explain the cryptic block of code in the `if (norm > (Real)0)` clause.

### SymmetricEigensolver3x3.h

**October 5, 2018.** Eliminated the `Function< T >` classes. Eliminated the header file `GteConstants.h` file, moving the contents into the new file `GteMath.h`. The new file also contains implementations for some convenient mathematics functions not found in `cmath`, all implemented in the `std` namespace. The `Function<T>` implementations that were in the deleted file are now in `GteBSNumber.h`, `GteBSRational.h` and `GteIEEEBinary16.h` but implemented within the `std` namespace. This breaks the dependencies of many of the geometric queries on `Function< T >` so that if you do not use exact precision or 16-bit floating-point arithmetic, you are not forced to use the `Function<T>` wrapper. The namespace qualifier `std::` was added to any math function call. For example, `sin` was replaced by `std::sin`.

```
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
GTMathematics.h  
GteMath.h  
GteConstants.h  
GteFunctions.h  
GteFunctionsBSNumber.h  
GteFunctionsBSRational.h  
GteFunctionsIEEEBinary16.h  
ACosEstimate.h  
ApprCone3.h  
ApprCylinder3.h  
ApprEllipse2.h  
ApprEllipseByArcs.h  
ApprEllipsoid3.h  
ApprGreatCircle3.h  
ApprQuadratic2.h  
ApprQuadratic3.h  
ApprTorus3.h  
ATanEstimate.h  
BandedMatrix.h  
BasisFunction.h  
BSNumber.h  
BSRational.h  
ChebyshevRatio.h  
CholeskyDecomposition.h  
Cone.h  
ContCapsule3.h  
ContCircle2.h  
ContCylinder3.h  
ContEllipse2.h  
ContEllipsoid3.h  
ContEllipsoid3MinCR.h  
ContSphere3.h  
CosEstimate.h  
CubicRootsQR.h  
DarbouxFrame.h  
DCPQuery.h
```

DistAlignedBox3OrientedBox3.h  
DistAlignedBoxAlignedBox.h  
DistCircle3Circle3.h  
DistLine3AlignedBox3.h  
DistLine3Circle3.h  
DistLineLine.h  
DistLineRay.h  
DistLineSegment.h  
DistOrientedBox3OrientedBox3.h  
DistPoint3Circle3.h  
DistPoint3ConvexPolyhedron3.h  
DistPoint3Cylinder3.h  
DistPoint3Frustum3.h  
DistPoint3Rectangle3.h  
DistPoint3Tetrahedron3.h  
DistPointAlignedBox.h  
DistPointHyperellipsoid.h  
DistPointLine.h  
DistPointRay.h  
DistPointSegment.h  
DistPointTriangle.h  
DistRayRay.h  
DistRaySegment.h  
DistRectangle3AlignedBox3.h  
DistRectangle3OrientedBox3.h  
DistSegmentSegment.h  
DistTriangle3AlignedBox3.h  
DistTriangle3OrientedBox3.h  
Exp2Estimate.h  
ExtremalQuery3BSP.h  
FIQuery.h  
FrenetFrame.h  
GenerateMeshUV.h  
GMatrix.h  
GVector.h  
Hyperellipsoid.h  
IEEEBinary16.h  
IntpBSplineUniform.h  
IntpSphere2.h  
IntpThinPlateSpline2.h  
IntpThinPlateSpline3.h  
IntrAlignedBox2Circle2.h  
IntrAlignedBox3Sphere3.h  
IntrCircle2Circle2.h  
IntrDisk2Sector2.h  
IntrEllipse2Ellipse2.h  
IntrEllipsoid3Ellipsoid3.h  
IntrHalfspace3Cylinder3.h

IntrHalfspace3Ellipsoid3.h  
IntrLine2Circle2.h  
IntrLine3Capsule3.h  
IntrLine3Cone3.h  
IntrLine3Cylinder3.h  
IntrLine3Ellipsoid3.h  
IntrLine3Sphere3.h  
IntrPlane3Circle3.h  
IntrPlane3Cylinder3.h  
IntrPlane3Ellipsoid3.h  
IntrPlane3Sphere3.h  
IntrSphere3Cone3.h  
IntrSphere3Sphere3.h  
InvSqrtEstimate.h  
LinearSystem.h  
Log2Estimate.h  
Math.h  
Matrix.h  
Matrix2x2.h  
Mesh.h  
MinimumAreaBox2.h  
MinimumAreaCircle2.h  
MinimumVolumeBox3.h  
MinimumVolumeSphere3.h  
Projection.h  
QuarticRootsQR.h  
RevolutionMesh.h  
RootsPolynomial.h  
Rotation.h  
Sector2.h  
SinEstimate.h  
SingularValueDecomposition.h  
SqrtEstimate.h  
SurfaceExtractor.h  
SymmetricEigensolver.h  
SymmetricEigensolver2x2.h  
SymmetricEigensolver3x3.h  
TanEstimate.h  
TIQuery.h  
Torus3.h  
TubeMesh.h  
UnsymmetricEigenvalues.h  
Vector.h  
ViewVolume.cpp  
BlendTransformController.cpp  
Controller.cpp  
MeshFactory.cpp  
CullingPlane.cpp



Culler.cpp  
 Trackball.cpp  
 BoundingSphere.cpp  
 BillboardNode.cpp  
 Lighting.cpp  
 Trackcylinder.cpp  
 ImageUtility2.cpp  
 Timer.cpp  
 IEEEBinary16.cpp  
 IntelSSE.cpp  
 Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp  
 Samples/Geometrics/IntersectBoxCone/IntersectBoxConeWindow.cpp  
 Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.cpp  
 Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp  
 Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow.cpp  
 Samples/Graphics/BspNodes/BspNodesWindow.cpp  
 Samples/Graphics/Castle/CastleWindow.cpp  
 Samples/Graphics/Lights/LightsWindow.cpp  
 Samples/Imagics/Convolution/ConvolutionWindow.cpp  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp  
 Samples/Mathematics/ApproximateEllipsesByArcs/ApproximateEllipsesByArcsWindow.cpp  
 Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.cpp  
 Samples/Mathematics/FitCylinder/FitCylinderWindow.cpp  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp  
 Samples/Mathematics/MovingCircleRectangle/MovingCircleRectangleWindow.cpp  
 Samples/Mathematics/MovingSphereBox/MovingSphereBoxWindow.cpp  
 Samples/Mathematics/NURBSCurveExample/NURBSCurveExampleWindow.cpp  
 Samples/Physics//BallHill/BallHillWindow.cpp  
 Samples/Physics/BallRubberBand/PhysicsModule.cpp  
 Samples/Physics/BouncingBall/BouncingBallWindow.cpp  
 Samples/Physics/BouncingBall/PhysicsModule.cpp  
 Samples/Physics/Cloth/PhysicsModule.cpp  
 Samples/Physics/DoublePendulum/PhysicsModule.cpp  
 Samples/Physics/FlowingSkirt/FlowingSkirtWindow.cpp  
 Samples/Physics/FoucaultPendulum/FoucaultPendulumWindow.cpp  
 Samples/Physics/FoucaultPendulum/PhysicsModule.cpp  
 Samples/Physics/FreeTopFixedTip/FreeTopFixedTipWindow.cpp  
 Samples/Physics/FreeTopFixedTip/PhysicsModule.cpp  
 Samples/Physics/HelixTubeSurface/HelixTubeSurfaceWindow.cpp  
 Samples/Physics/KeplerPolarForm/KeplerPolarFormWindow.cpp  
 Samples/Physics/KeplerPolarForm/PhysicsModule.{h,cpp}  
 Samples/Physics/MassPulleySpringSystem/MassPulleySpringSystemWindow.cpp  
 Samples/Physics/MassPulleySpringSystem/PhysicsModule.cpp  
 Samples/Physics/SimplePendulum/SimplePendulum.cpp  
 Samples/Physics/SimplePendulumFriction/SimplePendulumFrictionWindow.cpp  
 Samples/Physics/SimplePendulumFriction/PhysicsModule.cpp  
 Tools/GenerateApproximations/FitASin.h  
 Tools/GenerateApproximations/FitATan.h

Tools/GenerateApproximations/FitCos.h  
 Tools/GenerateApproximations/FitExp2.h  
 Tools/GenerateApproximations/FitInvSqrt.h  
 Tools/GenerateApproximations/FitLog2.h  
 Tools/GenerateApproximations/FitReciprocal.h  
 Tools/GenerateApproximations/FitSin.h  
 Tools/GenerateApproximations/FitSqrt.h  
 Tools/GenerateApproximations/FitTan.h

**October 4, 2018.** Replaced `fabs` and `Function<T>::Fabs` by `std::abs`. This is in preparation for eliminating the `Function` class, implementing `std::somefunction` in `BSNumber` and `BSRational` as needed. The idea is not to force users to include `GteFunctions.h`, instead just imposing a policy that `Real` in template classes must have various functions implemented for the template to compile and run.

ApprEllipseByArcs.h  
 ApprTorus3.h  
 Functions.h  
 FunctionsIEEEBinary16.h  
 GVector.h  
 IntrEllipse2Ellipse2.h  
 IntrConvexPolygonPlane.h  
 IntrOrientedBox2Sector2.h  
 IntrSegment2AlignedBox2.h  
 IntrTriangle3OrientedBox3.h  
 IntpAkimaUniform2.h  
 Polygon2.h  
 Polyhedron3.h  
 SymmetricEigensolver3x3.h  
 VertexCollapseMesh.h  
 Vector.h  
 Vector2.h  
 Vector3.h  
 Vector4.h  
 BlendTransformController.cpp  
 BoundingSphere.cpp  
 ViewVolume.cpp  
 Transform.cpp  
 Samples/Graphics/BumpMaps/SimpleBumpMapEffect.cpp  
 Samples/Graphics/Castle/CastleWindow.cpp  
 Samples/Physics/BouncingBall/DeformableBall.cpp  
 Samples/Physics/KeplerPolarForm/PhysicsModule.cpp  
 Samples/Physics/FlowingSkirt/FlowingSkirtWindow.cpp  
 Samples/Physics/FoucaultPendulum/PhysicsModule.cpp  
 Samples/Physics/FreeTopFixedTip/PhysicsModule.cpp

**October 4, 2018.** LLVM introduced the identifier `_Float16` in apple-clang 10.0. I had defined this as an integral type in `IEEEBinary16`. The naming rules for the compiler state that identifiers starting with one or two underscores followed by a capital letter are reserved names. Renamed mine to `GTEFloat16`.

## 51 Updates to Version 3.15

**October 3, 2018.** Added an implementation of the intersection query between a sphere and a box (considered as solids), each moving with a constant linear velocity. A PDF describing the algorithm is at the website, [Interesection of Moving Sphere and Box](#). A sample application has been added to serve as a unit tests and to show how the code is used. The oriented-box code was modified to share the query code for axis-aligned boxes.

```
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTBuildAll.{v12,v14,v15}.sln
IntrAlignedBox2Circle2.h
IntrAlignedBox3Sphere3.h
IntrOrientedBox3Sphere3.h
Samples/Mathematics/MovingSphereBox/MovingSphereBox.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/MovingSphereBox/MovingSphereBoxWindow.{h,cpp}
```

**October 3, 2018.** The Debug-build frame rate for BlendedAnimations is low, making it difficult to debug. The problem is that the Debug builds do not inline functions, so the `operator[]` function calls of `Vector4`, `Matrix4x4`, `std::array` and `std::vector` are slow when called billions of times as they are in the inner loop of the vertex-bone double loop. In a Release build, the matrix-vector multiplies in the inner loop are the bottleneck, taking about 25% of CPU time. To improve performance (both for Debug and Release), I replaced `Array2` members by `std::vector`. To avoid performance hit with the `lock()` called on the `std::weak_ptr` bones in the inner loop, I store the world transforms in a `std::vector` container before executing the double loop. Finally, I use typecasting to raw `float` pointers to avoid the no-inline problem and to bypass all the `Vector4`, `Matrix4x4`, `std::array` and `std::vector` framework. On my Intel i7-6700 3.40 GHz machine, the Debug build before the changes runs at 16 fps and after the changes runs at 223 fps. The Release build before the changes runs at 2390 fps (sync to vertical retrace disabled) and after the changes runs at 4170 fps. I also tried to partition the data and added multithreading (via `std::thread`), but the overhead for a simple approach (launch all threads, wait for completion via `join`) was significant enough that the multithreaded approach performed worse than the single-threaded approach.

```
SkinController.{h,cpp}
Samples/Graphics/BlendedAnimations/BipedManager.cpp
```

**September 27, 2018.** The texture coordinate at the south pole of the sphere generated by `CreateSphere` was  $(1/2, 1/2)$  but needed to be  $(1/2, 0)$ . to be consistent with the texture coordinate assignments at other sphere locations.

```
MeshFactory.cpp
```

When enabling and disabling the OpenGL state when independent blending is active, the `glEnable(GL_BLEND)` and `glDisable(GL_BLEND)` needed to be `glEnablei(GL_BLEND, i)` and `glDisablei(GL_BLEND, i)`.

```
GL4BlendState.cpp
```

**September 26, 2018.** Removed the include of `Functions.h` from classes implementing the distance queries via `DCPQuery.h` because the latter file already includes it. Added the include of `Functions.h` to `TIQuery.h` and `FIQuery.h` because it is invariably used by classes implementing intersection queries.

TIQuery.h  
 FIQuery.h  
 DistAlignedBoxAlignedBox.h  
 DistAlignedBox3OrientedBox3.h  
 DistCircle3Circle3.h  
 DistLine3Circle3.h  
 DistOrientedBox3OrientedBox3.h  
 DistPointHyperellipsoid.h  
 DistPoint3Circle3.h  
 DistRectangle3AlignedBox3.h  
 DistRectangle3OrientedBox3.h  
 DistTriangle3AlignedBox3.h  
 DistTriangle3OrientedBox3.h  
 IntrEllipse2Ellipse2.h

**September 21, 2018.** Made some minor changes to [InRegionEdgeOverlap](#) to be consistent with the new moving sphere-box find-intersection code.

[IntrAlignedBox2Circle2.h](#)

**September 18, 2018.** The [FindVertexRegionIntersection](#) has a block of code that calls [GetVertexIntersection](#). The latter function returns the contact time when the sphere intersects a vertex of the box. However, the contact point was incorrectly computed to be the line-sphere intersection for the line of motion and the octant of a sphere at the vertex of the box (which is part of the Minkowski sum of box and sphere). The contact point is simply the vector of extents.

[IntrAlignedBox3Sphere3.h](#)

The [FIQuery::operator\(\)](#) method needed to transform the contact point back to the original coordinate system.

[IntrOrientedBox3Sphere3.h](#)

Added a new sample application for testing the find-intersection queries between a sphere and a box (aligned or oriented), both moving with constant linear velocities.

```

GTBuildAll.{v12,v14,v15}.sln
Samples/Mathematics/MovingSphereBox/MovingSphereBox.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/MovingSphereBox/MovingSphereBoxWindow.{h,cpp}
  
```

## 52 Updates to Version 3.14

**September 8, 2018.** The [main](#) function enables a [LogReporter](#) for which the message-box logging is disabled. This was necessary because of an unexpected error generated by [glUniformi](#) for OpenGL builds. The error only occurs on the first drawing pass, after which the scene is drawn correctly. At one time I modified the order of the [LogReporter](#) parameters, which causes the message-box error to occur. Fixed this.

Samples/Graphics/CubeMaps/CubeMapsWindow.cpp

Added a pvw-matrix constant buffer to **VisualEffect** including set-get accessors. The derived classes all declared their own buffers and duplicated the interfaces. The design of **VisualEffect** is to support effects that get attached to **Visual** objects, so the common case is that these effects will require a pvw-matrix that combines the projection and view matrices of a camera and the world matrix of the **Visual** object.

```
VisualEffect.{h,cpp}
ConstantColorEffect.{h,cpp}
LightingEffect.{h,cpp}
Texture2Effect.{h,cpp}
Texture3Effect.{h,cpp}
VertexColorEffect.{h,cpp}
DirectionalLightEffect.cpp
DirectionalLightTextureEffect.cpp
PointLightEffect.cpp
PointLightTextureEffect.cpp
SpotLightEffect.cpp
Samples/Graphics/AreaLights/AreaLightEffect.{h,cpp}
Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.{h,cpp}
Samples/Graphics/BumpMaps/SimpleBumpMapEffect.{h,cpp}
Samples/Graphics/CubeMaps/CubeMapEffect.{h,cpp}
Samples/Graphics/GlossMaps/GlossMapEffect.{h,cpp}
Samples/Graphics/ProjectedTextures/ProjectedTextureEffect.{h,cpp}
Samples/Graphics/SphereMaps/SphereMapEffect.{h,cpp}
Samples/Graphics/VertexTextures/DisplacementEffect.{h,cpp}
```

The **VisualEffect** modifications are motivated by a feature request to use a spatial hierarchy update pass to determine potentially visible sets of **Visual** objects and have their pvw-matrices updated. Currently, if you use **PVWUpdater** to update the GPU memory corresponding to the CPU memory that stores the pvw matrices, you have to dynamically subscribe the matrix-cbuffer pairs for the potentially visible **Visual** objects to avoid synchronizing the GPU memory for all matrix-cbuffer pairs. The design of **PVWUpdater** did not include information about whether a matrix-cbuffer pair can be rejected because of nonvisibility. Now **PVWUpdater** has an update function whose input is the potentially visible set obtained from a **Culler** object. The **BspNodes** sample application was modified to illustrate how to use the new feature of **PVWUpdater**.

```
PVWUpdater.{h,cpp}
Samples/Graphics/BspNodes/BspNodesWindow.{h,cpp}
```

**August 20, 2018.** The eigenvector matrix type used an incorrect formula. Replaced **mlsRotation** and function **bool IsRotation()** by **mEigenvectorMatrixType** and **int GetEigenvectorMatrixType()**. Modified comments to **GetEigenvectors** to make it clear that the 1-dimensional array is filled in to represent an  $n \times n$  matrix that is stored in row-major order and whose columns are the eigenvectors.

```
SymmetricEigensolver.h
Hyperellipsoid.h
```

**July 31, 2018.** Added an implementation of the intersection query between a circle and a rectangle (considered as solids), each moving with a constant linear velocity. A PDF describing the algorithm is at the website, [Interesection of Moving Circle and Rectangle](#). A sample application has been added to serve as a unit tests and to show how the code is used. The oriented-box code was modified to share the query code for axis-aligned boxes.

```
GTMathematics.h
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTBuildAll.{v12,v14,v15}.sln
IntrOrientedBox2Circle2.h
IntrAlignedBox2Circle2.h
Samples/Mathematics/MovingCircleRectangle/MovingCircleRectangle.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/MovingCircleRectangle/MovingCircleRectangleWindow.{h,cpp}
```

**July 25, 2018.** Added an implementation of a virtual track cylinder.

```
GTGraphics.h
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
Trackcylinder.{h,cpp}
```

## 53 Updates to Version 3.13

**July 18, 2018.** Added implementations for Cholesky decomposition of symmetric matrices, for minimization using the Gauss-Newton algorithm and for minimization using the Levenberg-Marquardt algorithm. Added a least-squares algorithm for fitting a cone to a set of points in 3D. Added a least-squares algorithm for fitting a torus to a set of points in 3D.

```
GTMathematics.h
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTBuildAll.{v12,v14,v15}.sln
CholeskyDecomposition.h
GaussNewtonMinimizer.h
LevenbergMarquardtMinimizer.h
ApprCone3.h
ApprTorus3.h
```

Fixed compiler warnings in MSVS 2013 about not being able to automatically generated the assignment operator. One of the base class members is tagged with `const`. Added the `delete` modified for copy constructors and copy assignments and for move constructors and move assignments. Also fixed a compiler warning about a signed-unsigned mismatch when in a 32-bit build.

```
IntpBSplineUniform.h
```

Fixed a bug where the `extern` declaration of `wglSwapIntervalEXT` was different from that of `GteOpenGL.h`. This bug was introduced when I got `GTEngine` compiling under a MinGW environment.

```
Graphics/GL4/WGL/GteWGLEngine.cpp
```

Added libEGL to the linker line to support headless rendering.

[GeometricTools/GTEngine/Samples/makesample.gte](#)

**July 13, 2018.** Fixed a bug in the [Divide](#) algorithm when a constant divisor is used. Added [MakeMonic](#) to divide through by the leading coefficient, after which the highest-degree term is 1. Added [GreatestCommonDivisor](#) and [SquareFreeFactorization](#). The latter provides a list of polynomials, each having simple real-valued roots. The factorization is a preprocessing step for using Vincent's Theorem for computing root-bounding intervals for the real-valued roots.

[Polynomial1.h](#)

**July 2, 2018.** The picking system is based on intersection of lines, rays or segments with triangle primitives (triangle meshes, triangle strips). However, it does not correctly handle triangle primitives that have adjacency information. Added support for triangle meshes with adjacency. The other types will be implemented at a later date.

[IndexBuffer.cpp](#)

**June 22, 2018.** The [result.intersect](#) was uninitialized when the segment intersects the circle of the arc but the intersection points are not on the arc. Fixed this to ensure the [result.intersect](#) is set in all cases.

[IntrSegment2Arc2.h](#)

**June 21, 2018.** Added support for selecting at run time whether to use GLX or EGL for function pointer lookups on Linux distributions. If you want EGL, you must set the global variable [gUseEGLGetProcAddress](#) to [true](#) (default value is [false](#)) before calling [InitializeOpenGL](#). In particular, you should do so before creating a [GL4Engine](#) object.

[GTEngine/Source/Graphics/GL4/GLX/GteGLXExtensions.cpp](#)  
[GTEngine/Tools/GenerateOpenGLWrapper/GteOpenGL.h](#)

## 54 Updates to Version 3.12

**June 7, 2018.** Added implementations for B-spline interpolation of data defined on lattices in any dimensions Wild Magic 5 had implementations based on the BSplineInterpolation.pdf document, but that is quite old and has a translation bias. The document has been rewritten and the code in GTEngine is an implementation of the algorithm presented in the revised document. Also added a new sample application to illustrate how to use the interpolators and to act as unit tests.

[IntpBSplineUniform.h](#)  
[Samples/Imagics/BSplineInterpolation/BSplineInterpolation.{v12,v14,v15}.{sln,vcxproj,vcxproj.filters}](#)  
[Samples/Imagics/BSplineInterpolation/BSplineInterpolation.cpp](#)  
[Data/Molecule97x97x116.png](#)

```

GTMathematics.h
Polynomial1.h
GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}
GTBuildAll.{v12,v14,v15}.sln

```

**May 22, 2018.** Added default constructors. Removed the default parameters from the current constructors and added the `explicit` modifier.

```

EdgeKey.{h,cpp}
TriangleKey.{h,cpp}
TetrahedronKey.{h,cpp}

```

With the old code, C++ rule *13.3.1.7 Initialization by list-initialization* allows the following code.

```

std::set<EdgeKey<false>> keys;
int i0 = 1, i1 = 2;

// The initializer list is implicitly converted by choosing its first
// element as the argument to the EdgeKey constructor and then using
// the default parameter of -1 for the second argument, which is not
// the desired behavior.
keys.insert({ i0, i1 }); // acts like EdgeKey<false>(1,-1)

// If you add a default constructor and remove the default parameters
// for the current constructor, this code compiles because of the match
// rule 13.3.1.7.
keys.insert({ i0, i1 }); // acts like EdgeKeys<false>(1, 2);

// If the non-default constructor additionally is tagged as explicit,
// this code fails to compile.
keys.insert({ i0, i1 }); // fails to compile

// The constructor call with a 2-element initializer list still succeeds
// however.
EdgeKey<false> someKey{ i0, i1 }; // acts like EdgeKey<false>(i0, i1)

```

**May 19, 2018.** Modified the comments for defining a torus.

```
Torus3.h
```

**May 15, 2018.** Added a new folder that has a simple example for how to call GTEngine C++ code from C# code using a managed wrapper (C++/CLI). The example computes the minimum-volume bounding box for a set of points. You should run this in a Release build for speed (it is slow in a Debug build). The configuration manager preference is set for x64, so if you have only a 32-bit machine, you will want to change the configuration for x86. The framework is based on the nicely written article [Creating a C++/CLI Wrapper](#) by Mircea Oprea. If you read this article, the native library originally was created as a dynamic library, but that has an overstrike and is replaced by a static library. This is a consequence of the discussion at the end of the article where Maxence points out that this avoids DLL export problems. However, as Maxence says, you can add `__declspec(dllexport)` tags to the functions you want exported so that the DLL is actually generated by the native library (in this case, the CppLibrary).

```

GeometricTools/GTEngine/Samples/CSharpCppManaged
GeometricTools/GTEngine/Samples/CSharpCppManaged/CppLibrary

```



GeometricTools/GTEngine/Samples/CSharpCppManaged/CppLibrary/CppLibrary.h  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CppLibrary/CppLibrary.vcxproj  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CppLibrary/CppLibrary.vcxproj.filters  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CppLibrary/MinimumVolumeBox.cpp  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CppLibrary/MinimumVolumeBox.h  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/ManagedLibrary  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/ManagedLibrary/AssemblyInfo.cpp  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/ManagedLibrary/ManagedLibrary.vcxproj  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/ManagedLibrary/ManagedLibrary.vcxproj.filters  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/ManagedLibrary/ManagedObject.h  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/ManagedLibrary/MinimumVolumeBox.cpp  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/ManagedLibrary/MinimumVolumeBox.h  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CSharpApplication  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CSharpApplication/Properties  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CSharpApplication/Properties/AssemblyInfo.cs  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CSharpApplication/App.config  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CSharpApplication/CSharpApplication.csproj  
 GeometricTools/GTEngine/Samples/CSharpCppManaged/CSharpApplication/Program.cs

**April 28, 2018.** Fixed a typographical error in the comments. For open uniform splines, the number of unique knots is  $s = n - d + 1$ , not  $s = n - d - 1$ . Removed the comment about the *floating uniform* definition not occurring in the book by Riesenfeld et al. In fact the definition occurred on pages where I had not expected it.

BasisFunction.h

**April 15, 2018.** Added a new file for the containment queries for axis-aligned boxes.

ContAlignedBox.h  
 GTMathematics.h

**April 2, 2018.** Added new files to query a CPU for SIMD capabilities and related support.

Mathematics/MSW/GteCPUQueryInstructions.h  
 Source/MSW/GteCPUQueryInstructions.cpp  
 GTMathematics.h  
 GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}

**March 11, 2018.** Refactored the application and window system so that the code compiles with MinGW on a Windows PC without an MSYS environment. This is available at <http://mingw-w64.org/doku.php/download>, the package MingW-W64-builds, GCC version 7.2.0 and Mingw-w64 version 5.0.3.

GTEngine/GTEngine.{v12,v14,v15}.{vcxproj,vcxproj.filters}  
 GTMathematics.h  
 GTWindows.h

```

Include/Applications/MSW/GteMSWindowSystem.h
Include/Applications/MSW/DX11/GteWindowSystem.h
Include/Applications/MSW/WGL/GteWindowSystem.h
Source/Applications/GteEnvironment.cpp
Source/Applications/MSW/GteMSWindowSystem.cpp
Source/Applications/MSW/DX11/GteWindowSystem.cpp
Source/Applications/MSW/WGL/GteWindowSystem.cpp
Source/Applications/MSW/GteWICFileIO.cpp
Include/Graphics/GL4/GteOpenGL.h
Source/Graphics/GL4/GteOpenGL.cpp
Source/Graphics/GL4/WGL/GteWGLEngine.cpp
Source/Graphics/GL4/WGL/GteWGLExtensions.cpp

```

## 55 Updates to Version 3.11

**February 19, 2018.** This update is based solely on resolving warnings that occur with GCC 8.0.1 when compiling in the Fedora 28 (rawhide) environment.

Added `-Wall` to the make files that build the engine and samples.

```

GTEngine/makeengine.gte
GTEngine/Samples/makesample.gte

```

GCC 8.0.1 triggered a warning for `Vector<N,Real>::Vector(std::initializer_lists<Real>)`, claiming potential undefined behavior. The warning is enabled using `-Waggressive-loop-optimizations`. The code is provably correct. The unit tests generate correct results no matter how many elements are in the initializer list. I believe the warning is incorrect, but decided to modify the code to use `std::copy` and `std::fill` instead.

```
Vector.h
```

**February 17, 2018.** Fixed a typecast from `int` to `unsigned int` in order that a comparison occurs between two unsigned integers.

```
DrawTarget.cpp
```

Commented out several lines of computation where the results are not used later in the algorithm. The lines were left intact for instructive purposes.

```
Camera.cpp
```

The `name` member initialization was moved to its proper location in the constructor initializer list to reflect its order of declaration in the header file.

```
Spatial.cpp
```

Replaced a `memset` call for an array of `Vertex` by a loop over the array, setting the individual members of `Vertex` to the zero 2-tuple. The locally defined struct `Vertex` is plain-old-data (POD), but GCC 8.0.1 complains that cannot be initialized via `memset`. The compiler warning is incorrect.

Font.cpp

The `GL_INVALID_INDEX` in `glcorearb.h` is declared as an `unsigned int` constant and the examples for GLSL reflection make comparisons between this constant and `int` members of an array. Typecast the members in the comparison to avoid a GCC 8.0.1 signed-unsigned comparison warning.

GL4Engine.cpp  
GLSLReflection.cpp

Removed two unused variables and added a typecast to avoid a signed-unsigned comparison.

Applications/GLX/GteWindow.cpp

Initialized `pmin` and `pmax` to zero in `DrawTriangulation` for passing to `ComputeExtremes` in order to avoid a GCC 8.0.1 maybe-uninitialized warning when using the vectors later.

Samples/Geometrics/TriangulationCDTWindow.cpp

Reordered the initialization of the members of `TriangulateEC::Vertex` to the correct order as determined by the declarations in that nested class.

TriangulateEC.h

Removed computation of a direction vector because the result was not used in the function.

Samples/Graphics/CameraAndLightNodes/CameraAndLightNodesWindow.cpp

Reordered the initialization of the members in the constructor to the correct order as determined by the declarations in the class. Removed the local variable `currDistance` that existed for debugging but is not used in the code otherwise.

GenerateMeshUV.h

Replaced `memset` calls for `std::vector` members in order to zero the memory, avoiding a warning from GCC 8.0.1. The compiler complains that `Vector<N,Real>` is a nontrivial type, but in fact it is plain-old-data (POD). The compiler warning is incorrect.

BSplineCurve.h  
BSplineSurface.h  
BSplineVolume.h  
NURBSCurve.h

Modified the code to use `union` of a `float` and `unsigned int` to avoid breaking the strict aliasing rules of C++.

`Samples/Mathematics/RootFinding/RootFinding.cpp`

Modified `main` to return a value dependent on `iters` to avoid GCC 8.0.1 warning about unused variable. The `iters` variable was included for debugging/inspection just to see how many iterations the eigensolver uses.

`Samples/Mathematics/SymmetricEigensolver3x3/SymmetricEigensolver3x3.cpp`

Reordered the initialization of the members in the constructor to the correct order as determined by the declarations in the class.

`Samples/Physics/FreeFormDeformationWindow.cpp`

Initialized `key` and `dt` to avoid a GCC 8.0.1 compiler warning about potential use of uninitialized variables.

`NaturalSplineCurve.h`

## 56 Updates to Version 3.10

**February 8, 2018.** Implemented the virtual function `SetTitle` of X-Windows and GLX.

`Include/Applications/GLX/GteWindow.h`  
`Source/Applications/GLX/GteWindow.cpp`

The projects needed to include the template files for v15.

`Tools/GenerateProject/GenerateProject.v12.vcxproj`  
`Tools/GenerateProject/GenerateProject.v12.vcxproj.filters`

**February 6, 2018.** The `Picker` class queried for the total number of primitives to examine and assumed that all primitives are to be searched; that is, the picker used `GetNumPrimitives` and the search loop started at 0. Instead, only the number of active number of primitives need to be searched and the first primitive is not necessarily at index 0. That is, the picker needed to use `GetNumActivePrimitives` and `GetFirstPrimitive`.

`Picker.cpp`

**February 5, 2018.** Added support for mouse wheel events.

`Source/Applications/GLX/GteWindow.cpp`

**November 26, 2017.** Fixed the spelling of the function name to access the denominator of the rational number. It is now correctly called `GetDenominator`.

BSRational.h

**November 6, 2017.** The convenience header file was missing include statements for GteFunctionsBSNumber.h, GteFunctionsBSRational.h and GteFunctionsIEEEBinary16.h.

Mathematics.h

**October 22, 2017.** The functions [GetTrailingBit](#) for 64-bit inputs had a bug where an input of zero returned 32 when it should have been zero.

BitHacks.cpp

## 57 Updates to Version 3.9

**September 16, 2017.** Discontinued support for the Macintosh with OS X. Please read the installation and release notes for comments about this decision. The Xcode projects have been removed from the GTEngine distribution.

GTEngine.xcodeproj/project.pbxproj

MSVS 2013 does not support initializing static const members in the class declaration. Removed the static member, using instead its constant value in the small number of locations at which it occurred.

OBBTreeOfPoints.h

The [OnCharPress](#) override was calling the incorrect base-class function.

Samples/Graphics/CubeMaps/CubeMapsWindow.cpp

**September 5, 2017.** Broke the code during the upgrade of the [Matrix](#) class that adds support for initializer lists. Diagonal matrices that used to be constructed correctly now were initialized incorrectly. The ellipse-ellipse code had already been modified correctly.

IntrEllipsoid3Ellipsoide.h

Added an equality sign for consistency (older compilers might not support the code without it).

HLSLResource.cpp

**September 1, 2017.** Removed the include of [<initializer\\_list>](#) from the file because it is not needed by [GVector](#).

GVector.h

Added the missing header file [GteOBbTreeOfPoints.h](#) to the projects.

[GTEngine.{v12,v14,v15}.vcxproj](#)

Added a filter subfolder named [MSW](#) to the [Logger](#) filter and moved the MSWindows-specific files to it.

[GTEngine.{v12,v14,v15}.vcxproj.filters](#)

**August 10, 2017.** The attempt to use an initializer list for [Vector3](#) in the constructor initializer statement does not compile using Microsoft Visual Studio 2013. Moved the initialization to the constructor body.

[ApprCylinder3.h](#)

**August 3, 2017.** The eigenvectors returned by the non-iterative solver were supposed to form a right-handed set. A branch statement was causing the set to be left handed. Modified the code to return always a right-handed set. The [ComputeEigenvector0](#) and [ComputeEigenvector1](#) functions were passing the known eigenvalues by non-const reference. These are now passed by value. The [Subtract](#) function has a hard-coded [float](#) instead of [Real](#).

[SymmetricEigensolver3x3.h](#)

**July 26, 2017.** Added code for computing a bounding-volume tree of oriented bounding boxes of a set of points in 3D. This is a port of Wild Magic 5 code but for points instead of triangles. The code for computing an OBB tree for triangles will be posted soon.

[OBbTreeForPoints.h](#)

[GTMathematics.h](#)

The [MaxNeighbors](#) template parameter is used only by the [FindNeighbors](#) member function. This parameter was removed from the class and the [FindNeighbors](#) function now is a template member function whose parameter is [MaxNeighbors](#). Removed the helper class [SortFunctor](#), using instead a simple lambda function in the place where the comparison is needed.

[NearestNeighborQuery.h](#)

**July 25, 2017.** Added [const](#) modifiers to the cone arguments.

[IntrAlignedBox3Cone.h](#)

[IntrOrientedBox3Cone.h](#)

**July 6, 2017.** The code was added to generate MSVS 2017 projects and solutions but the main function did not call the new code.

[Tools/GenerateProject/GenerateProject.cpp](#)

**July 4, 2017.** Removed the `GTE_*` bit-hack macros. Some of them produce incorrect results because of sign extension issues with integer types.

`BitHacks.{h,cpp}`  
`BSNumber.h`  
`UIntegerALU32.h`  
`UIntegerFP32.h`  
`UIntegerAP32.cpp`

**July 2, 2017.** The partitioning of the angle samples for multithreading was incorrect. Added two more constructors. One constructor allows you to choose the cylinder axis to be any of the eigenvectors of the covariance matrix. The other constructor allows you to choose any cylinder axis. Using these constructors, the least-squares fit uses the specified axis and minimizes the error over centers and radii.

`ApprCylinder3.h`

The vertex shaders compute  $z/w$  for perspective depth. This quantity needs to be linearly interpolated, not perspectively interpolated, so the parameter need to be modified with `noperspective`. The comments were improved in the pixel shaders. The application created depth textures with 24-bit depth and 8-bit stencil, but the OpenGL version was failing on a call to `glGenBuffers` when creating the staging buffer for the depth texture. The depth texture is now created using 32-bit depth and no stencil bits and the overlay pixel shaders were modified to handle the floating-point depth values.

`Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp`  
`Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargets.hlsl`  
`Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargetsVertex.glsl`  
`Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargetsPixel.glsl`

**June 29, 2017.** Added the ability to specify whether the graphics engine uses a 24-bit depth and 8-bit stencil buffer or a 32-bit depth buffer. Previously, only the 24-8 format was supported. These changes are for GLX and for the applications that create non-graphics `WGLEngine` or `GLXEngine` objects.

`GTEngine/Include/Graphics/GL4/GLX/GLXEngine.h`  
`GTEngine/Source/Graphics/GL4/GLX/GLXEngine.cpp`  
`GTEngine/Include/Applications/GLX/WindowSystem.h`  
`GTEngine/Source/Applications/GLX/WindowSystem.cpp`  
`Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.cpp`  
`Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.cpp`  
`Samples/Basics/ShaderReflection/ShaderReflection.cpp`  
`Samples/Basics/DistanceSegments3/DistanceSegments3.cpp`  
`Samples/Basics/PartialSums/PartialSums.cpp`  
`Samples/Basics/RootFinding/RootFinding.cpp`

Added the ability to reset a `VertexFormat` object to the state produced by the default constructor. This allows reusing the object within a scope.

`VertexFormat.{h,cpp}`

**June 23, 2017.** Fixed the comment in the shader about the depth equation. The code had said the equation is for OpenGL, but in fact the equation is for Direct3D.

[Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargets.hlsl](#)

Added the ability to specify whether the graphics engine uses a 24-bit depth and 8-bit stencil buffer or a 32-bit depth buffer. Previously, only the 24-8 format was supported. The [GL4DrawTarget::Enable](#) call now needs to select whether the framebuffer attachment is depth-stencil or depth-only.

[GTEngine/Include/Applications/WindowBase.h](#)  
[GTEngine/Include/Applications/MSW/WGL/Window.h](#)  
[GTEngine/Include/Graphics/DX11/DX11Engine.h](#)  
[GTEngine/Include/Graphics/GL4/GL4Engine.h](#)  
[GTEngine/Include/Graphics/GL4/WGL/WGLEngine.h](#)  
[GTEngine/Source/Applications/WindowBase.cpp](#)  
[GTEngine/Source/Applications/MSW/DX11/WindowSystem.cpp](#)  
[GTEngine/Source/Applications/MSW/WGL/WindowSystem.cpp](#)  
[GTEngine/Source/Graphics/DX11/DX11Engine.cpp](#)  
[GTEngine/Source/Graphics/GL4/GL4Engine.cpp](#)  
[GTEngine/Source/Graphics/GL4/WGL/WGLEngine.cpp](#)  
[GTEngine/Source/Graphics/GL4/GL4DrawTarget.cpp](#)

Added a new channel type, [DF\\_UINT\\_24\\_8](#) to represent 24-bit depth and 8-bit stencil buffer values.

[GTEngine/Include/Graphics/DataFormat.{h,cpp}](#)  
[GTEngine/Source/Graphics/GL4/GL4Texture.cpp](#)

## 58 Updates to Version 3.8

**June 18, 2017.** Removed the [Arithmetic](#) class that used the tag-dispatch pattern. The class forces applications to include the classes [BSNumber](#), [BSRational](#) and [IEEEBinary16](#) even though these classes are not used by the applications. Applications that have a need for functions using [BSNumber](#), [BSRational](#) or [IEEEBinary16](#) will include the new specific header files.

[Arithmetic.h](#)  
[GTMathematics.h](#)  
[Functions.h](#)  
[FunctionsBSNumber.h](#)  
[FunctionsBSRational.h](#)  
[FunctionsIEEEBinary16.h](#)  
[GTEngine.v12.{vcxproj,vcxproj.filters}](#)  
[GTEngine.v14.{vcxproj,vcxproj.filters}](#)  
[GTEngine.v15.{vcxproj,vcxproj.filters}](#)

Added explicit typecasts to avoid double-to-float conversion warnings on Ubuntu 16.04. The [cmath](#) file is exposed to the source file, so the compiler warnings are in error.



Samples/HelixTubeSurface/HelixTubeSurfaceWindow.cpp

Removed the [ContourEdges](#) graphics sample from source control. This does not yet have a GLSL implementation, so the makefile fails the build on a Linux box.

**May 23, 2017.** The segments are transformed to box coordinates and the intersection points (if any) are computed in box coordinates. They needed to be transformed back to the original coordinate space.

IntrSegment3AlignedBox3.h  
IntrSegment3OrientedBox3.h

**April 18, 2017.** Replace the template typecasts in a couple of functions with the correct types.

Functions.h

**April 17, 2017.** Removed unnecessary include statements.

IntrEllipse2Ellipse2.h

## 59 Updates to Version 3.7

**April 1, 2017.** Added an [Environment](#) object to access the shader files so that the application can run from any folder. Added a console-window output when running FitCylinder in a Debug build using the mesh points; the program is very slow due to range and iterator checking for [std::array](#) and [std::vector](#).

DistanceSegments3.cpp  
MinimalCycleBasisWindow{h,cpp}  
VideoStreamsWindow.cpp  
FitCylinderWindow.cpp

**March 19, 2017.** Added projects and solution files for Microsoft Visual Studio 2017. Updated the [GenerateProject](#) tool to generate the skeleton files for MSVS 2017. Replaced the [TargetPlatformVersion](#) XML element with [WindowsTargetPlatformVersion](#); the former prevented the correct retargeting of projects in a solution.

GenerateProject.v15.{vcxproj, vcxproj.filters}  
ProjectTemplate.v15.{h,cpp}  
GenerateProject.v14.{vcxproj, vcxproj.filters}  
ProjectTemplate.v14.cpp

**February 23, 2017.** The arc-arc intersection code did not handle the case when the two arcs are the same. The code was fixed and the unit tests were updated to include a test for the equal-arcs case.

IntrArc2Arc2.h

## 60 Updates to Version 3.6

**February 6, 2017.** These files generated compiler errors with GCC-7.0.1 in Fedora Rawhide. They needed an include of `<functional>`.

`ImageUtility{2,3}.h`

Removed pragma to avoid warning with GCC-7.0.1 in Fedora Rawhide. Modified the code to eliminate the need to negate an unsigned integer (for a bit hack).

`BitHacks.cpp`

Removed the file because the implementation is not yet complete.

`DualQuaternion.h`

Removed the project because the port from Wild Magic 5 is not yet working.

`WaterDropFormation.{v12,v14}.{sln,vcxproj,vcxproj.filters}`  
`WaterDropFormation.{h,cpp}`

## 61 Updates to Version 3.5

**January 22, 2017.** The conversion from 32-bit float to 16-bit float was incorrect because of an unnecessary shift of the trailing significand.

`IEEEBinary16.cpp`

**January 2, 2017.** The `ETManifoldMesh::Insert` function inserts the triangle into the triangle map `mTMap` early in the function, but if a nonmanifold condition is encountered, the function exits early and the (bad) triangle is in the map. Moved the map insertion to the end of the function. Also, the `AssertOnNonmanifoldInsertion` function now returns the previous value of the internal state `mAssertOnNonmanifoldInsertion`.

`ETManifoldMesh.{h,cpp}`

**December 9, 2016.** Added support for the topology types involving adjacent primitives: line-list-adjacent, line-strip-adjacent, triangle-list-adjacent, and triangle-strip-adjacent.

`IndexFormat.h`  
`IndexBuffer.{h,cpp}`

**November 28, 2016.** Added another constructor to [VertexBuffer](#) to allow vertex-id for the vertex shaders but without a vertex buffer or structured buffer. The typical scenario is when the vertex shader itself uses the vertex-ids to generate the positions (a screen-space quad, for example).

```
Resource.cpp
VertexBuffer.{h,cpp}
DX11Engine.cpp
GL4Engine.cpp
```

## 62 Updates to Version 3.4

**November 27, 2016.** Added a new distance query for oriented boxes. Added a new sample application to test the query.

```
DistOrientedBox3OrientedBox3.h
Samples/Geometries/DistanceOrientedBoxes/DistanceOrientedBoxes.{v12,v14}.{sln, vcxproj, vcx-
proj.filters}
Samples/Geometries/DistanceOrientedBoxes/DistanceOrientedBoxes.{h,cpp}
```

**November 26, 2016.** Added a new distance query for aligned box and oriented boxes. Added a new sample application to test the query.

```
DistAlignedBox3OrientedBox3.h
Samples/Geometries/DistanceAlignedBox3OrientedBox3/DistanceAlignedBox3OrientedBox3.{v12,v14}.{sln,
vcxproj, vcxproj.filters}
Samples/Geometries/DistanceAlignedBox3OrientedBox3/DistanceAlignedBox3OrientedBox3Window.{h,cpp}
```

Added a new distance query for aligned boxes. Added a new sample application to test the query.

```
DistAlignedBoxAlignedBox.h
Samples/Geometries/DistanceAlignedBoxes/DistanceAlignedBoxes.{v12,v14}.{sln, vcxproj, vcx-
proj.filters}
Samples/Geometries/DistanceAlignedBoxes/DistanceAlignedBoxesWindow.{h,cpp}
```

**November 25, 2016.** Added a new distance query for point and convex polyhedron. Added a new sample application to test the query.

```
DistPoint3ConvexPolyhedron3.h
Samples/Geometries/DistancePointConvexPolyhedron/DistancePointConvexPolyhedron.{v12,v14}.{sln,
vcxproj, vcxproj.filters}
Samples/Geometries/DistancePointConvexPolyhedron/DistancePointConvexPolyhedronWindow.{h,cpp}
```

Fixed a typographical error in the signature of a constructor.

`ContPointInPolyhedron3.h`

**November 24, 2016.** Modified the LCP solver to be templated and support dimensions known at compile time or at run time.

`LCPSolver.h`

**November 23, 2016.** Added new distance queries for rectangles and boxes. Added a new sample application to test the query.

`DistRectangle3AlignedBox3.h`  
`DistRectangle3OrientedBox3.h`  
`Samples/Geometrics/DistanceRectangleBox/DistanceRectangleBox.{v12,v14}.{sln, vcxproj, vcxproj.filters}`  
`Samples/Geometrics/DistanceRectangleBox/DistanceRectangleBoxWindow.{h,cpp}`

Modified the mesh loading code to eliminate redundancy in the data sets. Many of the meshes can be reduced to much smaller vertex and index buffers.

`Samples/Graphics/Castle/CastleWindow.h`  
`Samples/Graphics/Castle/LoadData.cpp`

**November 20, 2016.** Added new distance queries for triangles and boxes. The LCP solver had a hard-coded maximum number of iterations:  $n + 1$  where  $n$  is the integer template parameter. This turns out to be insufficient; the maximum number depends on the query type and is effectively unknown. Added the ability to specify the maximum number of iterations; the default is currently  $n^2$ . Added a new sample application to test the query.

`LCPSolver.h`  
`DistTriangle3AlignedBox3.h`  
`DistTriangle3OrientedBox3.h`  
`Samples/Geometrics/DistanceTriangleBox/DistanceTriangleBox.{v12,v14}.{sln, vcxproj, vcxproj.filters}`  
`Samples/Geometrics/DistanceTriangleBox/DistanceTriangleBoxWindow.{h,cpp}`

Added a header dependency (when building without precompiled headers).

`ApprCylinder3.h`

**November 17, 2016.** The last occurrence of `result.segmentParameter` needed to be assigned `-segExtent`.

`DistSegment3AlignedBox3.h`

## 63 Updates to Version 3.3

**November 13, 2016.** Added a new implementation for the linear complementarity problem (LCP), which is a much simpler implementation than that of Wild Magic 5. It is templated and allows for exact rational arithmetic as well as floating-point types.

`LCPSolver.h`

Added new code for test-intersection query between boxes and cylinders. This uses the new implementation of the LCP solver. The test application verifies that the code works correctly.

`IntrAlignedBox3Cylinder3.h`  
`IntrOrientedBox3Cylinder3.h`  
`Samples/Geometrics/IntersectBoxCylinder/IntersectBoxCylinder.{v12,v14}.{sln, vcxproj, vcxproj.filters}`  
`Samples/Geometrics/IntersectBoxCylinder/IntersectBoxCylinderWindow.{h,cpp}`

Refactored the box-sphere intersection testing to obtain separate implementations for axis-aligned bounding boxes and oriented bounding boxes. The test application verifies that the code works correctly.

`IntrAlignedBox3Sphere3.h`  
`IntrOrientedBox3Sphere3.h`  
`Samples/Geometrics/IntersectBoxSphere/IntersectBoxSphere.{v12,v14}.{sln, vcxproj, vcxproj.filters}`  
`Samples/Geometrics/IntersectBoxSphere/IntersectBoxSphereWindow.{h,cpp}`

Added a bind call whose inputs are Direct3D 11 interfaces. This allows for binding DDS textures. The engine needs a DDS loaded, but for now you can use code that is available with the DirectX distribution.

`DX11Engine.{h,cpp}`  
`DX11Texture2.{h,cpp}`

Modified the depth-texture code to correctly created resources and shader resource views that allow depth-textures to be used as inputs to shader programs.

`TextureDS.{h,cpp}`  
`DX11TextureDS.{h,cpp}`

Modified the camera rig to process all active motions, which was the semantics of camera control in Wild Magic 5.

CameraRig.cpp

Added member accessors to set PVW matrices. This was needed in a Direct3D 12 sample where two sets of PVW matrices was needed per effect, one set for a draw call and the other set for an additional draw call. The matrix management was better handled by the application than internally in the effect classes.

ConstantColorEffect.{h,cpp}  
LightingEffect.{h,cpp}  
Texture2Effect.{h,cpp}  
Texture3Effect.{h,cpp}  
VertexColorEffect.{h,cpp}

Added a header file include statement to satisfy a dependency on maps.

MSWWindowSystem.h

Removed unused code.

Samples/Graphics/WireMesh/Shaders/WireMesh.hlsl

**October 31, 2016.** The [Get](#) template function that takes a handle as input needed to apply a static pointer cast to the returned value.

Shader.h

**October 12, 2016.** The [OnClose](#) callback was added to the window classes, but the call to the callback in the [WNDPROC](#) was missing.

MSWWindowSystem.cpp

Modified the device creation code when using the [DX11Engine](#) constructors that use null pointers for the adapters are called. The code now attempts to fall back to a version of Direct3D that the graphics card supports, and in the last try attempts to create a WARP (software) renderer. The default version strings of [HLSLProgramFactory](#) are also set accordingly, so the application writer does not need to hard-code attempts to select different versions of Direct3D until one is found that works.

DX11Engine.{h,cpp}

## 64 Updates to Version 3.2

**September 24, 2016.** Fixed some errors in the comments.

[Resource.h](#)

**September 12, 2016.** Starting support for Direct3D 12. The engine is not yet ready to support all the sample applications. It will be developed as time permits.

Files that have been modified to support DX12. Wrapped the code in [GTE\\_USE\\_DX12](#) preprocessor blocks. Hiding the dependencies on DX11/DX12 by using macros.

```
Include/GTEngine.h
Include/GTWindows.h
Include/Graphics/DX11/GteHLSLBaseBuffer.h
Include/Graphics/DX11/GteHLSLByteAddressBuffer.h
Include/Graphics/DX11/GteHLSLConstantBuffer.h
Include/Graphics/DX11/GteHLSLParameter.h
Include/Graphics/DX11/GteHLSLResource.h
Include/Graphics/DX11/GteHLSLResourceBindInfo.h
Include/Graphics/DX11/GteHLSLSamplerState.h
Include/Graphics/DX11/GteHLSLShader.h
Include/Graphics/DX11/GteHLSLShaderFactory.h
Include/Graphics/DX11/GteHLSLShaderType.h
Include/Graphics/DX11/GteHLSLShaderVariable.h
Include/Graphics/DX11/GteHLSLStructuredBuffer.h
Include/Graphics/DX11/GteHLSLTexture.h
Include/Graphics/DX11/GteHLSLTextureArray.h
Include/Graphics/DX11/GteHLSLTextureBuffer.h
Source/Graphics/DX11/GteHLSLBaseBuffer.cpp
Source/Graphics/DX11/GteHLSLByteAddressBuffer.cpp
Source/Graphics/DX11/GteHLSLConstantBuffer.cpp
Source/Graphics/DX11/GteHLSLParameter.cpp
Source/Graphics/DX11/GteHLSLResource.cpp
Source/Graphics/DX11/GteHLSLResourceBindInfo.cpp
Source/Graphics/DX11/GteHLSLSamplerState.cpp
Source/Graphics/DX11/GteHLSLShader.cpp
Source/Graphics/DX11/GteHLSLShaderFactory.cpp
Source/Graphics/DX11/GteHLSLShaderType.cpp
Source/Graphics/DX11/GteHLSLShaderVariable.cpp
Source/Graphics/DX11/GteHLSLStructuredBuffer.cpp
Source/Graphics/DX11/GteHLSLTexture.cpp
Source/Graphics/DX11/GteHLSLTextureArray.cpp
Source/Graphics/DX11/GteHLSLTextureBuffer.cpp
```

New files in GeometricTools/GTEngine folder.

GTEngineDX12.v14.sln  
 GTEngineDX12.v14.vcxproj  
 GTEngineDX12.v14.vcxproj.filters  
 Include/GTGraphicsDX12.h  
 Include/Applications/MSW/DX12/GteWindow.h  
 Include/Applications/MSW/DX12/GteWindowSystem.h  
 Source/Applications/MSW/DX12/GteWindow.cpp  
 Source/Applications/MSW/DX12/GteWindowSystem.cpp  
 Include/Graphics/DX12/d3dx12.h  
 Include/Graphics/DX12/GteDX12Buffer.h  
 Include/Graphics/DX12/GteDX12CompileShader.h  
 Include/Graphics/DX12/GteDX12ConstantBuffer.h  
 Include/Graphics/DX12/GteDX12DescriptorHeap.h  
 Include/Graphics/DX12/GteDX12Engine.h  
 Include/Graphics/DX12/GteDX12Exception.h  
 Include/Graphics/DX12/GteDX12GraphicsObject.h  
 Include/Graphics/DX12/GteDX12Include.h  
 Include/Graphics/DX12/GteDX12IndexBuffer.h  
 Include/Graphics/DX12/GteDX12InputLayout.h  
 Include/Graphics/DX12/GteDX12InputLayoutManager.h  
 Include/Graphics/DX12/GteDX12PipelineState.h  
 Include/Graphics/DX12/GteDX12Resource.h  
 Include/Graphics/DX12/GteDX12SamplerState.h  
 Include/Graphics/DX12/GteDX12Texture2.h  
 Include/Graphics/DX12/GteDX12VertexBuffer.h  
 Source/Graphics/DX12/GteDX12CompileShader.cpp  
 Source/Graphics/DX12/GteDX12ConstantBuffer.cpp  
 Source/Graphics/DX12/GteDX12DescriptorHeap.cpp  
 Source/Graphics/DX12/GteDX12Engine.cpp  
 Source/Graphics/DX12/GteDX12Exception.cpp  
 Source/Graphics/DX12/GteDX12GraphicsObject.cpp  
 Source/Graphics/DX12/GteDX12IndexBuffer.cpp  
 Source/Graphics/DX12/GteDX12InputLayout.cpp  
 Source/Graphics/DX12/GteDX12InputLayoutManager.cpp  
 Source/Graphics/DX12/GteDX12PipelineState.cpp  
 Source/Graphics/DX12/GteDX12Resource.cpp  
 Source/Graphics/DX12/GteDX12SamplerState.cpp  
 Source/Graphics/DX12/GteDX12Texture2.cpp  
 Source/Graphics/DX12/GteDX12VertexBuffer.cpp  
 Samples/DX12/Texturing/Texturing.sln  
 Samples/DX12/Texturing/Texturing.vcxproj  
 Samples/DX12/Texturing/Texturing.vcxproj.filters  
 Samples/DX12/Texturing/Texturing.cpp  
 Samples/DX12/Texturing/Texturing.h  
 Samples/DX12/VertexColoring/VertexColoring.sln  
 Samples/DX12/VertexColoring/VertexColoring.vcxproj  
 Samples/DX12/VertexColoring/VertexColoring.vcxproj.filters  
 Samples/DX12/VertexColoring/VertexColoring.cpp



Samples/DX12/VertexColoring/VertexColoring.h

**September 10, 2016.** Ported the NURBS 2D curve sample from Wild Magic 5 to GTEngine.

GTBuildAll.{v12,v14}.sln  
Samples/Mathematics/NURBSCurveExample/NURBSCurveExample.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Mathematics/NURBSCurveExample/NURBSCurveExample.{h,cpp}

Latest development on mesh refactoring. Added an input to [Mesh](#) that allows the derived classes to specify which topologies are valid in the [MeshDescription](#) constructor input. Added to [ParametricCurve](#) the ability to set a subinterval of  $t$  for the domain of the curve.

Mesh.h  
ParametricCurve.h  
RectangleMesh.h  
RectanglePatchMesh.h  
RevolutionMesh.h  
TubeMesh.h

**August 29, 2016.** Added member function [SetLayout](#). The [Shader](#) class is no longer a friend and can call the new member function directly. This also allows for development and testing of a Direct3D 12 engine. In D3D12, the constant buffer must be a multiple of 256 bytes, so [ConstantBuffer](#) has conditional compilation to enforce this constraint.

ConstantBuffer.{h,cpp}  
TextureBuffer.h  
Shader.h

**August 26, 2016.** Added convenience constructor for uniform nonperiodic splines.

BasisFunction.h  
Samples/Physics/Cloth/ClothWindow.cpp  
Samples/Physics/FlowingSkirt/FlowingSkirtWindow.cpp  
Samples/Physics/FreeFormDeformation/FreeFormDeformationWindow.cpp  
Samples/Physics/GelatinCube/GelatinCubeWindow.cpp  
Samples/Physics/MassPulleySpringSystem/MassPulleySpringSystemWindow.cpp  
Samples/Physics/Rope/RopeWindow.cpp

More refactoring to provide meshing outside the graphics subsystem.

GTMathematics.h  
RevolutionMesh.h

TubeMesh.h

**August 20, 2016.** Fixed some logic errors in the clamping of the line-cone intersection to the plane that truncates the cone. Modified the unit tests for full code coverage and validation of results.

IntrLine3Cone3.h

**August 17, 2016.** Started the refactoring of code to build meshes from curves and surfaces. The idea is to have code independent of the graphics subsystem but that can be used by graphics applications.

Mesh.h  
RectanglePatchMesh.h  
VertexAttribute.h  
TubeMesh.h  
RectangleMesh.h  
MeshFactory.{h,cpp}  
Samples/Physics/Cloth/ClothWindow.{h,cpp}  
Samples/Physics/GelatinCube/GelatinCubeWindow.{h,cpp}  
Samples/Physics/HelixTubeSurface/HelixTubeSurfaceWindow.cpp  
Samples/Physics/MassPulleySpringSystem/MassPulleySpringSystemWindow.cpp  
Samples/Physics/Rope/RopeWindow.cpp

Added a least-squares estimator for fitting a cylinder to points.

GTBuildAll.{v12,v14}.sln  
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GteMathematics.h  
ApprCylinder3.h  
Samples/Mathematics/FitCylinder/FitCylinder.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Mathematics/FitCylinder/FitCylinder.{h,cpp}  
Samples/Mathematics/FitCylinder/mesh.txt

**August 7, 2016.** The **Matrix** and **GMatrix** constructors now guarantee that the matrices are initialized to zero in the cases where previously the matrices were uninitialized by the constructor.

Matrix.h  
GMatrix.h

Added a Boolean input named **robust** that defaults to **false** to any functions involving **Length** or **Normalize**. The default uses the standard algorithm for normalizing a vector. The robust algorithms avoid floating-point overflow in the computation of length.

Vector.h  
Vector{2,3,4}.h

**July 28, 2016.** The last [Hyperplane](#) constructor listed in the header file had an off-by-one indexing error that led to incorrect construction of the plane.

[Hyperplane.h](#)

**July 25, 2016.** The [UpdateSupport](#) function needed to wrap the [j0](#) index from [-1](#) to [numVertices-1](#), but the test for negativity was incorrectly applied to [j1](#).

[MininumAreaBox2.h](#)

**July 23, 2016.** Added a new document to describe robust computation of the eigenvalues and eigenvectors of a  $2 \times 2$  symmetric matrix.

[RobustEigenSymmetric2x2.pdf](#) (*A Robust Eigensolver for  $2 \times 2$  Symmetric Matrices*)

**July 16, 2016.** Ported the simple pendulum with friction sample application from Wild Magic 5 to GTEngine.

[GTBuildAll.{v12,v14}.sln](#)  
[Samples/Physics/SimplePendulumFriction/SimplePendulumFriction.{v12,v14}.{sln,vcxproj,vcxproj.filters}](#)  
[Samples/Physics/SimplePendulumFriction/SimplePendulumFriction.{h,cpp}](#)  
[Samples/Physics/SimplePendulumFriction/PhysicsModule.{h,cpp}](#)

Added [ExitFullscreen](#) member function that does not require a [DXGIOutput](#) class object. If a user decides to go fullscreen in a GTEngine application by pressing [ALT+ENTER](#) but then terminates the application before returning to windowed mode, the application triggers an assertion about not all DX11 resources being freed. Adding a call to [ExitFullscreen](#) in the [Window](#) destructor fixes the problem.

[DX11Engine.{h,cpp}](#)  
[Source/Applications/MSW/DX11/Window.cpp](#)

Removed the copyright notices from the automatically generated h and cpp files.

[Tools/GenerateProject/ProjectTemplate.{v12,v14}.cpp](#)

**July 14, 2016.** Ported the simple pendulum sample application from Wild Magic 5 to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/SimplePendulum/SimplePendulum.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/SimplePendulum/SimplePendulum.cpp
```

**July 13, 2016.** Ported the mass-pulley-spring sample application from Wild Magic 5 to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/MassPulleySpringSystem/MassPulleySpringSystem.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/MassPulleySpringSystem/MassPulleySpringSystemWindow.{h,cpp}
Samples/Physics/MassPulleySpringSystem/PhysicsModule.{h,cpp}
Metal.png
```

**July 12, 2016.** Factored out common code in [RectangleSurface](#), [BoxSurface](#), and [TubeSurface](#) and moved it to base class [MeshSurface](#). Ported the helix tube surface sample application from Wild Magic 5 to GTEngine.

```
GTBuildAll.{v12,v14}.sln
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
GTMathematics.h
MeshSurface.h
RectangleSurface.h
BoxSurface.h
TubeSurface.h
Samples/Physics/Cloth/ClothWindow.{h,cpp}
Samples/Physics/Rope/RopeWindow.{h,cpp}
Samples/Physics/HelixTubeSurface/HelixTubeSurface.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/HelixTubeSurface/HelixTubeSurfaceWindow.{h,cpp}
```

**July 10, 2016.** Ported the gelatin cube sample application from Wild Magic 5 to GTEngine. This includes porting the [BoxSurface](#) class, which has been redesigned similar to [RectangleSurface](#) which is independent of the graphics system. Renamed the [Tessellate](#) member to [GetVertices](#), because the triangulation is fixed once parameter domain is specified (the user cannot retessellate without creating a new object). Updated the gelatin blob sample to use depth-stencil and culling state that the original sample used.

```
GTBuildAll.{v12,v14}.sln
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
GTMathematics.h
RectangleSurface.h
BoxSurface.h
Samples/Physics/GelatinCube/GelatinCube.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/GelatinCube/GelatinCubeWindow.{h,cpp}
Samples/Physics/GelatinCube/PhysicsModule.{h,cpp}
Samples/Physics/GelatinBlob/GelatinBlobWindow.{h,cpp}
```

## 65 Updates to Version 3.1

**July 6, 2016.** Added Linux-specific includes to be consistent with what is done on the Microsoft Windows platform.

GTEngine.h  
GTGraphicsGL4.h

Added the extension headers copied from the OpenGL Registry into our local directory structure and modified the includes of the extension headers to point to these.

Graphics/GL4/GL/glext.h  
Graphics/GL4/GL/glxext.h  
Graphics/GL4/GL/wglxt.h  
Graphics/GL4/GLX/GteGLXExtensions.cpp  
Graphics/GL4/WGL/GteWGLEExtensions.cpp

Fixed bugs introduced with the previous modifications.

NURBSSurface.h  
NURBSVolume.h

**July 3, 2016.** Removed the properties from the reflection queries that are from OpenGL 4.4 or 4.5. GTEngine is designed to run with minimum version 4.3. Added several missing **ENUM** members from the map; these are associated with cube map arrays.

GLSLReflection.cpp

**July 2, 2016.** Replaced the call to the OpenGL 4.1 function **glProgramUniform1i** by a call to the OpenGL 2.0 function **glUniform1i**. We already have an active program, so the correct location's value is set. Cleaned up the **Enable** and **Disable** calls for textures and texture arrays.

GL4Engine.cpp

Removed unnecessary include. Commented out function that is not used.

GLXExtensions.cpp

**July 1, 2016.** Removed **LogError** messages that duplicate ones reported in child function calls.

MSW/MSWWindowSystem.h  
GLX/WindowSystem.h

**June 30, 2016.** Modified the OpenGL subsystem to test for a required minimum version and to gracefully exit when that minimum is not met. Currently, the minimum version is OpenGL 4.3 to support compute shaders. The subsystem needs redesigning (and shaders rewritten) before we can allow the applications to specify the required minimum version. Also, Linux distributions might not ship the file [glcorearb.h](#). We have provided this in a subfolder within the GTEngine distribution to guarantee that the code will compile. If your Linux distribution has [glcorearb.h](#), read the release notes about how you can regenerate [GteOpenGL.cpp](#) for this file.

Graphics/GL4/GL/glcorearb.h  
GL4Engine.{h,cpp}  
GLX/GLXEngine.{h,cpp}  
GLX/WindowSystem.cpp  
WGL/WGLEngine.{h,cpp}  
WGL/WindowSystem.cpp  
Tools/GenerateOpenGLWrapper/GenerateOpenGLWrapper.cpp  
Tools/GenerateOpenGLWrapper/GteOpenGL.{h,cpp}  
Tools/GenerateOpenGLWrapper/Initialize.txt  
Tools/GenerateOpenGLWrapper/Version.txt

Modified the make file for a sample to work around an apparent bug in Ubuntu 14.04 regarding the [pthread](#) library. Removed the link of libraries [GLU](#) because GTEngine does not use this.

Samples/makesample.gte

Changed the [DarbouxFrame](#) and [FrenetFrame](#) constructors to accept shared pointers rather than raw pointers to be consistent with the GTEngine design. Redesigning [RectangleSurface](#) to use an interface that will be ported to other surface-type objects that will be ported from Wild Magic 5 to GTEngine.

DarbouxFrame.h  
FrenetFrame.h  
RectangleSurface.h  
TubeSurface.h  
Samples/Physics/Cloth/ClothWindow.cpp

## 66 Updates to Version 3.0

**June 28, 2016.** Ported the free-top-fixed-tip sample application from Wild Magic 5 to GTEngine.

GTBuildAll.{v12,v14}.sln  
Samples/Physics/FreeTopFixedTip/FreeTopFixedTip.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Physics/FreeTopFixedTip/FreeTopFixedTipWindow.{h,cpp}  
Samples/Physics/FreeTopFixedTip/PhysicsModule.{h,cpp}  
Samples/Data/TopTexture.png

Ported the gelatin blob sample application from Wild Magic 5 to GTEngine.

GTBuildAll.{v12,v14}.sln  
Samples/Physics/GelatinBlob/GelatinBlob.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Physics/GelatinBlob/GelatinBlobWindow.{h,cpp}  
Samples/Physics/GelatinBlob/PhysicsModule.{h,cpp}  
Samples/Data/Water.png

These files were tested on a Linux machine, but some changes to them were not carried over to the SVN repository on a PC. Fixed the out-of-sync code.

Source/Applications/GLX/GteWICFileIO.cpp  
Source/Applications/GLX/GteWindow.cpp

**June 26, 2016.** Fixed compiler errors on Fedora 24 with gcc-6.1.1.

Font.cpp  
MeshFactory.cpp

Converted the raw pointer member of [PickRecord](#) to a shared pointer to be consistent with other subsystems in GTEngine. The [Picker](#) internal member functions now pass shared pointers.

Picker.{h,cpp}  
PickRecord.{h,cpp}

The constructors required a nonnull pointer to data that is then copied into internal class members. Invariably applications have to allocate arrays, fill them, and then pass them to the constructors to be copied. The design is modified to avoid having to pass in data, but the internal members are still allocated. The application can then set the data after construction, thereby avoiding the double allocation.

BSplineCurve.h  
BSplineSurface.h  
BSplineVolume.h  
NURBSCurve.h  
NURBSurface.h  
NURBSVolume.h

Ported the free-form deformation sample application from Wild Magic 5 to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/FreeFormDeformation/FreeFormDeformation.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/FreeFormDeformation/FreeFormDeformationWindow.{h,cpp}
```

**June 25, 2016.** The DX11-specific samples were moved to a new folder [Samples/DX11](#). Modified the subfolder, project, solution, and file names to eliminate the redundant [D3D11](#) in those names.

```
Samples/DX11/LowLevel/*
Samples/DX11/LowLevelStream/*
Samples/DX11/RawBuffers/*
Samples/DX11/SharedTextures/*
Samples/DX11/RawBuffers/RawBuffers.cpp
```

Modified the file preamble in the templates for generating the default application source files.

```
Tools/GenerateProjects/ProjectTemplate.{v12,v14}.cpp
```

The ODE function was using [mState](#) rather than [input](#). The former quantity is updated in the ODE solver itself.

```
Samples/Physics/BallHill/PhysicsModule.cpp
```

Ported the Foucault pendulum sample application from Wild Magic 5 to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/FoucaultPendulum/FoucaultPendulum.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/FoucaultPendulum/FoucaultPendulumWindow.{h,cpp}
Samples/Physics/FoucaultPendulum/PhysicsModule.{h,cpp}
Samples/Data/Wood.png
```

**June 20, 2016.** The query needed to use [line.direction](#) in the dot product.

```
DistLine3OrientedBox3.h
```

## 67 Updates to Version 2.5

**June 19, 2016.** The port of Wild Magic 5 OpenGL graphics for Linux and GLX to GTEngine is complete.



**June 15, 2016.** The toggle between windowed and fullscreen mode used the `IDXGIOutput` value queried from the `IDXGIAdapter` objects. If an output goes fullscreen, an entry was added to a `std::map` with the output address as the key. However, these addresses change from query to query, so the toggle did not work. The code was modified to use the output display name as the key, which does uniquely identify which window to toggle between windowed and fullscreen mode.

`DX11Engine.{h,cpp}`

**June 13, 2016.** Modifications due to Cygwin g++ compiling inline functions whether or not they are used, as compared to Microsoft Visual Studio where they do not. The Cygwin environment found several problems with no-PCH. MSVS also appears to allow several standard C library functions to be used without having to include their header files.

`GTEngine.h`  
`GenerateMeshUV.h`  
`ConstantBuffer.{h,cpp}`  
`TextureBuffer.{h,cpp}`  
`Font.cpp`  
`Visual.cpp`  
`MeshFactory.cpp`  
`GL4InputLayout.cpp`  
`ImageUtility2.cpp`  
`Wrapper.cpp`  
`TetrahedronKey.cpp`

Added a `std::flush` so that messages are printed before a segmentation fault and core dump when using Cygwin.

`LogToStdout.cpp`

**June 12, 2016.** The explicit specializations of `Set` were declared inside the class scope but C++ requires them to occur outside the class scope.

`Shader.h`

The source file accesses members of the `StructuredBuffer`, so the header file for that class must be included.

`VertexBuffer.cpp`

Replaced `UINT` by `GLuint`.

## GL4Buffer.cpp

As of 12 June 2016, Cygwin's `glcorearb.h` is revision

```
** Khronos $Revision : 27684 $ on $Date : 2014 - 08 - 11 01:21 : 35
- 0700 (Mon, 11 Aug 2014) $
```

but the `glcorearb.h` we use on Microsoft Windows is revision

```
** Khronos $Revision : 28299 $ on $Date : 2014 - 09 - 25 04:11 : 58
- 0700 (Thu, 25 Sep 2014) $
```

The Cygwin file does not have declarations for the four functions

```
static PFNGLGETQUERYBUFFEROBJECTI64VPROC sglGetQueryBufferObjecti64v = nullptr;
static PFNGLGETQUERYBUFFEROBJECTIVPROC sglGetQueryBufferObjectiv = nullptr;
static PFNGLGETQUERYBUFFEROBJECTUI64VPROC sglGetQueryBufferObjectui64v = nullptr;
static PFNGLGETQUERYBUFFEROBJECTUIVPROC sglGetQueryBufferObjectuiv = nullptr;
```

There are some `#define` variations also, but these do not affect compilation of GTEngine. Added conditional compilation to avoid the compiler errors on Cygwin. Also, the GL extension string parsing for versions of OpenGL prior to 3.0 was incorrect and used string functions specific to Microsoft Windows. Replaced the parsing with `std::string` functions.

## OpenGL.cpp

Tools/GenerateOpenGLWrapper/Initialize.txt

Moved `WICFileIO` files to the `MSW` subfolder, because they are dependent on Microsoft Windows.

```
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
WICFileIO.{h,cpp}
Samples/Graphics/BlendedAnimations/BipedManager.cpp
Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.cpp
Samples/Graphics/BumpMaps/SimpleBumpMapEffect.cpp
```

The class header was missing an include of `cstdint`, which Microsoft Visual Studio appears not to complain about (but Cygwin g++ did). The `SplitPath` and `FullPath` functions are not used in the engine and are specific to Microsoft Windows, so they were removed. The `CreateString*` functions were used only in two sample applications, but they can be replaced by instead using `std::to_string` for creating strings with unformatted data or `std::stringstream` for formatted data.

## Environment.{h,cpp}

Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp  
Samples/Imagics/VideoStreams/VideoStreamsWindow.cpp

Added static constants for key identifiers, key modifiers, mouse buttons, mouse state, and mouse modifiers. Removed the enumerations that were previously used for the mouse. This mimics what Wild Magic 5 does and hides platform-specific values (each OS platform defines the static members with the appropriate values).

```
WindowBase.{h,cpp}  
Window3.cpp  
MSWWindow.cpp  
MSWWindowSystem.cpp  
GLX/Window.cpp
```

A modification was made in [DX11TextureCube](#) that indicated a cube map cannot be a dynamic-update resource. The same modification needed to be made in [DX11TextureCubeArray](#).

```
DX11TextureCubeArray.cpp
```

**June 11, 2016.** Refactored the [Window](#) and [WindowSystem](#) classes into [WindowBase](#), which is independent of operating system; [MSWindow](#) and [MSWindowSystem](#), which are for dependent on the Microsoft Windows platform but are independent of graphics API, and platform-specific versions of [Window](#) and [WindowSystem](#). The [Application](#) folder now has subfolders that partition the files based on operating system and graphics API. This change is part of the incorporation of GLX support for Linux into GTEngine.

```
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
Include/GTApplications.h  
Include/GTWindows.h  
Include/Applications/WindowBase.h  
Include/Applications/Window{2,3}.h  
Include/Applications/MSW/MSWWindows.h  
Include/Applications/MSW/MSWWindowSystem.h  
Include/Applications/MSW/DX11/Window.h  
Include/Applications/MSW/DX11/WindowSystem.h  
Include/Applications/MSW/WGL/Window.h  
Include/Applications/MSW/WGL/WindowSystem.h  
Source/Applications/WindowBase.cpp  
Source/Applications/MSW/MSWWindows.cpp  
Source/Applications/MSW/MSWWindowSystem.cpp  
Source/Applications/MSW/DX11/Window.cpp  
Source/Applications/MSW/DX11/WindowSystem.cpp  
Source/Applications/MSW/WGL/Window.cpp  
Source/Applications/MSW/WGL/WindowSystem.cpp
```

Moved the Intel SSE code to a new subfolder because it is specific to Microsoft Windows.

```
GTMathematics.h  
Include/Mathematics/MSW/IntelSSE.h
```

Source/Mathematics/MSW/IntelSSE.cpp

Cygwin's Linux shell defines `WIN32`, which exposes blocks of GTEngine code that are not intended for Linux. Revised the logic of testing the macros for underlying operating system. Also, Cygwin's include of `glcorearb.h` occurs without turning off the annoying `min` and `max` macros of `Windows.h`. Turned them off inside `OpenGL.h` before the include of `glcorearb.h`.

GTEngineDEF.h  
OpenGL.h

An HLSL-dependent header file was included without conditional compilation for DX11 versus GL4. Moved it into a conditional compilation block, which led compiler complaints when `GTE_DEV_OPENGL` is defined and when the Cygwin min/max problem was not yet fixed. The Cygwin fixes eliminate the compiler complaints and the HLSL file is now protected. Also then had to include `GteLogger.h` that is used by `GteShader.h`. And finally, this broke a sample application that used both HLSL and GLSL related blocks of code, which is now fixed by conditional compilation.

Shader.h  
BlendedTerrainEffect.cpp

**June 5, 2016.** Created new folders GLX and WGL to store OpenGL code specific to platforms. Moved the WGL-specific files to the WGL folder.

GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GTGraphicsGL4.h  
WGLEngine.{h,cpp}  
WGLExtensions.cpp  
WindowSystem.cpp  
Samples/Basics/ShaderReflection/ShaderReflection.cpp

Factored out Microsoft-Windows-specific files and code to new folders. Added new macro `__MSWINDOWS__` that is enabled when `WIN32` or `_WIN64` is defined. This makes it clearer in the code when conditional compilation enables or disables OS-specific blocks of code.

GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GTPhysics.h  
OpenGL.{h,cpp}  
LogReporter.{h,cpp}  
Timer.h  
Wrapper.cpp  
LogToMessageBox.{h,cpp} (MSWindows-specific)  
LogToOutputWindow.{h,cpp} (MSWindows-specific)

TetrahedronKey.h  
Samples/Basics/AppendConsumeBuffer/AppendConsumeBuffers.cpp  
Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.cpp  
Samples/Basics/ShaderReflection/ShaderReflection.cpp  
Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp  
Samples/Graphics/Castle/CastleWindow.cpp  
Samples/Mathematics/PartialSums/PartialSums.cpp  
Samples/Mathematics/RootFinding/RootFinding.cpp  
Tools/GenerateOpenGLWrapper/GenerateOpenGLWrapper.cpp  
Tools/GenerateOpenGLWrapper/GteOpenGL.h  
Tools/GenerateProject/ProjectTemplate.{v12,v14}.cpp

Cygwin complained about the `-fPIC` option specified as a `CFLAGS` option. Removed it; Wild Magic 5 does not have it in `CFLAGS` either.

GTEngine/makefile.gte

**June 2, 2016.** Added a custom visualizer file for the `Vector` and `Matrix` classes. We will add more visualizers as needed.

gte.natvis

**June 1, 2016.** Revised the `VertexBuffer` interface to require the structured buffer to be passed to the constructor when rendering by vertex-id is desired. This is a convenient encapsulation that allows you to access the vertex data through the vertex buffer.

VertexBuffer.{h,cpp}  
DX11Engine.cpp  
GL4Engine.cpp  
Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.cpp  
Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp  
Samples/Physics/MassSprings3D/MassSprings3DWindow.cpp

**May 31, 2016.** A major revision of the document. The new version shows how to estimate vertex tangents and vertex normals for a parameterized mesh (or mesh with texture coordinates) at each vertex using the entire set of triangles that share the vertex. The algorithm is useful for constructing the vertex normals and tangents whose interpolated values are used in a pixel shader for tangent-space normal mapping.

MeshDifferentialGeometry.pdf (*Mesh Differential Geometry*)

The nonuniform Akima interpolation code needed to be ported along with the uniform interpolation code. The associated PDF had pseudocode that referenced Wild Magic 5 code, so it was modified for GTEngine (and tested with real code).

[IntpAkimaNonuniform1.h](#)  
[AkimaInterpolation.pdf](#) (*Akima Interpolation for Nonuniform 1D Data*)

**May 29, 2016.** The [Result](#) structure now returns parameters for the  $t$ -interval  $[0, 1]$  (the endpoint form of the segment) and for the  $s$ -interval  $[-e, e]$  (for the center-direction-extent form of the segment).

[IntrSegment2AlignedBox2.h](#)  
[IntrSegment2OrientedBox2.h](#)

## 68 Updates to Version 2.4

**May 25, 2016.** The find-intersection queries needed to translate its points of intersection back to the original coordinate system by adding the box center. The unit tests had only boxes with centers at the origin (updated these tests). Modified the [result.parameter](#) values to be  $t$ -values for the segment parameterization  $(1 - t)P_0 + tP_1$  for  $t \in [0, 1]$ . They had been relative to the center-direction-extent form which is computed internally in the queries,  $C + sD$ , where  $D$  is unit length and  $s \in [-\varepsilon, \varepsilon]$  with  $\varepsilon$  the extent.

[IntrSegment2AlignedBox2.h](#)  
[IntrSegment2OrientedBox2.h](#)

**May 24, 2016.** Removed the [LogWarning](#) from [Shader::Get](#) that returns a handle. It is reasonable for an application to use [Shader::Get](#) to determine whether a [Shader::Set](#) call will be successful for the specified resource name.

[Shader.cpp](#)

The test-intersection query for [Ray2](#) and [AlignedBox2](#) had an incorrect ordering of parameters in the [DoQuery](#) call.

[IntrRay2AlignedBox2.h](#)

**May 22, 2016.** Ported WM5 code for partitioning a convex polygon by a plane in 3D and made the code robust when the polygon is nearly parallel to the plane. Also ported test-intersection and find-intersection queries for triangles and oriented boxes in 3D. Added a sample application that serves as the test code.

[GTMathematics.h](#)  
[GteIntrConvexPolygonPlane.h](#)  
[GteIntrTriangle3OrientedBox3.h](#)  
[Samples/Geometrics/IntersectTriangleBox/IntersectTriangleBox.{v12,v14}.{sln,vcxproj,vcxproj.filters}](#)  
[Samples/Geometrics/IntersectTriangleBox/IntersectTriangleBoxWindow.{h,cpp}](#)

**May 18, 2016.** The `Window::SetTitle` declaration had the `inline` modifier, but the body was not inline, which hides the actual definition. Removed the modifier.

`Window.h`

**May 15, 2016.** Added an `Inverse` member function that returns the inverse of a `Transform` as another `Transform` object.

`Transform.{h,cpp}`

Modified the generated code to include the next version number.

`Tools/GenerateProject/ProjectTemplate.{v12,v14}.cpp`

Added function `HLift` to embed a  $3 \times 3$  matrix as the upper block of a  $4 \times 4$  matrix. Added `HProject` to extract a  $3 \times 3$  matrix from the upper block of a  $4 \times 4$  matrix.

`Matrix.h`

Removed redundant and unused code.

`Samples/Graphics/BumpMaps/BumpMapsWindow.cpp`

**May 13, 2016.** When a D3D11 texture is created that shares another texture, if the original texture has a staging texture associated with it, one must also be created for the newly sharing texture.

`DX11Texture2.cpp`

**May 11, 2016.** Changed a `LogError` to `LogWarning` regarding an invalid object type encountered during picking. An application might very well have such a class that should not participate in picking, so you can tailor the logging system not to launch a dialog box when these objects are encountered during picking.

`Picker.cpp`

Fixed some comments (removed reference to obsolete class member functions).

`CameraRig.h`

**May 5, 2016.** The [WICFileIO::Load](#) function had two places where it was returning [false](#) instead of [nullptr](#).

[WICFileIO.cpp](#)

**May 1, 2016.** New files that implement the QR algorithm for computing eigenvalues of unsymmetric matrices and for using the same algorithm for computing the roots of cubic and quartic polynomials.

[UnsymmetricEigenvalues.h](#)

[CubicRootsQR.h](#)

[QuarticRootsQR.h](#)

Fixed a compiler warning that now occurs with MSVS 2015 Update 2.

[Integration.h](#)

**April 29, 2016.** Reverted the changes to the buffer updating that was posted on April 1, 2016 for Version 2.3. The text drawing system of GTEngine appears not to work properly when the no-overwrite mode is used on different vendor graphics cards. If you need to update subbuffers, set up the buffer resource so that it is enabled for copies from CPU to GPU and use [CopyCpuToGpu](#) instead.

[DX11ConstantBuffer.cpp](#)

[DX11IndexBuffer.cpp](#)

[DX11IndirectArgumentsBuffer.cpp](#)

[DX11RawBuffer.cpp](#)

[DX11StructuredBuffer.cpp](#)

[DX11TextureBuffer.cpp](#)

[DX11VertexBuffer.cpp](#)

[DX11Buffer.cpp](#)

Instead of creating and destroying a query object on each call to [WaitForFinish](#), the query is now created in the first call and saved as a class member. That object is released on destruction.

[DX11Engine.{h,cpp}](#)

**April 27, 2016.** Added functions to copy GPU to GPU directly. Only the DX11Engine versions have been implemented (we need them at the moment). GL4Engine versions will be implemented later.

[GraphicsEngine.h](#)

[DX11Engine.{h,cpp}](#)

[DX11Resource.h](#)

[DX11Buffer.{h,cpp}](#)



DX11Texture.{h,cpp}  
GL4Engine.{h,cpp}  
GL4Resource.h  
GL4TextureSingle.h  
GL4TextureArray.h

Exposed the ability to flush the GPU command buffer in order for shared textures to be updated on one device when another device modifies the data. The new base class function is called `Flush()`.

GraphicsEngine.h  
DX11Engine.{h,cpp}  
GL4Engine.{h,cpp}  
Samples/Graphics/SharedTexturesD3D11/SharedTexturesWindow.cpp

**April 26, 2016.** Added `BindProgram` to allow explicit binding before the first call to a compute shader.

GraphicsEngine.h  
DX11Engine.{h,cpp}  
GL4Engine.{h,cpp}

**April 17, 2016.** Replace two occurrences of hard-coded `float` with template parameter `Real`.

ApprEllipseByArcs.h

Added new 2D intersection queries.

GTMathematics.h  
Sector2.h  
IntrDisk2Sector2.h  
IntrHalfspace2Polygon2.h  
IntrOrientedBox2Sector2.h

**April 16, 2016.** The `DestroyStorage` function is intended to free up the CPU memory for the resource, but `clear()` does not do this; the capacity remains the same. Added an additional call to `shrink_to_fit` to free up the memory. Replaced `&mStorage[0]` by `mStorage.data()`.

Resource.{h,cpp}

**April 13, 2016.** Ported the Wild Magic 5 code for approximating an axis-aligned ellipse by circular arcs. Ported and upgraded the sample application (that was only in Wild Magic 4) to illustrate the approximation. The PDF describing the algorithm had pseudocode and references to the Wild Magic 4 sample but did not

have pseudocode for the implementation of the algorithm. The PDF has been updated to eliminate the WM4 reference and to include an implementation. Added new functions to [ImageUtility2](#) and [Window2](#) to draw axis-aligned ellipses using a Bresenham-style algorithm.

```
GTBuildAll.{v12,v14}.sln
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
ImageUtility2.{h,cpp}
Windows.{h,cpp}
ApprEllipseByArcs.h
Samples/Mathematics/ApproximateEllipseByArcs/ApproximateEllipseByArcs.{v12,v14}.{vcxproj,vcxproj.filters,sln}
Samples/Mathematics/ApproximateEllipseByArcs/ApproximateEllipseByArcsWindow.{h,cpp}
ApproximateEllipse.pdf (Approximating an Ellipse by Circular Arcs)
```

**April 12, 2016.** Removed the [LogError](#) code when [Shader::Get](#) cannot find a resource by name. It is reasonable that an application might have a generic shader system for which a resource might be attached to some shaders but not to others, and [Shader::Get](#) is a way to determine this.

```
Shader.h
```

**April 10, 2016.** The wrong flag was tested in [WindowSystem::MessagePump](#) when the user requests no idle loop.

```
WindowSystem.h
```

## 69 Updates to Version 2.3

**March 12, 2016.** Ported the Wild Magic 5 sample application [MorphFaces](#).

```
GTBuildAll.{v12,v14}.sln
Samples/Graphics/MorphFaces/MorphFaces.{v12,v14}.{sln, vcxproj, vcxproj.filters}
Samples/Graphics/MorphFaces/MorphFaces.cpp
Samples/Graphics/MorphFaces/MorphFacesWindow.{h,cpp}
Samples/Graphics/MorphFaces/CubicInterpolator.h
Samples/Graphics/MorphFaces/Data/Eye.png
Samples/Graphics/MorphFaces/Data/LightColorSampler.txt
Samples/Graphics/MorphFaces/Data/SharedTexTri.txt
Samples/Graphics/MorphFaces/Data/M*.txt (25 morph targets)
```

**March 13, 2016.** Factored the WGL code out of [GL4Engine](#) into a new derived class [WGLEngine](#). This makes [GL4Engine](#) independent of the windowing system in preparation for adding GLX and Linux support.

WGLEngine.{h,cpp}  
 GL4Engine.{h,cpp}  
 WindowSystem.cpp  
 Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.cpp  
 Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.cpp  
 Samples/Basics/ShaderReflection/ShaderReflection.cpp  
 Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp  
 Samples/Mathematics/PartialSums/PartialSums.cpp  
 Samples/Mathematics/RootFinding/RootFinding.cpp

Removed unused functions from the public interface. Moved the message pump code from the `main` function in the applications into the `WindowSystem` class. This leads to an interface that is independent of operating system and windowing system in preparation for adding GLX and Linux support. Moved the `main` functions into the corresponding application window classes to reduce the number of files to maintain.

WindowSystem.h  
 Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.vcxproj.filters  
 Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.cpp  
 Samples/Geometrics/AllPairsTriangles/AllPairsTriangles.cpp  
 Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow.vcxproj.filters  
 Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow.cpp  
 Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunay2D.cpp  
 Samples/Geometrics/ConvexHull2D/ConvexHull2DWindow.vcxproj.filters  
 Samples/Geometrics/ConvexHull2D/ConvexHull2DWindow.cpp  
 Samples/Geometrics/ConvexHull2D/ConvexHull2D.cpp  
 Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow.vcxproj.filters  
 Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow.cpp  
 Samples/Geometrics/ConvexHull3D/ConvexHull3D.cpp  
 Samples/Geometrics/Delaunay2D/Delaunay2DWindow.vcxproj.filters  
 Samples/Geometrics/Delaunay2D/Delaunay2DWindow.cpp  
 Samples/Geometrics/Delaunay2D/Delaunay2D.cpp  
 Samples/Geometrics/Delaunay3D/Delaunay3DWindow.vcxproj.filters  
 Samples/Geometrics/Delaunay3D/Delaunay3DWindow.cpp  
 Samples/Geometrics/Delaunay3D/Delaunay3D.cpp  
 Samples/Geometrics/IntersectBoxCone/IntersectBoxConeWindow.vcxproj.filters  
 Samples/Geometrics/IntersectBoxCone/IntersectBoxConeWindow.cpp  
 Samples/Geometrics/IntersectBoxCone/IntersectBoxCone.cpp  
 Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasisWindow.vcxproj.filters  
 Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasisWindow.cpp  
 Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasis.cpp  
 Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.vcxproj.filters  
 Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.cpp  
 Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2D.cpp  
 Samples/Geometrics/MinimumAreaCircle2D/MinimumAreaCircle2DWindow.vcxproj.filters  
 Samples/Geometrics/MinimumAreaCircle2D/MinimumAreaCircle2DWindow.cpp  
 Samples/Geometrics/MinimumAreaCircle2D/MinimumAreaCircle2D.cpp  
 Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.vcxproj.filters

Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp  
 Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3D.cpp  
 Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3DWindow.vcxproj.filters  
 Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3DWindow.cpp  
 Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3D.cpp  
 Samples/Geometrics/ShortestPath/ShortestPathWindow.vcxproj.filters  
 Samples/Geometrics/ShortestPath/ShortestPathWindow.cpp  
 Samples/Geometrics/ShortestPath/ShortestPath.cpp  
 Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow.vcxproj.filters  
 Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow.cpp  
 Samples/Geometrics/TriangulationCDT/TriangulationCDT.cpp  
 Samples/Geometrics/TriangulationEC/TriangulationECWindow.vcxproj.filters  
 Samples/Geometrics/TriangulationEC/TriangulationECWindow.cpp  
 Samples/Geometrics/TriangulationEC/TriangulationEC.cpp  
 Samples/Geometrics/VertexCollapseMesh/VertexCollapseMeshWindow.vcxproj.filters  
 Samples/Geometrics/VertexCollapseMesh/VertexCollapseMeshWindow.cpp  
 Samples/Geometrics/VertexCollapseMesh/VertexCollapseMesh.cpp  
 Samples/Graphics/AreaLights/AreaLightsWindow.vcxproj.filters  
 Samples/Graphics/AreaLights/AreaLightsWindow.cpp  
 Samples/Graphics/AreaLights/AreaLights.cpp  
 Samples/Graphics/BillboardNodes/BillboardNodesWindow.vcxproj.filters  
 Samples/Graphics/BillboardNodes/BillboardNodesWindow.cpp  
 Samples/Graphics/BillboardNodes/BillboardNodes.cpp  
 Samples/Graphics/BlendedAnimations/BlendedAnimationsWindow.vcxproj.filters  
 Samples/Graphics/BlendedAnimations/BlendedAnimationsWindow.cpp  
 Samples/Graphics/BlendedAnimations/BlendedAnimations.cpp  
 Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.vcxproj.filters  
 Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp  
 Samples/Graphics/BlendedTerrain/BlendedTerrain.cpp  
 Samples/Graphics/BlownGlass/BlownGlassWindow.vcxproj.filters  
 Samples/Graphics/BlownGlass/BlownGlassWindow.cpp  
 Samples/Graphics/BlownGlass/BlownGlass.cpp  
 Samples/Graphics/BspNodes/BspNodesWindow.vcxproj.filters  
 Samples/Graphics/BspNodes/BspNodesWindow.cpp  
 Samples/Graphics/BspNodes/BspNodes.cpp  
 Samples/Graphics/BumpMaps/BumpMapsWindow.vcxproj.filters  
 Samples/Graphics/BumpMaps/BumpMapsWindow.cpp  
 Samples/Graphics/BumpMaps/BumpMaps.cpp  
 Samples/Graphics/CameraAndLightNodes/CameraAndLightNodesWindow.vcxproj.filters  
 Samples/Graphics/CameraAndLightNodes/CameraAndLightNodesWindow.cpp  
 Samples/Graphics/CameraAndLightNodes/CameraAndLightNodes.cpp  
 Samples/Graphics/Castle/CastleWindow.vcxproj.filters  
 Samples/Graphics/Castle/CastleWindow.cpp  
 Samples/Graphics/Castle/Castle.cpp  
 Samples/Graphics/CubeMaps/CubeMapsWindow.vcxproj.filters  
 Samples/Graphics/CubeMaps/CubeMapsWindow.cpp  
 Samples/Graphics/CubeMaps/CubeMaps.cpp  
 Samples/Graphics/GeometryShaders/GeometryShadersWindow.vcxproj.filters

Samples/Graphics/GeometryShaders/GeometryShadersWindow.cpp  
 Samples/Graphics/GeometryShaders/GeometryShaders.cpp  
 Samples/Graphics/GlossMaps/GlossMapsWindow.vcxproj.filters  
 Samples/Graphics/GlossMaps/GlossMapsWindow.cpp  
 Samples/Graphics/GlossMaps/GlossMaps.cpp  
 Samples/Graphics/Lights/LightsWindow.vcxproj.filters  
 Samples/Graphics/Lights/LightsWindow.cpp  
 Samples/Graphics/Lights/Lights.cpp  
 Samples/Graphics/LightTexture/LightTextureWindow.vcxproj.filters  
 Samples/Graphics/LightTexture/LightTextureWindow.cpp  
 Samples/Graphics/LightTexture/LightTexture.cpp  
 Samples/Graphics/MorphFaces/MorphFacesWindow.vcxproj.filters  
 Samples/Graphics/MorphFaces/MorphFacesWindow.cpp  
 Samples/Graphics/MorphFaces/MorphFaces.cpp  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.vcxproj.filters  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargets.cpp  
 Samples/Graphics/Picking/PickingWindow.vcxproj.filters  
 Samples/Graphics/Picking/PickingWindow.cpp  
 Samples/Graphics/Picking/Picking.cpp  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersectionWindow.vcxproj.filters  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersectionWindow.cpp  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersection.cpp  
 Samples/Graphics/ProjectedTextures/ProjectedTexturesWindow.vcxproj.filters  
 Samples/Graphics/ProjectedTextures/ProjectedTexturesWindow.cpp  
 Samples/Graphics/ProjectedTextures/ProjectedTextures.cpp  
 Samples/Graphics/SphereMaps/SphereMapsWindow.vcxproj.filters  
 Samples/Graphics/SphereMaps/SphereMapsWindow.cpp  
 Samples/Graphics/SphereMaps/SphereMaps.cpp  
 Samples/Graphics/StructuredBuffers/StructuredBuffersWindow.vcxproj.filters  
 Samples/Graphics/StructuredBuffers/StructuredBuffersWindow.cpp  
 Samples/Graphics/StructuredBuffers/StructuredBuffers.cpp  
 Samples/Graphics/TextureArrays/TextureArraysWindow.vcxproj.filters  
 Samples/Graphics/TextureArrays/TextureArraysWindow.cpp  
 Samples/Graphics/TextureArrays/TextureArrays.cpp  
 Samples/Graphics/TextureUpdating/TextureUpdatingWindow.vcxproj.filters  
 Samples/Graphics/TextureUpdating/TextureUpdatingWindow.cpp  
 Samples/Graphics/TextureUpdating/TextureUpdating.cpp  
 Samples/Graphics/Texturing/TexturingWindow.vcxproj.filters  
 Samples/Graphics/Texturing/TexturingWindow.cpp  
 Samples/Graphics/Texturing/Texturing.cpp  
 Samples/Graphics/VertexColoring/VertexColoringWindow.vcxproj.filters  
 Samples/Graphics/VertexColoring/VertexColoringWindow.cpp  
 Samples/Graphics/VertexColoring/VertexColoring.cpp  
 Samples/Graphics/VertexTextures/VertexTexturesWindow.vcxproj.filters  
 Samples/Graphics/VertexTextures/VertexTexturesWindow.cpp  
 Samples/Graphics/VertexTextures/VertexTextures.cpp  
 Samples/Graphics/WireMesh/WireMeshWindow.vcxproj.filters

Samples/Graphics/WireMesh/WireMeshWindow.cpp  
 Samples/Graphics/WireMesh/WireMesh.cpp  
 Samples/Imagics/Convolution/ConvolutionWindow.vcxproj.filters  
 Samples/Imagics/Convolution/ConvolutionWindow.cpp  
 Samples/Imagics/Convolution/Convolution.cpp  
 Samples/Imagics/GaussianBlurring/GaussianBlurringWindow.vcxproj.filters  
 Samples/Imagics/GaussianBlurring/GaussianBlurringWindow.cpp  
 Samples/Imagics/GaussianBlurring/GaussianBlurring.cpp  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.vcxproj.filters  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.cpp  
 Samples/Imagics/MedianFiltering/MedianFiltering.cpp  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.vcxproj.filters  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp  
 Samples/Imagics/SurfaceExtraction/SurfaceExtraction.cpp  
 Samples/Imagics/VideoStreams/VideoStreamsWindow.vcxproj.filters  
 Samples/Imagics/VideoStreams/VideoStreamsWindow.cpp  
 Samples/Imagics/VideoStreams/VideoStreams.cpp  
 Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.vcxproj.filters  
 Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.cpp  
 Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitter.cpp  
 Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.vcxproj.filters  
 Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.cpp  
 Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitter.cpp  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.vcxproj.filters  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVs.cpp  
 Samples/Mathematics/Interpolation2D/Interpolation2DWindow.vcxproj.filters  
 Samples/Mathematics/Interpolation2D/Interpolation2DWindow.cpp  
 Samples/Mathematics/Interpolation2D/Interpolation2D.cpp  
 Samples/Mathematics/PlaneEstimation/PlaneEstimationWindow.vcxproj.filters  
 Samples/Mathematics/PlaneEstimation/PlaneEstimationWindow.cpp  
 Samples/Mathematics/PlaneEstimation/PlaneEstimation.cpp  
 Samples/Physics/BallHill/BallHillWindow.vcxproj.filters  
 Samples/Physics/BallHill/BallHillWindow.cpp  
 Samples/Physics/BallHill/BallHill.cpp  
 Samples/Physics/BallRubberBand/BallRubberBandWindow.vcxproj.filters  
 Samples/Physics/BallRubberBand/BallRubberBandWindow.cpp  
 Samples/Physics/BallRubberBand/BallRubberBand.cpp  
 Samples/Physics/BouncingBall/BouncingBallWindow.vcxproj.filters  
 Samples/Physics/BouncingBall/BouncingBallWindow.cpp  
 Samples/Physics/BouncingBall/BouncingBall.cpp  
 Samples/Physics/Cloth/ClothWindow.vcxproj.filters  
 Samples/Physics/Cloth/ClothWindow.cpp  
 Samples/Physics/Cloth/Cloth.cpp  
 Samples/Physics/DoublePendulum/DoublePendulumWindow.vcxproj.filters  
 Samples/Physics/DoublePendulum/DoublePendulumWindow.cpp  
 Samples/Physics/DoublePendulum/DoublePendulum.cpp  
 Samples/Physics/ExtremalQuery/ExtremalQueryWindow.vcxproj.filters

Samples/Physics/ExtremalQuery/ExtremalQueryWindow.cpp  
 Samples/Physics/ExtremalQuery/ExtremalQuery.cpp  
 Samples/Physics/Fluids2D/Fluids2DWindow.vcxproj.filters  
 Samples/Physics/Fluids2D/Fluids2DWindow.cpp  
 Samples/Physics/Fluids2D/Fluids2D.cpp  
 Samples/Physics/Fluids3D/Fluids3DWindow.vcxproj.filters  
 Samples/Physics/Fluids3D/Fluids3DWindow.cpp  
 Samples/Physics/Fluids3D/Fluids3D.cpp  
 Samples/Physics/IntersectingBoxes/IntersectingBoxesWindow.vcxproj.filters  
 Samples/Physics/IntersectingBoxes/IntersectingBoxesWindow.cpp  
 Samples/Physics/IntersectingBoxes/IntersectingBoxes.cpp  
 Samples/Physics/IntersectingRectangles/IntersectingRectanglesWindow.vcxproj.filters  
 Samples/Physics/IntersectingRectangles/IntersectingRectanglesWindow.cpp  
 Samples/Physics/IntersectingRectangles/IntersectingRectangles.cpp  
 Samples/Physics/KeplerPolarForm/KeplerPolarFormWindow.vcxproj.filters  
 Samples/Physics/KeplerPolarForm/KeplerPolarFormWindow.cpp  
 Samples/Physics/KeplerPolarForm/KeplerPolarForm.cpp  
 Samples/Physics/MassSprings3D/MassSprings3DWindow.vcxproj.filters  
 Samples/Physics/MassSprings3D/MassSprings3DWindow.cpp  
 Samples/Physics/MassSprings3D/MassSprings3D.cpp  
 Samples/Physics/Rope/RopeWindow.vcxproj.filters  
 Samples/Physics/Rope/RopeWindow.cpp  
 Samples/Physics/Rope/Rope.cpp  
 Tools/GenerateProject/ProjectTemplate.{v12,v14}.{h,cpp}

Ported the Wild Magic 5 sample application [FlowingSkirt](#).

GTBuildAll.{v12,v14}.sln  
 Samples/Physics/FlowingSkirt/FlowingSkirt.{v12,v14}.{sln, vcxproj, vcxproj.filters}  
 Samples/Physics/FlowingSkirt/FlowingSkirtWindow.{h,cpp}

**March 14, 2016.** Fixed the PDF link in the comments at the beginning of the header file.

[ConvertCoordinates.h](#)

**March 17, 2016.** Fixed several bugs in the test-intersection query for a line segment and a bounding sphere. The replacement code now matches the discussion in *3D Game Engine Design (2nd edition)*, Section 15.4.3. The first bug was the computation of [segExtent](#), which works when [tmin](#) is zero. For positive [tmin](#), the segment extent is instead  $(t_{\max} - t_{\min})/2$ . The second bug was that there must be a test  $a_0 \leq 0$  immediately after the computation of  $a_0$  (the book mentions this). The third bug was that the final block of code does not match the discussion in the book (and is incorrect); the book description is correct.

[BoundingSphere.cpp](#)



Removed the debugCounter test code. Moved the inline body of `Vertex::operator<` to the end of the file where the other inline functions are implemented (for consistent coding practice).

`MinimalCycleBasis.h`

**March 23, 2016.** Of all the OpenGL buffer classes, only `GL4VertexBuffer` and `GL4IndexBuffer` were calling `glDeleteBuffers` to free up the resource handles. Added a destructor to `GL4Buffer` to call `glDeleteBuffers` and removed the destructors from the derived classes.

`GL4Buffer.{h,cpp}`  
`GL4VertexBuffer.{h,cpp}`  
`GL4IndexBuffer.{h,cpp}`

**March 28, 2016.** The `Update`, `CopyCpuToGpu`, and `CopyGpuToCpu` for `DX11Buffer` and `GL4Buffer` had bugs when the buffer had a positive offset. The various functions and data types involved require values set in terms of number of bytes when the resource is a buffer. Added a new sample application to demonstrate how to update only a portion of a buffer.

`DX11Buffer.cpp`  
`GL4Buffer.cpp`  
`GTBuildAll.{v12,v14}.sln`  
`Samples/Graphics/BufferUpdating/BufferUpdating.{v12,v14}.{sln, vcxproj, vcxproj.filters}`  
`Samples/Graphics/BufferUpdating/BufferUpdating.{h,cpp}`

**April 1, 2016.** Dynamic constant buffers in Direct3D 11.0 cannot be mapped using `D3D11_MAP_WRITE_NO_OVERWRITE`, but they can in Direct 3D 11.1. The MSDN web page for `D3D11_MAP` has a note about this and suggests how to test whether no-overwrite may be used by calling `CheckFeatureSupport` on the device with feature `D3D11_FEATURE_D3D11_OPTIONS`. Unfortunately, the documentation for `D3D11_FEATURE_D3D11_OPTIONS` states that this option may only be used for Direct3D 11.1 and later. This mechanism fails on an NVIDIA Quadro K2200 (driver 362.13 and previous). A call to the device `GetFeatureLevel` returns `D3D_FEATURE_LEVEL_11_0` but a call to `CheckFeatureSupport` shows that `MapNoOverwriteOnDynamicConstantBuffer` is 1 (so no-overwrite is supposed to be allowed). Unfortunately, this appears to cause problems in rendering. Worse is that our text rendering (`TextEffect`) uses dynamic vertex buffers and has strange behavior when using no-overwrite. All text renders correctly with the discard mode. For now, we have added a member `DX11Buffer::mUpdateMapMode` whose default value is `D3D11_MAP_WRITE_DISCARD` but is set to `D3D11_MAP_WRITE_NO_OVERWRITE` when the feature level is found to be `D3D_FEATURE_LEVEL_11_1` or later.

`DX11Buffer.{h,cpp}`  
`DX11ConstantBuffer.cpp`  
`DX11IndexBuffer.cpp`  
`DX11IndirectArgumentsBuffer.cpp`  
`DX11RawBuffer.cpp`  
`DX11StructuredBuffer.cpp`



DX11TextureBuffer.cpp  
DX11VertexBuffer.cpp

**April 2, 2016.** Updated the cycle-basis algorithm based on the revised discussion in the PDF.

MinimalCycleBasis.h  
Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasisWindow.{vcxproj,vcxproj.filters}  
Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasisWindow.{h,cpp}  
Samples/Geometrics/MinimalCycleBasis/Data/SimpleGraph{0,1,2,3,4,5}.txt

## 70 Updates to Version 2.2

**January 30, 2016.** Delete the sample application [Samples/Basics/PerformanceAMD](#) and the associated tools folder [Tools/GPUPerfAPI-2.11.739.0](#).

**January 31, 2016.** Replaced type [int](#) by [int32\\_t](#) for consistent notation in the class.

GteUIntegerALU32.h

Added a tool to illustrate the use of [BSPrecision](#). Currently, it computes the N-values for the primal queries which determine the N-values for construction of convex hulls and Delaunay triangulations. Updated the N-values for computing with [BSNumber](#) or [BSRational](#).

GTBuildAll.{v12,v14}.sln  
Tools/Imagics/PrecisionCalculator/PrecisionCalculator.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Tools/PrecisionCalculator/PrecisionCalculator.cpp  
GtePrimalQuery{2,3}.h  
GteConvexHull{2,3}.h  
GteDelaunayHull{2,3}.h

Moved an assertion inside the [GTE\\_DEV\\_OPENGL](#) block.

Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp

Removed the [Convert](#) functions. C++ 11 already supports iterated-based copying between objects of type [std::string](#) and [std::wstring](#).

Environment.{h,cpp}  
LogToMessageBox.cpp  
LogToOutputWindow.cpp

Replaced raw `new` and `delete` calls by vector, shared pointer, or unique pointer wrappers. Replaced the application layer engine and factory objects with shared pointers of the base-class types. This supports refactoring the DX11 and OpenGL graphics engine into separate projects.

```
Environment.{h,cpp}  
WICFileIO.cpp  
DX11Engine.cpp  
HLSLProgramFactory.cpp  
GL4Engine.cpp  
IndexBuffer.h  
Window.{h,cpp}  
Window3.cpp  
WindowSystem.cpp  
LogReporter.{h,cpp} AmbientLightEffect.{h,cpp}  
ConstantColorEffect.{h,cpp}  
DirectionalLightEffect.{h,cpp}  
DirectionalLightTextureEffect.{h,cpp}  
Font.{h,cpp}  
FontArialW400H18.{h,cpp}  
LightingEffect.{h,cpp}  
OverlayEffect.{h,cpp}  
PlanarReflectionEffect.{h,cpp}  
PointLightEffect.{h,cpp}  
PointLightTextureEffect.{h,cpp}  
SpotLightEffect.{h,cpp}  
TextEffect.{h,cpp}  
Texture2Effect.{h,cpp}  
Texture3Effect.{h,cpp}  
VertexColorEffect.{h,cpp}  
MeshFactory.cpp  
ComputeModel.h  
GenerateMeshUV.h  
Fluid{2,3}.{h,cpp}  
Fluid{2,3}AdjustVelocity.{h,cpp}  
Fluid{2,3}ComputeDivergence.{h,cpp}  
Fluid{2,3}EnforceStateBoundary.{h,cpp}  
Fluid{2,3}InitializeSource.{h,cpp}  
Fluid{2,3}InitializeState.{h,cpp}  
Fluid{2,3}SolvePoisson.{h,cpp}  
Fluid{2,3}UpdateState.{h,cpp}  
Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.cpp  
Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow.cpp  
Samples/Geometrics/Delaunay3D/Delaunay3DWindow.cpp  
Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp  
Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp  
Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3D.cpp  
Samples/Geometrics/ShortestPath/ShortestPathWindow.cpp  
Samples/Geometrics/ShortestPath/GpuShortestPath.{h,cpp}
```

Samples/Geometrics/VertexCollapseMesh/VertexCollapseMeshWindow.cpp  
 Samples/Graphics/BlendedAnimations/BipedManager.{h,cpp}  
 Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.{h,cpp}  
 Samples/Graphics/BlownGlass/BlownGlassWindow.cpp  
 Samples/Graphics/BumpMaps/SimpleBumpMapEffect.{h,cpp}  
 Samples/Graphics/CubeMaps/CubeMapEffect.{h,cpp}  
 Samples/Graphics/GeometryShaders/GeometryShadersWindow.cpp  
 Samples/Graphics/GlossMaps/GlossMapEffect.{h,cpp}  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp  
 Samples/Graphics/Picking/PickingWindow.cpp  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersectionWindow.cpp  
 Samples/Graphics/ProjectedTextures/ProjectedTextureEffect.{h,cpp}  
 Samples/Graphics/SphereMaps/SphereMapEffect.{h,cpp}  
 Samples/Graphics/StructuredBuffers/StructuredBuffersWindow.cpp  
 Samples/Graphics/TextureArrays/TextureArraysWindow.cpp  
 Samples/Graphics/VertexTextures/DisplacementEffect.{h,cpp}  
 Samples/Graphics/WireMesh/WireMeshWindow.cpp  
 Samples/Imagics/Convolution/ConvolutionWindow.cpp  
 Samples/Imagics/GaussianBlurring/GaussianBlurringWindow.cpp  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.cpp  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp  
 Samples/Imagics/VideoStreams/FileVideoStream.{h,cpp}  
 Samples/Imagics/VideoStreams/VideoStream.{h,cpp}  
 Samples/Imagics/VideoStreams/VideoStreamsWindow.cpp  
 Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.cpp  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp  
 Samples/Mathematics/PlaneEstimation/PlaneEstimationWindow.cpp  
 Samples/Physics/Cloth/ClothWindow.cpp  
 Samples/Physics/Fluids2D/Fluids2DWindow.cpp  
 Samples/Physics/Fluids3D/Fluids3DWindow.cpp  
 Samples/Physics/MassSprings3D/MassSprings3DWindow.cpp  
 Samples/Physics/MassSprings3D/GpuMassSpringVolume.{h,cpp}  
 Samples/Physics/Rope/RopeWindow.cpp  
 Tools/GenerateOpenGLWrapper/Initialize.txt  
 Tools/GenerateOpenGLWrapper/Version.txt  
 OpenGL.cpp

Window creation and destruction now involve shared pointers rather than raw pointers.

Window.h  
 Samples/Geometrics/AllPairsTriangles/AllPairsTriangles.cpp  
 Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunay2D.cpp  
 Samples/Geometrics/ConvexHull2D/ConvexHull2D.cpp  
 Samples/Geometrics/ConvexHull3D/ConvexHull3D.cpp  
 Samples/Geometrics/Delaunay2D/Delaunay2D.cpp  
 Samples/Geometrics/Delaunay3D/Delaunay3D.cpp  
 Samples/Geometrics/IntersectBoxCone/IntersectBoxCone.cpp

Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2D.cpp  
Samples/Geometrics/MinimumAreaCircle2D/MinimumAreaCircle2D.cpp  
Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3D.cpp  
Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3D.cpp  
Samples/Geometrics/ShortestPath/ShortestPath.cpp  
Samples/Geometrics/TriangulationCDT/TriangulationCDT.cpp  
Samples/Geometrics/TriangulationEC/TriangulationEC.cpp  
Samples/Geometrics/VertexCollapseMesh/VertexCollapseMesh.cpp  
Samples/Graphics/BillboardNodes/BillboardNodes.cpp  
Samples/Graphics/BlendedAnimations/BlendedAnimations.cpp  
Samples/Graphics/BlendedTerrain/BlendedTerrain.cpp  
Samples/Graphics/BrownGlass/BrownGlass.cpp  
Samples/Graphics/BspNodes/BspNodes.cpp  
Samples/Graphics/BumpMaps/BumpMaps.cpp  
Samples/Graphics/CameraAndLightNodes/CameraAndLightNodes.cpp  
Samples/Graphics/Castle/Castle.cpp  
Samples/Graphics/CubeMaps/CubeMaps.cpp  
Samples/Graphics/GeometryShaders/GeometryShaders.cpp  
Samples/Graphics/GlossMaps/GlossMaps.cpp  
Samples/Graphics/Lights/Lights.cpp  
Samples/Graphics/LightTexture/LightTexture.cpp  
Samples/Graphics/MultipleRenderTargets/MultipleRenderTargets.cpp  
Samples/Graphics/Picking/Picking.cpp  
Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersection.cpp  
Samples/Graphics/ProjectedTextures/ProjectedTextures.cpp  
Samples/Graphics/SharedTextures/SharedTextures.cpp  
Samples/Graphics/SharedTextures/SharedTexturesWindow.cpp  
Samples/Graphics/SphereMaps/SphereMaps.cpp  
Samples/Graphics/StructuredBuffers/StructuredBuffers.cpp  
Samples/Graphics/TextureArrays/TextureArrays.cpp  
Samples/Graphics/TextureUpdating/TextureUpdating.cpp  
Samples/Graphics/Texturing/Texturing.cpp  
Samples/Graphics/VertexColoring/VertexColoring.cpp  
Samples/Graphics/VertexTextures/VertexTextures.cpp  
Samples/Graphics/WireMesh/WireMesh.cpp  
Samples/Imagics/Convolution/Convolution.cpp  
Samples/Imagics/GaussianBlurring/GaussianBlurring.cpp  
Samples/Imagics/MedianFiltering/MedianFiltering.cpp  
Samples/Imagics/SurfaceExtraction/SurfaceExtraction.cpp  
Samples/Imagics/VideoStreams/VideoStreams.cpp  
Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitter.cpp  
Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitter.cpp  
Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVs.cpp  
Samples/Mathematics/Interpolation2D/Interpolation2D.cpp  
Samples/Mathematics/PlaneEstimation/PlaneEstimation.cpp  
Samples/Physics/BallHill/BallHill.cpp  
Samples/Physics/BallRubberBand/BallRubberBand.cpp  
Samples/Physics/BouncingBall/BouncingBall.cpp

Samples/Physics/Cloth/Cloth.cpp  
 Samples/Physics/DoublePendulum/DoublePendulum.cpp  
 Samples/Physics/ExtremalQuery/ExtremalQuery.cpp  
 Samples/Physics/Fluids2D/Fluids2D.cpp  
 Samples/Physics/Fluids3D/Fluids3D.cpp  
 Samples/Physics/IntersectingBoxes/IntersectingBoxes.cpp  
 Samples/Physics/IntersectingRectangles/IntersectingRectangles.cpp  
 Samples/Physics/KeplerPolarForm/KeplerPolarForm.cpp  
 Samples/Physics/MassSprings3D/MassSprings3D.cpp  
 Samples/Physics/Rope/Rope.cpp  
 Tools/GenerateProject/ProjectTemplate.{v12,v14}.cpp

**February 1, 2016.** Renamed `Array2` to `LexicoArray2`. To avoid the raw `new` and `delete` calls in the memory management functions of `GteMemory.h`, those functions have been converted to classes (to have state). The new classes are `Array2`, `Array3`, and `Array4`.

LexicoArray2.h  
 Array2.h (the old file)  
 BandedMatrix.h  
 GaussianElimination.h  
 LinearSystem.h  
 Array2.h (the new file)  
 Array3.h  
 Array4.h

Replaced raw `new` and `delete` calls by vector, shared pointer, or unique pointer wrappers, or by `Array2`, `Array3`, or `Array4`. Removed the old memory management.

GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
 Memory.h  
 GTLowLevel.h  
 Histogram.{h,cpp}  
 ApprPolynomial{2,3,4}.h  
 BasisFunction.h  
 BezierCurve.h  
 BSplineCurveFit.h  
 BSplineSurfaceFit.h  
 GaussianElimination.h  
 IntpVectorField2.h  
 IntpSphere2.h  
 IntpAkimaUniform{2,3}.h  
 KeyframeController.{h,cpp}  
 SkinController.{h,cpp}  
 Samples/Graphics/BlendedAnimations/BipedManager.cpp  
 Samples/Graphics/SharedTexturesD3D11/SharedTexturesWindow.{h,cpp}

```

Samples/Imagics/VideoStreams/VideoStreamManager.{h,cpp}
Samples/Imagics/VideoStreams/VideoStreamsWindow.{h,cpp}
Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.{h,cpp}
Samples/Mathematics/Interpolation2D/Interpolation2DWindow.cpp
Samples/Physics/Cloth/ClothWindow.cpp
Samples/Physics/Rope/RopeWindow.cpp
Tools/BitmapFontCreator/BitmapFontCreator.cpp

```

**February 2, 2016.** The class `Image2` was used to provide a 2-dimensional wrapper around the `Weights` texture using the data-pointer-sharing mechanism of `Image`. Replaced this by `Array2` so that we can remove the sharing mechanism in `Image` to simplify the semantics of the class. (The sample application is the only consumer of `Image` sharing mechanism.)

```

Samples/Geometrics/ShortestPath/ShortestPathWindow.h
Samples/Geometrics/ShortestPath/CpuShortestPath.{h,cpp}

```

The `Image` classes had a lot of infrastructure for metadata and for accessing image values using the syntax `myImage2[]` and `myImage3[][]`. The infrastructure was added in support of some specific applications not part of the source code distribution. The infrastructure has been removed and the classes greatly simplified. File I/O was removed so that `PixelType` is no longer required to be plain-old-data (POD). If you need to load and save data, you can roll your own depending on the nature of `PixelType`.

```

Histogram.{h,cpp}
GTImagics.h
Image.h
Image2.h
Image3.h
Image.cpp
Image1.h

```

Removed unused header file (for `GMatrix`).

```

MinimumAreaCircle2.h

```

**February 3, 2016.** Replaced raw `new` and `delete` calls by vector, shared pointer, or unique pointer wrappers.

```

ImageUtility{2,3}.{h,cpp}
Samples/Graphics/BlendedAnimations/BipedManager.{h,cpp}

```

Fixed memory/object leak in the controller system. The `ControlledObject` class needed to own the `Controller` objects in the list. Also, clarified comments about why `std::weak_ptr` cannot be used to avoid reference-count cycles when the scene graph is created internally rather than by an external manager (internally, we do not know the owning shared pointer objects from which we can generate weak pointers).

```
ControlledObject.{h,cpp}  
Controller.{h,cpp}  
Spatial.{h,cpp}
```

The bone array now uses `std::weak_ptr<Node>` rather than `Node*` to avoid the reference-count cycles in the scene graph.

```
SkinController.{h,cpp}
```

Removed the dynamic deletion code in `TriangulateEC` and `TriangulateCDT`, replaced the `Polygon` by a typedef to `std::vector`, and added a constructor that takes a `std::vector` of points. This is part of the work to remove raw new and delete calls from the engine.

```
TriangulateEC.h  
TriangulateCDT.h  
Samples/Geometrics/TriangulationEC/TriangulationECWindow.{h,cpp}  
Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow.cpp
```

**February 4, 2016.** Removed the raw new and delete calls in the manifold mesh classes, replacing them with `std::shared_ptr` and `std::weak_ptr` wrappers.

```
Delaunay{2,3}.h  
ETManifoldMesh.{h,cpp}  
ExtremalQuery3BSP.h  
GenerateMeshUV.h  
MinimumVolumeBox3.h  
PlanarMesh.h  
TSManifoldMesh.{h,cpp}  
VEManifoldMesh.{h,cpp}  
VETManifoldMesh.{h,cpp}  
VertexCollapseMesh.h
```

Modified `WICFileIO` to use `std::shared_ptr` rather than raw new and delete calls.

```
WICFileIO.{h,cpp}  
Samples/Graphics/BillboardNodes/BillboardNodesWindow.cpp  
Samples/Graphics/BlendedAnimations/BipedManager.cpp  
Samples/Graphics/BlendedAnimations/BlendedAnimationsWindow.cpp  
Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp  
Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.cpp  
Samples/Graphics/BspNodes/BspNodesWindow.cpp  
Samples/Graphics/BumpMaps/BumpMapsWindow.cpp
```

Samples/Graphics/BumpMaps/SimpleBumpMapEffect.cpp  
 Samples/Graphics/CameraAndLightNodes/CameraAndLightNodesWindow.cpp  
 Samples/Graphics/Castle/CastleWindow.cpp  
 Samples/Graphics/CubeMaps/CubeMapsWindow.cpp  
 Samples/Graphics/GeometryShaders/GeometryShadersWindow.cpp  
 Samples/Graphics/GlossMaps/GlossMapsWindow.cpp  
 Samples/Graphics/LightTexture/LightTextureWindow.cpp  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp  
 Samples/Graphics/Picking/PickingWindow.cpp  
 Samples/Graphics/ProjectedTextures/ProjectedTexturesWindow.cpp  
 Samples/Graphics/SphereMaps/SphereMapsWindow.cpp  
 Samples/Graphics/StructuredBuffers/StructuredBuffersWindow.cpp  
 Samples/Graphics/TextureArrays/TextureArraysWindow.cpp  
 Samples/Graphics/Texturing/TexturingWindow.cpp  
 Samples/Graphics/VertexColoring/VertexColoringWindow.cpp  
 Samples/Graphics/VertexTextures/VertexTexturesWindow.cpp  
 Samples/Imagics/Convolution/ConvolutionWindow.cpp  
 Samples/Imagics/GaussianBlurring/GaussianBlurringWindow.cpp  
 Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.cpp  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp  
 Samples/Mathematics/Interpolation2D/Interpolation2DWindow.cpp  
 Samples/Physics/BallHill/BallHillWindow.cpp  
 Samples/Physics/BouncingBall/BouncingBallWindow.cpp  
 Samples/Physics/Cloth/ClothWindow.cpp  
 Samples/Physics/Fluids2D/Fluids2DWindow.cpp  
 Samples/Physics/Rope/RopeWindow.cpp

Modified the graphics engine code to eliminate raw new and delete calls.

GraphicsEngine.{h,cpp}  
 DX11BlendState.{h,cpp}  
 DX11ComputeShader.{h,cpp}  
 DX11ConstantBuffer.{h,cpp}  
 DX11DepthStencilState.{h,cpp}  
 DX11DrawTarget.{h,cpp}  
 DX11Engine.cpp  
 DX11GeometryShader.{h,cpp}  
 DX11GraphicsObject.h  
 DX11IndexBuffer.{h,cpp}  
 DX11IndirectArgumentsBuffer.{h,cpp}  
 DX11InputLayoutManager.{h,cpp}  
 DX11PixelShader.{h,cpp}  
 DX11RasterizerState.{h,cpp}  
 DX11RawBuffer.{h,cpp}  
 DX11SamplerState.{h,cpp}  
 DX11StructuredBuffer.{h,cpp}  
 DX11Texture1.{h,cpp}



```

DX11Texture1Array.{h,cpp}
DX11Texture2.{h,cpp}
DX11Texture2Array.{h,cpp}
DX11Texture3.{h,cpp}
DX11TextureBuffer.{h,cpp}
DX11TextureCube.{h,cpp}
DX11TextureCubeArray.{h,cpp}
DX11TextureDS.{h,cpp}
DX11TextureRT.{h,cpp}
DX11VertexBuffer.{h,cpp}
DX11VertexShader.{h,cpp}
GL4AtomicCounterBuffer.{h,cpp}
GL4BlendState.{h,cpp}
GL4ConstantBuffer.{h,cpp}
GL4DepthStencilState.{h,cpp}
GL4DrawTarget.{h,cpp}
GL4Engine.cpp
GL4IndexBuffer.{h,cpp}
GL4InputLayoutManager.{h,cpp}
GL4RasterizerState.{h,cpp}
GL4SamplerState.{h,cpp}
GL4StructuredBuffer.{h,cpp}
GL4Texture1.{h,cpp}
GL4Texture1Array.{h,cpp}
GL4Texture2.{h,cpp}
GL4Texture2Array.{h,cpp}
GL4Texture3.{h,cpp}
GL4TextureCube.{h,cpp}
GL4TextureCubeArray.{h,cpp}
GL4TextureDS.{h,cpp}
GL4TextureRT.{h,cpp}
GL4VertexBuffer.{h,cpp}

```

Modified projects so that DX11 and GL4 are mutually exclusive, even though it is possible to create both types of engines in an application.

```

GTEngine.{v12,v14}.vcxproj
ComputeShader.{h,cpp}
GeometryShader.{h,cpp}
PixelShader.{h,cpp}
VertexShader.{h,cpp}
Shader.{h,cpp}

```

**February 6, 2016.** Fixed a typographical error in a preprocessor macro used in the creation of a perspective projection matrix.

[Matrix4x4.h](#)

**February 8, 2016.** Removed an unused header file.

[MinHeap.h](#)

**February 16, 2016.** The interval intersection query results needed to be propagated to the query results for ray-circle and segment-circle.

[IntrRay2Circle2.h](#)

[IntrSegment2Circle2.h](#)

**February 25, 2016.** Removed unnecessary include of [array](#).

[UniqueVerticesTriangle.h](#)

**February 26, 2016.** [Window3::OnResize](#) need to return [true](#) in its conditional statement.

[Window3.cpp](#)

**February 27, 2016.** Added missing cases when the intersection of two co-circular arcs contains two disjoint components (two arcs, one arc and one point, or two points). Added internal unit tests for 100 % code coverage and verification of correctness.

[IntrArc2Arc2.h](#)

**March 1, 2016.** The specular term was incorrectly coded in [GetShaderSourceLitFunctionGLSL](#).

[LightingEffect.cpp](#)

New sample application to illustrate area lights.

[GTBuildAll.{v12,v14}.sln](#)

[Samples/Graphics/AreaLights/AreaLights.{v12,v14}.{sln,vcxproj,vcxproj.filters}](#)

[Samples/Graphics/AreaLights/AreaLights.cpp](#)

[Samples/Graphics/AreaLights/AreaLightsWindow.{h,cpp}](#)

[Samples/Graphics/AreaLights/AreaLightEffect.{h,cpp}](#)

[Samples/Graphics/AreaLights/Shaders/AreaLight.hlsl](#)

[Samples/Graphics/AreaLights/Shaders/AreaLight{VS,PS}.glsl](#)

**March 2, 2016.** The port of the find-intersection query from Wild Magic was missing the assignment of the circle radius and circle plane-normal when there is a circle of intersection.

[IntrPlane3Sphere3.h](#)

**March 4, 2016.** The first-order derivative in the  $w$ -variable was computed incorrectly because inputs [vOrder](#) and [wOrder](#) were swapped.

[NURBSVolume.h](#)

**March 6, 2016.** Removed the obsolete include of the [GteEnvironment](#) header.

[GteLogToOutputWindow.cpp](#)

[GteLogToMessageBox.cpp](#)

Fixed compile errors when precompiled headers are turned off.

[GTEnginePCH.h](#)

[WindowSystem.cpp](#)

[DX11Engine.cpp](#)

[GL4DrawTarget.cpp](#)

[GL4Engine.cpp](#)

[GL4SamplerState.cpp](#)

[GL4StructuredBuffer.cpp](#)

[GL4TextureArray.cpp](#)

[GL4TextureDS.cpp](#)

[GL4TextureRT.cpp](#)

[GL4TextureSingle.cpp](#)

[GLSLReflection.cpp](#)

[Fluid{2,3}AdjustVelocity.cpp](#)

[Fluid{2,3}ComputeDivergence.cpp](#)

[Fluid{2,3}EnforceStateBoundary.cpp](#)

[Fluid{2,3}InitializeSource.cpp](#)

[Fluid{2,3}InitializeState.cpp](#)

[Fluid{2,3}SolvePoisson.cpp](#)

[Fluid{2,3}UpdateState.cpp](#)

Ported the Wild Magic 5 sample for computing cycle bases. The original code was flawed, so this sample includes a major rewrite of the algorithm and documentation. The code has had significant testing.

[GteIsPlanarGraph.h](#)

[GteMinimalCycleBasis.h](#)

GTBuildAll.{v12,v14}.sln  
GTMathematics.h  
Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasis.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasis.cpp  
Samples/Geometrics/MinimalCycleBasis/MinimalCycleBasis.{h,cpp}  
Documentation/MinimalCycleBasis.pdf  
MinimalCycleBasis.pdf (*Constructing a Cycle Basis for a Planar Graph*)

## 71 Updates to Version 2.1

**January 26, 2016.** Added a workaround for an apparent OpenGL bug in the Intel HD 4600 graphics drivers. Frequently, shader storage blocks that are used in shaders are reported as unreferenced by the shaders. The workaround is effectively to parse the shader source code and determine whether in fact the storage block is referenced. (A bug report has been filed with Intel.)

GLSLReflection.{h,cpp}

Modified the shaders to link correctly when using Intel HD 4600 OpenGL 4.3. Moved the shaders to a subfolder, the pattern used in other sample applications.

Samples/Basics/ShaderReflection/Shaders/  
Samples/Basics/ShaderReflection/Billboards{VS,GS,PS}.glsl

Removed an orphan reference to a file (GteDistLine3Cylinder3.h) in the projects. The reference was causing the projects to think they were out-of-date even though they were not.

GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}

The `noperspective` tag for `edgeDistance` in the geometry shader was not also used in the pixel shader. NVIDIA and AMD drivers are fine with this, because the pixel shader is called after the interpolation has occurred. The Intel HD OpenGL 4.3 complained during linking that it could not match `edgeDistance` between the geometry and pixel shaders without both matching exactly in all attributes.

Samples/Graphics/WireMesh/Shaders/WireMeshPS.glsl

**January 30, 2016.** Added a preprocessor wrapper around the include of `GTEngine.h` so that you can disable the precompile header system. Without precompiled headers, the compilation of the engine and samples is extremely slow. However, until the GTEngine projects are decomposed into smaller libraries, enabling precompiled headers leads to all source code compiled (on Win32 machines) including DX11 graphics code, OpenGL graphics code (if enabled), and the application layer.

GTEnginePCH.h

## 72 Updates to Version 2.0

**September 27, 2015.** Ported BallHill physics sample from WM5 to GTE2.

GTBuildAll.v12.sln  
GTBuildAll.v14.sln  
Samples/Physics/BallHill/BallHill.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Physics/BallHill/BallHill.cpp  
Samples/Physics/BallHill/BallHillWindow.{h,cpp}  
Samples/Physics/BallHill/PhysicsModule.{h,cpp}

**September 28, 2015.** Added [Window2](#) to share code among 2D windowed applications. Various projects were modified accordingly. Added [WaitMessage](#) calls to the message pump to allow the thread to be suspended until messages are actually received.

Window2.{h,cpp}  
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GTApplications.h  
Samples/Geometries/ConstrainedDelaunay2D/ConstrainedDelaunay2D.cpp  
Samples/Geometries/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow.{h,cpp}  
Samples/Geometries/ConvexHull2D/ConvexHull2D.cpp  
Samples/Geometries/ConvexHull2D/ConvexHull2DWindow.{h,cpp}  
Samples/Geometries/Delaunay2D/Delaunay2D.cpp  
Samples/Geometries/Delaunay2D/Delaunay2DWindow.{h,cpp}  
Samples/Geometries/MinimumAreaBox2D/MinimumAreaBox2D.cpp  
Samples/Geometries/MinimumAreaBox2D/MinimumAreaBox2DWindow.{h,cpp}  
Samples/Geometries/MinimumAreaCircle2D/MinimumAreaCircle2D.cpp  
Samples/Geometries/MinimumAreaCircle2D/MinimumAreaCircle2DWindow.{h,cpp}  
Samples/Geometries/TriangulationCDT/TriangulationCDT.cpp  
Samples/Geometries/TriangulationCDT/TriangulationCDTWindow.{h,cpp}  
Samples/Geometries/TriangulationEC/TriangulationEC.cpp  
Samples/Geometries/TriangulationEC/TriangulationECWindow.{h,cpp}

Removed some white space and added C++ keyword [override](#) to virtual functions.

Window3.{h,cpp}

Moved HLSL files to the shader folders of the project (Visual Studio bug that allows you add HLSL files to a folder, but when you save the project those files show up outside the folder).

```
Samples/Basics/ShaderReflection/ShaderReflection.v14.vcxproj.filters
Samples/Geometries/AllPairsTriangles/AllPairsTriangles.v14.vcxproj.filters
Samples/Geometries/ShortestPath/ShortestPath.v14.vcxproj.filters
Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersection.v14.vcxproj.filters
Samples/Imagics/Convolution/Convolution.v14.vcxproj.filters
Samples/Imagics/MedianFiltering/MedianFiltering.v14.vcxproj.filters
Samples/Mathematics/PlaneEstimation/PlaneEstimation.v14.vcxproj.filters
Samples/Physics/MassSprings3D/MassSprings3D.v14.vcxproj.filters
```

**September 29, 2015.** Ported BallRubberBand physics sample from WM5 to GTE2. Added test for [Window2](#) to GTVerify and fixed header issues exposed when precompiled headers are turned off.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/BallRubberBand/BallHill.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/BallRubberBand/BallRubberBand.cpp
Samples/Physics/BallRubberBand/BallRubberBandWindow.{h,cpp}
Samples/Physics/BallRubberBand/PhysicsModule.{h,cpp}
```

**September 30, 2015.** Ported BeadSlide physics sample from WM5 to GTE2.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/BallSlide/BallSlide.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/BallSlide/BallSlide.cpp
Samples/Physics/BallSlide/PhysicsModule.{h,cpp}
```

**October 8, 2015.** Replaced [VisibleSet](#) by a [std::vector](#) container. Added more variations of [DX11Engine::Draw](#) to support native [Visual](#) pointers. Modified the [DX11Engine::CreateDevice](#) to loop over each allowable feature level, searching for a feature level that the adapter supports. This avoids the special-case behavior when DX11.1 is requested and the device does not support it.

```
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
DX11Engine.{h,cpp}
Culler.{h,cpp}
Samples/Graphics/BillboardNodes/BillboardNodesWindow.cpp
Samples/Graphics/BspNodes/BspNodesWindow.cpp
Samples/Graphics/Castle/CastleWindow.cpp
VisibleSet.{h,cpp}
```

Updated Marching Cubes algorithm to be more efficient. Ported BouncingBall physics sample from WM5 to GTE2.

```
GTBuildAll.{v12,v14}.sln
MarchingCubes.{h,cpp}
```

```
SurfaceExtractor.h
UniqueVerticesTriangles.h
Samples/Data/Floor.png
Samples/Data/Wall1.png
Samples/Physics/BouncingBall/BouncingBall.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/BouncingBall/BouncingBall.cpp
Samples/Physics/BouncingBall/BouncingBallWindow.{h,cpp}
Samples/Physics/BouncingBall/DeformableBall.{h,cpp}
```

Encountered a custom OpenGL implementation for which `glGetIntegerv` does not set the major and minor versions to zero. The version numbers need to be initialized before the calls.

```
Tools/GenerateOpenGLWrapper/Version.txt
```

**October 11, 2015.** Added function `GetGTEPath` to encapsulate the common code used in sample applications to query for the `GTE_PATH` environment variable.

```
Windows.{h,cpp}
```

Factored out the pvw-matrix updating system from `CameraRig` to a separate class `PVWUpdater`. The camera rig is a convenience for sample applications but the pvw-updater is a more general concept that can be used in applications written by others.

```
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
GTGraphics.h
CameraRig.{h,cpp}
Windows3.{h,cpp}
PVWUpdater.{h,cpp}
```

A large number of sample applications were modified to use the last two changes. Also, added `override` modifiers to the derived-class virtual functions.

**October 17, 2015.** Modified the signature of the `Draw` functions to remove `const` modifiers on the `Visual` objects.

```
DX11Engine.{h,cpp}
GL4Engine.{h,cpp}
```

Added functions to construct projection and reflection matrices.

```
Matrix4x4.h
```

Ported a global effect from Wild Magic 5, [PlanarReflectionEffect](#), and added it to the [BouncingBall](#) sample physics application just like WM5 had.

```
PlanarReflectionEffect.{h,cpp}  
GTGraphics.h  
Samples/Physics/BouncingBall/BouncingBallWindow.{h,cpp}
```

**October 18, 2015.** Ported [LCPSolver](#), [LCPPolyDist](#), and [BouncingSpheres](#) from Wild Magic 5 to GTEngine2.

```
GTBuildAll.{v12,v14}.sln  
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GTPhysics.h  
LCPSolver.{h,cpp}  
LCPPolyDist.h  
Samples/Physics/BouncingSpheres/BouncingSpheres.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Physics/BouncingSpheres/BouncingSpheres.cpp  
Samples/Physics/BouncingSpheres/BouncingSpheresWindow.{h,cpp}  
Samples/Physics/BouncingSpheres/RigidBall.{h,cpp}
```

**October 20, 2015.** Ported [IntersectingRectangles](#) from Wild Magic 5 to GTEngine2.

```
GTBuildAll.{v12,v14}.sln  
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GTPhysics.h  
RectangleManager.h  
Samples/Physics/IntersectingRectangles/IntersectingRectangles.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Physics/IntersectingRectangles/IntersectingRectangles.cpp  
Samples/Physics/IntersectingRectangles/IntersectingRectanglesWindow.{h,cpp}
```

Added get/set support for  $3 \times 3$  rotation matrices.

```
Transform.{h,cpp}
```

**October 21, 2015.** Specifying `std::ios::in` — `std::ios::binary` for `std::ifstream` objects of `std::ios::out` — `std::ios::binary` for `std::ofstream` objects is not necessary. The modifier `std::ios::binary` is all that is necessary.

```
Image.cpp  
Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.cpp  
Samples/Graphics/BlendedAnimations/BipedManager.cpp  
Samples/Graphics/BlownGlass/BlownGlassWindow.cpp  
Samples/Imagics/VideoStreams/VideoStreamsWindow.cpp
```



Ported [IntersectingBoxes](#) from Wild Magic 5 to GTEngine2.

```
GTBuildAll.{v12,v14}.sln
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
GTPhysics.h
BoxManager.h
Samples/Physics/IntersectingBoxes/IntersectingBoxes.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/IntersectingBoxes/IntersectingBoxes.cpp
Samples/Physics/IntersectingBoxes/IntersectingBoxesWindow.{h,cpp}
```

**October 22, 2015.** Ported [DoublePendulum](#) from Wild Magic 5 to GTEngine2.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/DoublePendulum/DoublePendulum.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/DoublePendulum/DoublePendulum.cpp
Samples/Physics/DoublePendulum/DoublePendulumWindow.{h,cpp}
Samples/Physics/DoublePendulum/PhysicsModule.{h,cpp}
```

Ported [KeplerPolarForm](#) from Wild Magic 5 to GTEngine2.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/KeplerPolarForm/KeplerPolarForm.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/KeplerPolarForm/KeplerPolarForm.cpp
Samples/Physics/KeplerPolarForm/KeplerPolarFormWindow.{h,cpp}
Samples/Physics/KeplerPolarForm/PhysicsModule.{h,cpp}
```

**October 25, 2015.** Fixed comments, replaced [std::abs](#) by [fabs](#), and fixed validation code in constructor for number of indices required for polyhedron.

```
Polygon2.h
Polyhedron3.h
```

**November 1, 2015.** Added find-intersection query for oriented boxes in 2D.

```
IntrOrientedBox2OrientedBox2.h
```

**November 15, 2015.** Implemented a vertex-edge-triangle manifold mesh class [VETManifoldMesh](#) that derives from the edge-triangle [ETManifoldMesh](#) class. The new class provides adjacency information at each vertex of the mesh. This is a replacement for the hacked [BasicMesh](#) of Wild Magic 5.

```
VETManifoldMesh.{h,cpp}
ETManifoldMesh.{h,cpp}
```

```
GTMathematics.h
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
```

Ported the extremal queries for convex polyhedra and the extremal query sample from Wild Magic 5.

```
ExtremalQuery3.h
ExtremalQuery3BSP.h
ExtremalQuery3PRJ.h
GTPhysics.h
GTBuildAll.{v12,v14}.sln
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
Samples/Physics/ExtremalQuery/ExtremalQuery.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/ExtremalQuery/ExtremalQuery.cpp
Samples/Physics/ExtremalQuery/ExtremalQuery.{h,cpp}
```

Fixed a bug in `Environment::GetPath`. The read/write constants passed to `__access_s` were reversed.

```
Environment.cpp
```

Fixed a compile error when developing using OpenGL. The signature of the `Draw` function had been modified.

```
PlanarReflectionEffect.cpp
```

**November 18, 2015.** The classes were missing implementations of member accessors.

```
DX11TextureSingle.cpp
DX11TextureArray.cpp
```

Added subresource index support for texture arrays, texture cubes, and texture cube array.

```
TextureArray.h
TextureCubeArray.h
```

Added memory copy functions to `DX11Engine` for texture cubes.

```
DX11Engine.{h,cpp}
```

Fixed a bug in the shader reflection code. The texture cube objects were being classified as single textures but needed to be classified as texture arrays.

HLSLShaderFactory.cpp  
HLSLTexture.cpp  
HLSLTextureArray.cpp

**November 23, 2015.** New OpenGL code and corresponding modifications and/or fixes in the DX11 code.

GTBuildAll.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
DataFormat.h  
OverlayEffect.{h,cpp}  
Shader.{h,cpp}  
TextureArray.h  
TextEffect.cpp  
Texture2Effect.cpp  
TextureCube.cpp  
TextureCubeArray.cpp  
DX11Engine.{h,cpp}  
GTGraphicsGL4.h  
GL4Buffer.cpp  
GL4Engine.{h,cpp}  
GL4Resource.cpp  
GL4Texture.{h,cpp}  
GLSLProgramFactory.cpp  
GLSLReflection.cpp  
GL4SamplerState.{h,cpp}  
GL4Texture1.{h,cpp}  
GL4Texture1Array.{h,cpp}  
GL4Texture2.{h,cpp}  
GL4Texture2Array.{h,cpp}  
GL4Texture3.{h,cpp}  
GL4TextureArray.{h,cpp}  
GL4TextureCube.{h,cpp}  
GL4TextureCubeArray.{h,cpp}  
GL4TextureSingle.{h,cpp}

Ported **BillboardNodes** from DX11 to OpenGL.

Samples/Graphics/BillboardNodes/BillboardNodes.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/BillboardNodes/BillboardNodesWindow.cpp

Ported **BlendedTerrain** from DX11 to OpenGL.

Samples/Graphics/BlendedTerrain/BlendedTerrain.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.cpp  
Samples/Graphics/BlendedTerrain/Shaders/BlendedTerrain{Pixel,Vertex}.glsl

Ported [TextureArrays](#) from DX11 to OpenGL.

```
Samples/Graphics/TextureArrays/TextureArrays.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/TextureArrays/TextureArraysWindow.cpp  
Samples/Graphics/TextureArrays/Shader/TextureArrays{Pixel,Vertex}.glsl
```

Ported [Texturing](#) from DX11 to OpenGL.

```
Samples/Graphics/Texturing/Texturing.{v12,v14}.{sln,vcxproj,vcxproj.filters}
```

Ported [PlaneEstimation](#) from DX11 to OpenGL. The sample apparently works on an AMD Radeon 7970 but it is failing an OpenGL call on an NVIDIA Quadro K2200; it needs further work.

```
Samples/Mathematics/PlaneEstimation/PlaneEstimation.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Mathematics/PlaneEstimation/PlaneEstimationWindow.{h,cpp}  
Samples/Mathematics/PlaneEstimation/Shader/EvaluateBezier.glsl  
Samples/Mathematics/PlaneEstimation/Shader/PlaneEstimation.glsl  
Samples/Mathematics/PlaneEstimation/Shader/PlaneVisualize.glsl  
Samples/Mathematics/PlaneEstimation/Shader/PositionVisualize.glsl
```

Added a new sample [TextureUpdating](#).

```
Samples/Graphics/TextureUpdating/TextureUpdating.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/TextureUpdating/TextureUpdating.cpp  
Samples/Graphics/TextureUpdating/TextureUpdating.{h,cpp}
```

Added a new sample [CubeMap](#) that compiles and runs but is not working correctly; it needs further work.

```
Data/{Xm,Xp,Ym,Yp,Zm,Zp}Face.png  
Samples/Graphics/CubeMaps/CubeMaps.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/CubeMaps/CubeMaps.cpp  
Samples/Graphics/CubeMaps/CubeMapsWindow.{h,cpp}  
Samples/Graphics/CubeMaps/CubeMapEffect.{h,cpp}  
Samples/Graphics/CubeMaps/ReflectTexture.{h,cpp}
```

The [BouncingTetrahedra](#) sample compile and runs, but the LCP solver is not working correctly; it needs further work.

```
Samples/Physics/BouncingTetrahedra/BouncingTetrahedra.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Physics/BouncingTetrahedra/BouncingTetrahedra.cpp  
Samples/Physics/BouncingTetrahedra/BouncingTetrahedra.{h,cpp}  
Samples/Physics/BouncingTetrahedra/RigidTetra.{h,cpp}
```

**December 3, 2015.** Fixed a comment in the region-4 code. The closest point is V1, not V0.

`DistPointTriangleExact.h`

Added a new Boolean member `mDepthRangeZeroOne` to `ViewVolume`. The value is true when the depth range for the view volume is  $[0, 1]$ , which is the DirectX convention. The value is false when the depth range is  $[-1, 1]$ , which is the OpenGL convention. Modified `Camera` and `Light` constructors accordingly. Modified engine and sample applications that construct such objects.

`ViewVolume.{h,cpp}`  
`Camera.{h,cpp}`  
`Light.{h,cpp}`  
`Window3.cpp`  
`Sample/Graphics/CameraAndLightNodes/CameraAndLightNodesWindow.cpp`  
`Sample/Graphics/Castle/CastleWindow.cpp`  
`Sample/Physics/ExtremalQueryExtremalQueryWindow.cpp`

Microsoft Visual Studio 2015 Update 1 introduced a bug where a warning is generated for static class members of type `std::vector` that are initialized in the source file. The bug has been fixed for Update 2. Added Microsoft-specific code to disable the warning via the pragma system.

`Tools/GenerateProject/ProjectTemplate.{v12,v14}.cpp`  
`Sample/Graphics/Castle/CastleWindow.cpp`

**December 5, 2015.** DX11 does not allow texture cubes to be dynamically updated. Modified the usage flag to `D3D11.USAGE_DEFAULT`.

`GteDX11TextureCube.cpp`

Fixed a bug in the constructor for `Texture`. The level-zero offsets were all set to zero for texture arrays, which is incorrect for items with positive index.

`GteTexture.cpp`

Finished the port of the Wild Magic sample `CubeMaps`.

`GTBuildAll.{v12,v14}.sln`  
`Samples/Graphics/CubeMaps/CubeMaps.{v12,v14}.{sln,vcxproj,vcxproj.filters}`  
`Samples/Graphics/CubeMaps/CubeMapsWindow.{h,cpp}`  
`Samples/Graphics/CubeMaps/CubeMapEffect.{h,cpp}`  
`Samples/Graphics/CubeMaps/Shaders/CubeMap.hlsl`  
`Samples/Graphics/CubeMaps/ReflectTexture.{h,cpp}`

**December 6, 2015.** Ported the Wild Magic 5 sample [GlossMaps](#) to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Graphics/GlossMaps/GlossMaps.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/GlossMaps/GlossMapsWindow.{h,cpp}
Samples/Graphics/GlossMaps/GlossMapEffect.{h,cpp}
Samples/Graphics/GlossMaps/Shaders/GlossMap.hlsl
Samples/Data/Magic.png
```

**December 8, 2015.** Ported the Wild Magic 5 sample [ProjectedTextures](#) to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Graphics/ProjectedTextures/ProjectedTextures.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/ProjectedTextures/ProjectedTexturesWindow.{h,cpp}
Samples/Graphics/ProjectedTextures/ProjectedTextureEffect.{h,cpp}
Samples/Graphics/ProjectedTextures/Shaders/ProjectedTexture.hlsl
Samples/Data/Magician.png
```

**December 9, 2015.** Ported the Wild Magic 5 sample [SphereMaps](#) to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Graphics/SphereMaps/SphereMaps.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/SphereMaps/SphereMapsWindow.{h,cpp}
Samples/Graphics/SphereMaps/SphereMapEffect.{h,cpp}
Samples/Graphics/SphereMaps/Shaders/SphereMap.hlsl
Samples/Data/SphereMap.png
```

Ported the Wild Magic 5 sample [VertexTextures](#) to GTEngine.

```
GTBuildAll.{v12,v14}.sln
Samples/Graphics/VertexTextures/VertexTextures.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/VertexTextures/VertexTexturesWindow.{h,cpp}
Samples/Graphics/VertexTextures/DisplacementEffect.{h,cpp}
Samples/Graphics/VertexTextures/Shaders/Displacement.hlsl
Samples/Data/HeightField.png
```

**December 10, 2015.** Added support for cube maps and draw targets in OpenGL. Modified the GLSL reflection. Other code changes are based on adding support for OpenGL features.

```
GTBuildAll.{v12,v14}.sln
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}
GTGraphicsGL4.h
```

GL4Engine.{h,cpp}  
 GL4DrawTarget.{h,cpp}  
 GL4TextureRT.{h,cpp}  
 GL4TextureDS.{h,cpp}  
 GL4Texture.{h,cpp}  
 GL4Texture1.{h,cpp}  
 GL4Texture1Array.{h,cpp}  
 GL4Texture2.{h,cpp}  
 GL4Texture2Array.{h,cpp}  
 GL4Texture3.{h,cpp}  
 GL4TextureArray.{h,cpp}  
 GL4TextureCube.{h,cpp}  
 GL4TextureCubeArray.{h,cpp}  
 GL4TextureSingle.{h,cpp}  
 GLSLReflection.{h,cpp}  
 GLSLProgramFactory.cpp  
 DataFormat.cpp  
 OverlayEffect.cpp  
 Shader.cpp  
 TextEffect.cpp  
 Texture2Effect.cpp  
 Texture3Effect.cpp  
 VertexColorEffect.cpp  
 Fluid3AdjustVelocity.cpp  
 Fluid3ComputeDivergence.cpp  
 Fluid3EnforceStateBoundary.cpp  
 Fluid3InitializeSource.cpp  
 Fluid3InitializeState.cpp  
 Fluid3SolvePoisson.cpp  
 Fluid3UpdateState.cpp  
 Samples/Basics/ShaderReflection/ShaderReflection.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
 Samples/Basics/ShaderReflection/ShaderReflection.cpp  
 Samples/Basics/ShaderReflection/Billboards{GS,PS,VS}.glsl  
 Samples/Basics/ShaderReflection/SimpleBuffers.glsl  
 Samples/Basics/ShaderReflection/TextureArrays{PS,VS}.glsl  
 Samples/Basics/ShaderReflection/Texturing{PS,VS}.glsl  
 Samples/Basics/ShaderReflection/VertexColoring{PS,VS}.glsl  
 Samples/Graphics/BlendedTerrain/Shaders/BlendedTerrain{Pixel,Vertex}.glsl  
 Samples/Graphics/BlownGlass/BlownGlass.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
 Samples/Graphics/BlownGlass/BlownGlassWindows.{h,cpp}  
 Samples/Graphics/BlownGlass/Shaders/VolumeRender{PS,VS}.glsl  
 Samples/Graphics/CubeMaps/CubeMaps.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
 Samples/Graphics/CubeMaps/CubeMapsWindows.{h,cpp}  
 Samples/Graphics/CubeMaps/CubeMapsEffect.cpp  
 Samples/Graphics/CubeMaps/Shaders/CubeMap{PS,VS}.glsl  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargets.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargetsWindows.{h,cpp}  
 Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargets{Pixel,Vertex}.glsl

Samples/Graphics/MultipleRenderTargets/Shaders/MultipleRenderTargets.hlsl  
Samples/Graphics/TextureArrays/Shaders/TextureArraysVertex.glsl  
Samples/Mathematics/PlaneEstimation/Shaders/EvaluateBezier.glsl  
Samples/Mathematics/PlaneEstimation/Shaders/PlaneEstimation.glsl  
Samples/Physics/Rope/Rope.{v12,v14}.{sln,vcxproj}

Disabled the message-box logger to avoid the unexpected warnings reported by the OpenGL error system.

Samples/Graphics/CubeMaps/CubeMaps.cpp

Added GL4 configurations to the cloth sample.

Samples/Physics/Cloth/Cloth.{v12,v14}.{sln,vcxproj}

**December 13, 2015.** Added test for simple polygon and test for convex polygon.

Polygon2.h

Fixed a bug in `VETManifoldMesh` where the base-class vertex creator was called rather than the member-function override.

VETManifoldMesh.cpp

**December 14, 2015.** Got `BlendedAnimations` and `BumpMaps` to work using OpenGL.

GTBuildAll.{v12,v14}.sln  
Samples/Graphics/BlendedAnimations/BlendedAnimations.{v12,v14}.{sln,vcxproj}  
Samples/Graphics/BlendedAnimations/BlendedAnimationsWindow.{h,cpp}  
Samples/Graphics/BlendedAnimations/BipedManager.{h,cpp}  
Samples/Graphics/BumpMaps/BumpMaps.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/BumpMaps/SimpleBumpMapEffect.cpp  
Samples/Graphics/BumpMaps/Shaders/SimpleBumpMap{PS,VS}.glsl

**December 15, 2015.** Latest code changes and sample ports. In the engine, replaced an OpenGL 4.4 function call with functions that are supported in OpenGL 4.3. The blend state includes color and sample masks. These must be set regardless of whether blending is enabled. In the draw target, the binding needed to be for depth and stencil together.

GTBuildAll.{v12,v14}.sln  
LightingEffect.{h,cpp}



Texture.h  
 AmbientLightEffect.cpp  
 ConstantColorEffect.cpp  
 DirectionalLightEffect.cpp  
 DirectionalLightTextureEffect.cpp  
 PointLightEffect.cpp  
 PointLightTextureEffect.cpp  
 SpotLightEffect.cpp  
 GL4BlendState.cpp  
 GL4DrawTarget.cpp  
 GL4Engine.cpp  
 GLSLReflection.cpp  
 Samples/Basics/ShaderReflection/ShaderReflection.v12.{sln,vcxproj,vcxproj.filters}  
 Samples/Basics/ShaderReflection/ShaderReflection.v14.vcxproj.filters  
 Samples/Basics/ShaderReflection/NestedStruct.glsl  
 Samples/Graphics/BumpMaps/Shaders/SimpleBumpMapPS.glsl  
 Samples/Graphics/CameraAndLightNodes/CameraAndLightNodes.{v12,v14}.{sln,vcxproj}  
 Samples/Graphics/CameraAndLightNodes/CameraAndLightNodesWindow.cpp  
 Samples/Graphics/GeometryShaders/GeometryShaders.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
 Samples/Graphics/GeometryShaders/GeometryShadersWindow.cpp  
 Samples/Graphics/GeometryShaders/Shaders/RandomSquareDirect{GS,VS}.glsl  
 Samples/Graphics/GeometryShaders/Shaders/RandomSquareIndirect{GS,VS}.glsl  
 Samples/Graphics/GeometryShaders/Shaders/RandomSquaresPS.glsl  
 Samples/Graphics/GlossMaps/GlossMaps.{v12,v14}.{sln,vcxproj}  
 Samples/Graphics/GlossMaps/GlossMapsEffect.cpp  
 Samples/Graphics/Lights/Lights.{v12,v14}.{sln,vcxproj}  
 Samples/Graphics/LightTexture/LightTexture.{v12,v14}.{sln,vcxproj}  
 Samples/Graphics/MultipleRenderTargets/MultipleRenderTargets.v12.vcxproj  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersection.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersectionWindow.cpp  
 Samples/Graphics/PlaneMeshIntersection/Shaders/DrawIntersections.glsl  
 Samples/Graphics/PlaneMeshIntersection/Shaders/PlaneMeshIntersection{PS,VS}.glsl  
 Samples/Graphics/ProjectedTextures/ProjectedTextures.{v12,v14}.{sln,vcxproj}  
 Samples/Graphics/ProjectedTextures/ProjectedTextureEffect.cpp  
 Samples/Graphics/SphereMaps/SphereMaps.{v12,v14}.{sln,vcxproj}  
 Samples/Graphics/SphereMaps/SphereMapEffect.cpp  
 Samples/Graphics/VertexTextures/VertexTextures.{v12,v14}.{sln,vcxproj}  
 Samples/Graphics/VertexTextures/DisplacementEffect.cpp  
 Samples/Physics/BouncingSpheres/BouncingSpheres.{v12,v14}.{sln,vcxproj}

**December 18, 2015.** Added a filter for shader files and added the Gaussian blurring HLSL file to it.

Samples/Imagics/GaussianBlurring/GaussianBlurring.v14.{vcxproj,vcxproj.filters}

Latest OpenGL changes to support indirect vertex access and structured buffers.

Samples/Graphics/GeometryShaders/GeometryShadersWindows.cpp  
Samples/Graphics/GeometryShaders/Shaders/RandomSquaresDirect{GS,VS}.glsl  
Samples/Graphics/GeometryShaders/Shaders/RandomSquaresIndirect{GS,VS}.glsl  
Samples/Graphics/GeometryShaders/Shaders/RandomSquaresPS.glsl

**December 19, 2015.** The path to the \*.cso files depends on the compiler version.

Samples/Basics/LowLevelD3D11/Applications.cpp

**December 20, 2015.** Implemented a vertex-collapse algorithm for manifold meshes that preserves the manifold condition for each collapse. Added a sample application to illustrate its use. Fixed the memory leaks (of the vertex data structures) in [VETManifoldMesh](#).

GTBuildAll.{v12,v14}.sln  
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GTMathematics.h  
VertexCollapseMesh.h  
VETManifoldMesh.cpp  
Samples/Mathematics/VertexCollapseMesh/VertexCollapseMesh.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Mathematics/VertexCollapseMesh/VertexCollapseMeshWindow.{h,cpp}  
Samples/Mathematics/VertexCollapseMesh/VertexCollapseMesh.cpp

**December 22, 2015.** Added OpenGL support for structured buffers with atomic counters. Modified some samples to run using OpenGL.

GTBuildAll.{v12,v14}.sln  
GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}  
GTGraphicsGL4.h  
GL4AtomicCounterBuffer.{h,cpp}  
GL4Buffer.{h,cpp}  
GL4ConstantBuffer.{h,cpp}  
GL4Engine.{h,cpp}  
GL4IndexBuffer.cpp  
GL4StructuredBuffer.{h,cpp}  
GL4VertexBuffer.cpp  
GLSLReflection.{h,cpp}  
PlanarReflectionEffect.cpp  
MemberLayout.h  
Shader.{h,cpp}  
Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.cpp  
Samples/Basics/AppendConsumeBuffers/Shaders/AppendConsume.{glsl,hlsli}  
Samples/Basics/ShaderReflection/ShaderReflection.{v12,v14}.{vcxproj,vcxproj.filters}  
Samples/Basics/ShaderReflection/ShaderReflection.cpp

[Samples/Basics/ShaderReflection/AppendConsume.{gsl,h}](#)  
[Samples/Graphics/GeometryShaders/GeometryShadersWindow.{h,cpp}](#)  
[Samples/Graphics/GeometryShaders/Shaders/RandomSquaresIndirect{GS,VS}.gsl](#)  
[Samples/Graphics/StructuredBuffers/StructuredBuffers.{v12,v14}.{sln,vcxproj,vcxproj.filters}](#)  
[Samples/Graphics/StructuredBuffers/StructuredBuffersWindow.cpp](#)  
[Samples/Graphics/StructuredBuffers/Shaders/StructuredBuffers{PS,VS}.gsl](#)  
[Samples/Imagics/SurfaceExtraction/SurfaceExtraction.{v12,v14}.{sln,vcxproj,vcxproj.filters}](#)  
[Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.{h,cpp}](#)  
[Samples/Imagics/SurfaceExtraction/Shaders/DrawSurfaceIndirect{GS,PS,VS}.gsl](#)  
[Samples/Imagics/SurfaceExtraction/Shaders/ExtractSurface.gsl](#)  
[Samples/Imagics/SurfaceExtraction/Shaders/ExtractSurfaceIndirect.gsl](#)  
[Samples/Physics/BouncingBall/BouncingBall.{v12,v14}.{sln,vcxproj}](#)

**December 23, 2015.** Modified the vertex collapse function [DoCollapse](#) not to return when the collapse is deferred (the user does not care), instead just updating the min-heap and selecting another vertex to collapse. Removed the high-resolution mesh, keeping only the mesh built after collapses; the caller can store a copy of the high-resolution mesh if needed. Encapsulated the collapse results into a single structure.

[VertexCollapseMesh.h](#)  
[Samples/Mathematics/VertexCollapseMesh/VertexCollapseMeshWindow.{h,cpp}](#)

**December 26, 2015.** Added an include of [GTEngineDEF.h](#) to access the define for [GTE\\_IMPEXP](#).

[GLSLReflection.h](#)

Restructured the header includes and class forward declarations to make the graphics engine headers similar.

[DX11Engine.{h,cpp}](#)  
[GL4Engine.{h,cpp}](#)

**January 13, 2016.** Added abstract base classes to support polymorphic passing of the graphics engine and other objects to functions (engine is DX11 or GL4). This also supports refactoring the [DX11Engine](#) and [GL4Engine](#) classes.

[GraphicsEngine.{h,cpp}](#) [GEDrawTarget.{h,cpp}](#) [GEInputLayoutManager.h](#) [GEObject.{h,cpp}](#) [GTGraphics.h](#)  
(1)

Replaced a D3D11 enumeration by an integer constant so that the [Window::Parameters](#) initialization is not tied to D3D11 header files. Removed the reference to GTEngine1 in the window class name. Fixed some other parameters.

[Window.h](#)  
[WindowSystem.cpp](#)

Added `GetWindowClassName` member function.

`WindowSystem.h`

Changed the listeners for destruction from raw pointers to shared pointers.

`DrawTarget.{h,cpp}`  
`GraphicsObjects.{h,cpp}`

The z-parameter of the clip position for 2D drawing needs to be  $-1$  for OpenGL, not  $0$  as for Direct3D.

`OverlayEffect.cpp`  
`TextEffect.cpp`

Major refactoring to avoid explicit derived-class engine names in resource creation. Moved various members to inline status.

`DX11*.h,cpp`  
`GL4*.h,cpp`  
`GLSL*.h,cpp`

Added DebugGL4 and ReleaseGL4 configurations to projects.

`GTBuildAll.{v12,v14}.sln`  
`GTEngine.{v12,v14}.{vcxproj,vcxproj.filters}`  
`Samples/Geometries/ConstrainedDelaunay2D/ConstrainedDelaunay2D.{sln,vcxproj}`  
`Samples/Geometries/ConvexHull2D/ConvexHull2D.{sln,vcxproj}`  
`Samples/Geometries/ConvexHull3D/ConvexHull3D.{sln,vcxproj}`  
`Samples/Geometries/Delaunay2D/Delaunay2D.{sln,vcxproj}`  
`Samples/Geometries/Delaunay3D/Delaunay3D.{sln,vcxproj}`  
`Samples/Geometries/IntersectBoxCone/IntersectBoxCone.{sln,vcxproj}`  
`Samples/Geometries/MinimumAreaBox2D/MinimumAreaBox2D.{sln,vcxproj}`  
`Samples/Geometries/MinimumAreaCircle2D/MinimumAreaCircle2D.{sln,vcxproj}`  
`Samples/Geometries/MinimumVolumeBox3D/MinimumVolumeBox3D.{sln,vcxproj}`  
`Samples/Geometries/MinimumVolumeSphere3D/MinimumVolumeSphere3D.{sln,vcxproj}`  
`Samples/Geometries/ShortestPath/ShortestPath.{sln,vcxproj}`  
`Samples/Geometries/TriangulationCDT/TriangulationCDT.{sln,vcxproj}`  
`Samples/Geometries/TriangulationEC/TriangulationEC.{sln,vcxproj}`  
`Samples/Graphics/BspNodes/BspNodes.{sln,vcxproj}`  
`Samples/Graphics/Castle/Castle.{sln,vcxproj}`  
`Samples/Graphics/Picking/Picking.{sln,vcxproj}`  
`Samples/Graphics/VideoStreams/VideoStreams.{sln,vcxproj}`

Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitter.{sln,vcxproj}  
 Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitter.{sln,vcxproj}  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVs.{sln,vcxproj}  
 Samples/Mathematics/Interpolation2D/Interpolation2D.{sln,vcxproj}  
 Samples/Mathematics/SymmetricEigensolver3x3/SymmetricEigensolver3x3.{sln,vcxproj}  
 Samples/Physics/BallHill/BallHill.{sln,vcxproj}  
 Samples/Physics/BallRubberBand/BallRubberBand.{sln,vcxproj}  
 Samples/Physics/BeadSlide/BeadSlide.{sln,vcxproj}  
 Samples/Physics/BouncingTetrahedra/BouncingTetrahedra.{sln,vcxproj,vcxproj.filters}  
 Samples/Physics/DoublePendulum/DoublePendulum.{sln,vcxproj}  
 Samples/Physics/ExtremalQuery/ExtremalQuery.{sln,vcxproj}  
 Samples/Physics/IntersectingBoxes/IntersectingBoxes.{sln,vcxproj}  
 Samples/Physics/IntersectingRectangles/IntersectingRectangles.{sln,vcxproj}  
 Samples/Physics/KeplerPolarForm/KeplerPolarForm.{sln,vcxproj}

The GL4-based code used a [Window](#)-based application to create an OpenGL engine. Rewrote the application to use the new GL4 constructor that hides the backing window for the device, making the code similar to that for DX11.

Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.cpp

The engine [Execute](#) function that took a [ComputeShader](#) input has been removed, so the application code needed to be updated accordingly to use the [Execute](#) function that takes a [ComputeProgram](#) input.

GenerateMeshUV.h  
 Fluid2AdjustVelocity.cpp  
 Fluid2ComputeDivergence.cpp  
 Fluid2EnforceStateBoundary.cpp  
 Fluid2InitializeSource.cpp  
 Fluid2InitializeState.cpp  
 Fluid2SolvePoisson.cpp  
 Fluid2UpdateState.cpp  
 Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.cpp  
 Samples/Basics/RawBuffers/RawBuffers.cpp  
 Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.cpp  
 Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp  
 Samples/Geometrics/ShortestPath/ShortestPathWindow.cpp  
 Samples/Geometrics/ShortestPath/GpuShortestPath.cpp  
 Samples/Imagics/Convolution/ConvolutionWindow.cpp  
 Samples/Imagics/GaussianBlurring/GaussianBlurringWindow.cpp  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.{h,cpp}  
 Samples/Mathematics/PartialSums/PartialSums.cpp  
 Samples/Mathematics/RootFinding/RootFinding.cpp  
 Samples/Physics/MassSprings3D/GpuMassSpringVolume.cpp

The text `Draw` function now takes a color that is `std::array<float,4>` rather than `Vector4<float>`.

```
Samples/Geometrics/ConvexHull3D/ConvexHull3D.cpp
Samples/Graphics/BlendedAnimations/BlendedAnimationsWindow.cpp
Samples/Graphics/Castle/CastleWindow.cpp
Samples/Graphics/Lights/LightsWindow.cpp
Samples/Graphics/LightTexture/LightTextureWindow.cpp
Samples/Imagics/Convolution/ConvolutionWindow.cpp
Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp
Samples/Imagics/VideoStreams/VideoStreamsWindow.cpp
Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.cpp
Samples/Physics/BouncingBall/BouncingBallWindow.cpp
Samples/Physics/BouncingSpheres/BouncingSpheresWindow.cpp
```

Replaced the `DX11Engine*` parameter by the base class `GraphicsEngine`.

```
Samples/Geometrics/ShortestPath/GpuShortestPath.{h,cpp}
Samples/Imagics/VideoStreams/FileVideoStream.{h,cpp}
Samples/Imagics/VideoStreams/VideoStream.{h,cpp}
```

The application was missing a line of code that indicates the 2D screen needs to be updated in video memory.

```
Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow.cpp
```

Removed the conditional compilation on engine type to use the generic base class `GraphicsEngine`.

```
PlanarReflectionEffect.{h,cpp}
```

**January 17, 2016.** Implemented the GLSL shaders for the sample application. Modified some application code to handle the problem with GLSL wanting to pad `vec3` arrays in the shaders as if they had `vec4` elements.

```
GTBuildAll.{v12,v14}.sln
Samples/Physics/MassSprings3D/MassSprings3D.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/MassSprings3D/Shaders/RungeKutta.hlsl
Samples/Physics/MassSprings3D/MassSprings3DWindow.cpp
Samples/Physics/MassSprings3D/GpuMasSpringVolume.{h,cpp}
Samples/Physics/MassSprings3D/Shaders/DrawUsingVertexID{VS,PS}.glsl
Samples/Physics/MassSprings3D/Shaders/RungeKutta*.glsl
```

Implemented the GLSL shaders for the sample application. Modified the application code as needed.

```

Fluid2.{h,cpp}
Fluid2AdjustVelocity.{h,cpp}
Fluid2ComputeDivergence.{h,cpp}
Fluid2EnforceStateBoundary.{h,cpp}
Fluid2InitializeSource.{h,cpp}
Fluid2InitializeState.{h,cpp}
Fluid2SolvePoisson.{h,cpp}
Fluid2UpdateState.{h,cpp}
GTBuildAll.{v12,v14}.sln
Samples/Physics/Fluids2D/Fluids2D.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/Fluids2D/Fluids2DWindow.cpp
Samples/Physics/Fluids2D/Shaders/DrawDensity.glsl

```

Implemented the GLSL shaders for the sample application. Modified the application code as needed.

```

Fluid3.{h,cpp}
Fluid3AdjustVelocity.{h,cpp}
Fluid3ComputeDivergence.{h,cpp}
Fluid3EnforceStateBoundary.{h,cpp}
Fluid3InitializeSource.{h,cpp}
Fluid3InitializeState.{h,cpp}
Fluid3SolvePoisson.{h,cpp}
Fluid3UpdateState.{h,cpp}
GTBuildAll.{v12,v14}.sln
Samples/Physics/Fluids3D/Fluids3D.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Physics/Fluids3D/Fluids3DWindow.cpp
Samples/Physics/Fluids3D/Shaders/VolumeRender{VS,PS}.glsl

```

Implemented the GLSL shaders for the sample application. Modified the application code as needed.

```

GTBuildAll.{v12,v14}.sln
Samples/Graphics/WireMesh/WireMesh.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Graphics/WireMesh/WireMeshWindow.cpp
Samples/Graphics/WireMesh/Shaders/WireMesh{VS,PS,GS}.glsl

```

Replaced the [Window](#)-based approach to get a GL4 engine by using the [GL4Engine](#) constructor that hides the backing window.

```

Samples/Basics/ShaderReflection/ShaderReflection.cpp

```

**January 18, 2016.** The GL4 texture classes copied CPU data to the GPU on initial creation only when the texture object was not marked as [SHADER.OUTPUT](#); however, this prevents a texture from being read-write in the shaders. Modified the code to copy CPU data to the GPU when the CPU data exists, just as in the DX11 engine.

```
GL4TextureSingle.cpp
GL4TextureArray.cpp
GL4TextureCubeArray.cpp
```

Implemented the GLSL shaders for the sample application. Modified the application code as needed. GLSL will not expand an expression in a conditional define that turns out to be a known constant. Commented out the defines both in the HLSL and GLSL code and required the application to set the defines directly.

```
GTBuildAll.{v12,v14}.sln
Samples/Mathematics/PartialSums/PartialSums.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/PartialSums/PartialSums.cpp
Samples/Mathematics/PartialSums/Shaders/PartialSums.hlsl
Samples/Mathematics/PartialSums/Shaders/PartialSums.glsl
```

Implemented the GLSL shaders for the sample application. Modified the application code as needed. Fixed an out-of-date comment in the HLSL file.

```
GTBuildAll.{v12,v14}.sln
Samples/Mathematics/RootFinding/RootFinding.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Mathematics/RootFinding/RootFinding.cpp
Samples/Mathematics/RootFinding/Shaders/RootFinding.hlsl
Samples/Mathematics/RootFinding/Shaders/RootFinding.glsl
```

Implemented the GLSL shaders for the sample application. Modified the application code as needed. Changed the shader resource names from **input** and **output** to **inImage** and **outImage**, because GLSL has the keyword **output**.

```
GTBuildAll.{v12,v14}.sln
Samples/Imagics/GaussianBlurring/GaussianBlurring.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/GaussianBlurring/GaussianBlurringWindow.cpp
Samples/Imagics/GaussianBlurring/Shaders/GaussianBlur3x3.hlsl
Samples/Imagics/GaussianBlurring/Shaders/GaussianBlur3x3.glsl
```

Implemented the GLSL shaders for the sample application. Modified the application code as needed. Changed the shader resource names from **input** and **output** to **inImage** and **outImage**, because GLSL has the keyword **output**.

```
GTBuildAll.{v12,v14}.sln
Samples/Imagics/MedianFiltering/MedianFiltering.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/MedianFiltering/MedianFilteringWindow.cpp
Samples/Imagics/MedianFiltering/Shaders/Median3x3.hlsl
Samples/Imagics/MedianFiltering/Shaders/Median5x5.hlsl
```



Samples/Imagics/MedianFiltering/Shaders/MedianBySort.hlsl  
Samples/Imagics/MedianFiltering/Shaders/Median3x3.glsl  
Samples/Imagics/MedianFiltering/Shaders/Median5x5.glsl  
Samples/Imagics/MedianFiltering/Shaders/MedianBySort.glsl

**January 19, 2016.** Added layout information for GLSL.

VertexColorEffect.cpp

Implemented the GLSL shaders for the sample application. Modified the application code as needed. Modified the shaders so that the structured buffers use 4-tuple vectors rather than 3-tuple vectors.

GTBuildAll.{v12,v14}.sln  
Samples/Geometrics/AllPairsTriangles/AllPairsTriangles.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.cpp  
Samples/Geometrics/AllPairsTriangles/Shaders/DrawUsingVertexID.hlsl  
Samples/Geometrics/AllPairsTriangles/Shaders/TriangleIntersection.hlsl  
Samples/Geometrics/AllPairsTriangles/Shaders/DrawUsingVertexID{VS,}.glsl  
Samples/Geometrics/AllPairsTriangles/Shaders/InitializeColors.glsl  
Samples/Geometrics/AllPairsTriangles/Shaders/TriangleIntersection.glsl  
Samples/Geometrics/AllPairsTriangles/Shaders/VertexColorIndexed{VS,}.glsl

**January 21, 2016.** Replaced calls to [glBufferStorage](#) by [glBufferData](#) based on the requirement that one need only OpenGL 4.3 to compile and run the code.

GL4Buffer.cpp  
GL4StructuredBuffer.cpp

Implemented the GLSL shaders for the sample application. Modified the application code as needed.

GTBuildAll.{v12,v14}.sln  
Samples/Geometrics/DistanceSegments3/DistanceSegments3.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp  
Samples/Geometrics/DistanceSegments3/Shaders/DistanceSeg3Seg3.{hlsl,glsl}  
Samples/Geometrics/DistanceSegments3/DistanceSeg3Seg3.hlsl

Implemented the GLSL shaders for the sample application. Modified the application code as needed.

GTBuildAll.{v12,v14}.sln  
Samples/Graphics/ShortestPath/ShortestPath.{v12,v14}.{sln,vcxproj,vcxproj.filters}  
Samples/Graphics/ShortestPath/ShortestPathWindow.cpp

```

Samples/Graphics/ShortestPath/GpuShortestPathWindow.{h,cpp}
Samples/Graphics/ShortestPath/CpuShortestPathWindow.cpp
Samples/Graphics/ShortestPath/Shaders/PartialSumsDiagToCol.hlsl
Samples/Graphics/ShortestPath/Shaders/PartialSumsDiagToRow.hlsl
Samples/Graphics/ShortestPath/Shaders/WeightsShader.hlsl
Samples/Graphics/ShortestPath/Shaders/InitializeDiagToCol.glsl
Samples/Graphics/ShortestPath/Shaders/InitializeDiagToRow.glsl
Samples/Graphics/ShortestPath/Shaders/PartialSumsDiagToCol.glsl
Samples/Graphics/ShortestPath/Shaders/PartialSumsDiagToRow.glsl
Samples/Graphics/ShortestPath/Shaders/UpdateShader.glsl
Samples/Graphics/ShortestPath/Shaders/WeightsShader.glsl

```

Implemented the GLSL shaders for the sample application. Modified the application code as needed.

```

GTBuildAll.{v12,v14}.sln
Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Basics/IEEEFloatingPoint/IEEEFloatingPoint.cpp
Samples/Basics/IEEEFloatingPoint/Shaders/TestSubnormals.hlsl
Samples/Basics/IEEEFloatingPoint/Shaders/TestSubnormals.glsl

```

Moved the bodies of functions of [ComputeModel](#) from the cpp file to the header. Instead of activating GPGPU via the [Win32](#) define, a new define has been added called [GTE\\_COMPUTE\\_MODEL\\_ALLOW\\_GPGPU](#). This is currently not exposed so that the mathematics system does not include the graphics system. You can either expose the define by editing the file or you can add the define to preprocessor options in the projects. The [GenerateMeshUVs](#) sample application uses the latter choice.

```

GTBuildAll.{v12,v14}.sln
ComputeModel.h
ComputeModel.cpp
GenerateMeshUV.{h,cpp}
Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVs.{v12,v14}.vcxproj
Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp
Samples/Mathematics/GenerateMeshUVs/Shaders/TestSubnormals.hlsl
Samples/Mathematics/GenerateMeshUVs/Shaders/TestSubnormals.glsl

```

Implemented the GLSL shaders for the sample application. Modified the application code as needed.

```

GTBuildAll.{v12,v14}.sln
Samples/Imagics/Convolution/Convolution.{v12,v14}.{sln,vcxproj,vcxproj.filters}
Samples/Imagics/Convolution/ConvolutionWindow.cpp
Samples/Imagics/Convolution/Shaders/Convolve.hlsl
Samples/Imagics/Convolution/Shaders/ConvolveGS.hlsl
Samples/Imagics/Convolution/Shaders/ConvolveSeparableH.hlsl
Samples/Imagics/Convolution/Shaders/ConvolveSeparableHGS.hlsl

```

Samples/Imagics/Convolution/Shaders/ConvolveSeparableHGS2.hlsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableV.hlsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableVGS.hlsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableVGS.hlsl  
Samples/Imagics/Convolution/Shaders/Convolve.glsl  
Samples/Imagics/Convolution/Shaders/ConvolveGS.glsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableH.glsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableHGS.glsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableHGS2.glsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableV.glsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableVGS.glsl  
Samples/Imagics/Convolution/Shaders/ConvolveSeparableVGS.glsl

**January 23, 2016.** Removed the projects [RawBuffers](#) and [SharedTextures](#) from the build-all solutions. Renamed them to [RawBuffersD3D11](#) and [SharedTexturesD3D11](#) because they use features specific to D3D11. The build-all solutions now have projects, each having configurations for D3D11 ([Debug](#), [Release](#)) and OpenGL4.3 ([DebugGL4](#), [ReleaseGL4](#)).

## 73 Updates to Version 1.14

**June 7, 2015.** Added MSVS 2015 solutions and projects for GTEngine library.

GTEngine.v14.sln  
GTEngine.v14.vcxproj  
GTEngine.v14.vcxproj.filters

**June 27, 2015.** Added MSVS 2015 solutions and projects for all samples.

**June 28, 2015.** Fixed a typographical error in the comments before [SqrDistanceSpecial](#).

[DistPointHyperellipsoid.h](#)

Fixed a bug that was introduced into the GTEngine code after it was ported from Wild Magic 5. The order of parameters in the [DoQuery](#) calls was incorrect.

[IntrRay3AlignedBox3.h](#)

Fixed compiler warnings in MSVS 2015 about name in one scope visible to the same name in another scope.

[DistCircle3Circle3.h](#)  
[Integration.h](#)

IntrEllipse2Ellipse2.h  
IntrEllipsoid3Ellipsoid3.h  
SingularValueDecomposition.h

Minor change. Modified variable name to be consistent with other DX11 resource files.

DX11Buffer.{h,cpp}

**July 12, 2015.** The level offsets for a [TextureArray](#) without mipmaps were all zero. They need to be set to multiples of the number of bytes of each texture in the array.

Texture.cpp

**July 13, 2015.** The [Matrix](#) constructor with initializer list input was missing an increment of the row counter when the number of initializers fills a row only partially.

Matrix.inl

**July 26, 2015.** Removed the thread ID check in [DX11Engine](#). This was a Geometric Tools Engine constraint, forcing the programmer to use an engine object in the same thread because the device context is not thread safe. However, you may use the engine object in multiple threads as long as you provide the critical section to avoid concurrent access. Rewrote the creation and destruction for the swap chain and back buffer to ensure that the application shuts down gracefully. In the previous code, if the device creation failed, the immediate context was null and then dereferenced during the destruction phase. The new code was tested using fault injection to produce a failure at each attempt to query for an interface or to create a resource.

DX11Engine.{h,cpp}

**July 29, 2015.** The template alias for 2D distance from point to box was defined incorrectly (currently no engine code is using the alias).

DistPointOrientedBox.h

Added support for saving [Texture2](#) objects to JPEG.

WICFileIO.{h,cpp}

**August 1, 2015.** The Boolean value of interval-interval find-intersection was not assigned to the Boolean value of the result.

IntrSegment2AlignedBox2.h  
IntrRay2AlignedBox2.h

**August 2, 2015.** Enclosed the class in namespace gte.

HLSLParameter.h

**August 5, 2015.** `DX11Texture1` needed to derive from `DX11TextureSingle` rather than `DX11Texture`.

`DX11Texture1.{h,cpp}`

**August 9, 2015.** The y-coordinate of the Platonic texture coordinates was not computed (a WM5 porting error).

`MeshFactory.cpp`

**August 11, 2015.** The ESC key was handled in the window procedure outside of `OnCharPress` and is mapped to exiting the application with a `PostQuitMessage(0)` call. This made it impossible to override. The handling has been moved to `Window::OnCharPress` to allow applications to override the behavior.

`Window.{h,cpp}`  
`WindowSystem.cpp`

The generation of project files was not creating exactly the character pattern to allow the Microsoft Visual Studio Selector to recognize which version of Visual Studio to launch when a solution is selected. The SLN files are UTF8 and require `0xEF`, `0xBB`, `0xBF`, `0x0D`, `0x0A` as the starting characters.

`ProjectTemplate.{v12,v14}.{h,cpp}`

**August 12, 2015.** Eliminated unnecessary `c_str()` call.

`HLSLShaderFactory.cpp`

The function `DX11Engine::Share` needed to create a regular 2D texture, a render-target texture, or a depth-stencil texture based on the type information in the `GraphicsObject` class.

`DX11Engine.cpp`

**August 15, 2015.** The subscribe and unsubscribe procedures for listeners to participate in updates of pvw-matrices and w-matrices was more complicated than it should be. Removed hiding the complexity. The w-matrix processing is handled now by explicitly manipulating the `mTrackballNode` object. The pvw-matrix subscribe and unsubscribe functions have appropriate names and require you to pass in explicitly the pair of world transform and constant buffer. Sample applications were modified accordingly.

`Window.{h,cpp}`

**August 16, 2015.** Fixed a porting error for creating a torus mesh. The texture coordinates were incorrect at the wrap-around.

`MeshFactory.cpp`

**August 21, 2015.** Made several functions protected to prevent applications from calling them. The Spatial and Visual classes must call these from public scope, so they were made friends of Culler.

`Culler.h`

**August 23, 2015.** Factored the trackball code out of `Window` and into a class `Trackball`. Applications that require a virtual trackball must create an object of the new class and implement `MouseClicked` and `MouseMotion` callbacks to manage the trackball. Many of our sample applications have the new system, so see those for examples of how to do this. The modified sample files are not listed here.

`Trackball.{h,cpp}`  
`Window.{h,cpp}`

The `LogReporter` objects in the `main` functions of the sample applications are now exposed only in debug configurations. The `Window::Parameters` structure was given a new constructor for the common case of specifying the title-bar string, the window origin, and the window dimensions. Such windows are not resizable. If you need additional parameters set, you can do so after the constructor call—or you can set all members explicitly after a default-constructor call. The modified sample files are not listed here.

`Window.h`

Moved `Window::GetPickLine` to `Camera` and removed the explicit dependency on the `DX11Engine` by requiring that the viewport be passed to `GetPickLine`.

`Window.{h,cpp}`  
`Camera.{h,cpp}`  
`Samples/Graphics/Picking/PickingWindow.cpp`

**August 24 to September 23, 2015.** Major revision of the lighting effects, including adding classes `Light` and `Material`. Added a class `CameraRig` that encapsulates camera motion and updating the dependent pvw-matrices. Added a class `Window3`, derived from `Window`, that encapsulates the common code for 3D sample applications. Ported Wild Magic 5 graphics samples: `BillboardNodes`, `BlendedAnimations`, `BspNodes`, `BumpMaps`, `CameraAndLightNodes`, and `Castle`. Added scene-graph classes as needed to support these. Tested the distribution when the convention `GTE_USE_VEC_MAT` is selected (default convention is `GTE_USE_MAT_VEC` and fixed any problems that arose.

## 74 Updates to Version 1.13

**June 3, 2015.** Changes to get code to compile using MSVS 2015 RC. All errors were actually warnings about reusing variable names in a nested scope.

```
HLSLShaderFactory.cpp
ConvexHull2.h
Delaunay2.h
Delaunay3.h
ETManifoldMesh.cpp
TriangulateEDT.h
TriangulateEC.h
TubeSurface.h
Samples/Basics/LowLevelD3D11/Application.cpp
```

**June 7, 2015.** The intersection queries were missing the `public` modifier. Enabled the internal unit tests for these classes (all tests succeed).

```
IntrPlane3Capsule3.h
IntrPlane3Cylinder3.h
IntrPlane3Ellipsoid3.h
IntrPlane3OrientedBox3.h
IntrPlane3Sphere3.h
```

Added `-fPIC` to the CC flags for dynamic library builds. This avoids a compiler-linker error in Fedora 21.

```
makefile.gte
```

## 75 Updates to Version 1.12

**April 23, 2015.** Major rewrite of the document on converting between coordinate systems. The original version of this document was entitled *Conversion of Left-Handed Coordinates to Right-Handed Coordinates* and was written to handle the conversion of LightWave coordinate systems (left-handed) to Wild Magic

coordinate systems (right-handed). The process was specific to LightWave's choice of representing rotations using Euler angles, and the discussion included how to deal with cameras, lights, and transformation hierarchies. The new version is the general process of converting between any two coordinate systems. An implementation is provided that automates the process.

[ConvertingBetweenCoordinateSystems.pdf](#) (*Converting Between Coordinate Systems*)

[ConvertCoordinates.h](#)

[LeftHandedToRightHanded.pdf](#) (*Conversion of Left-Handed Coordinates to Right-Handed Coordinates*)

**April 29, 2015.** Converted some accessor functions to inline.

[DX11GraphicsObject.{h,cpp}](#)

Changed [LogWarning](#) to [LogError](#) when the preparation for copy fails.

[DX11Resource.cpp](#)

**April 30, 2015.** Removed the [Set\\*](#) members from the class. These are never called in any GTEngine applications, nor should they. Once you create a visual effect, it should remain immutable (so to speak).

[VisualEffect.h](#)

**May 3, 2015.** Removed the unused template classes derived from [StructuredBuffer](#).

[GTEngine.{h,vcxproj,vcxproj.filters}](#)

[StructuredBuffer{1,2,3}.h](#)

**May 10, 2015.** Removed errant [inline](#) modifiers on functions that are not likely to be inlined.

[MinimumAreaBox2.h](#)

**May 17, 2015.** Modified the algorithm based on the analysis and description in the modified PDF for the minimum-area rectangle containing points. For 256-point convex polygons with random vertices, the new code executes nearly twice as fast as the old code.

[MinimumAreaBox2.h](#)

[MinimumAreaRectangle.pdf](#) (*Minimum-Area Rectangle Containing a Set of Points*)

**May 18, 2015.** Modified the implementation of [MinimumVolumeBox3](#) to be similar to the new changes in [MinimumAreaBox2](#). There is some performance improvement (about 10% faster). Added the ability to specify that the [ProcessEdges](#) function should be run in a thread concurrently when [ProcessFaces](#) is executing. The speed-up is noticeable (about 20% for a test data set of about 6000 points).



### MinimumVolumeBox3.h

Removed `mVisited` as a class member and moved it to local scope in a function. This had to be done in `MinimumVolumeBox3` to avoid concurrent access to `mVisited` when multithreading is used. Made the same change to `MinimumAreaBox2` in case we decide to add threading support.

### MinimumAreaBox2.h

**May 19, 2015.** As mentioned, if `ComputeType` is not an exact arithmetic type, the Delaunay triangulation can fail because of incorrect sign classification due to numerical rounding errors. The class still had several places where failures of this type were not trapped and handled gracefully. Checks were added in the appropriate locations so that `Update` now reports a Boolean value that is `true` when successful. The failure is plumbed all the way back to the application call of `operator(...)`.

### Delaunay2.h

**May 22, 2015.** Ported `Polynomial1` from Wild Magic 5 to GTEngine.

GTEngine.{h,vcxproj,vcxproj.filters}  
Polynomial1.h

**May 28, 2015.** Modified the point-circle algorithm to return a Boolean flag `equidistant` rather than number of closest circle points. Modified the comments. Added unit tests.

### DistPoint3Circle3.h

**May 29, 2015.** Ported the line-circle distance algorithm from Wild Magic 5, but modified the bisection approach to be easier to read. Added the polynomial-based approach that finds roots of at most a degree-4 polynomial. Added unit tests internally.

GTEngine.{h,vcxproj,vcxproj.filters}  
DistLine3Circle3.h

**May 31, 2015.** Added `GetMaxBisections` to the `Functions` wrapper that hides the details of determining the maximum number of iterations for using bisection with a floating-point number type. This is useful in `RootsBisection::Find`.

Functions.h  
DistPointHyperellipsoid.h

Added a function [GetOrthogonal](#) to generate one vector perpendicular to the input vectors. The returned vector can be selected to be normalized (or not). The functions [ComputeOrthogonalComplement](#) compute a set of basis vectors for the orthogonal complement of an input, but in some algorithms not all are needed.

## Vector.h

Added a document that combines three previous documents regarding distance queries involving circles in 3D. The new document provides much greater detail about circle-circle queries than the brief note in the original version. Source code was updated based on the new document and unit tests were added internally.

[DistanceToCircle3.pdf](#) (*Distance to Circles in 3D*)  
[DistPoint3Circle3.h](#)  
[DistLine3Circle3.h](#)  
[DistCircle3Circle3.h](#)  
[DistancePoint3Circle3.pdf](#) (*Distance Between Point and Circle or Disk in 3D*)  
[DistanceLine3Circle3.pdf](#) (*Distance Between Line and Circle or Disk in 3D*)  
[DistanceCircle3Circle3.pdf](#) (*Distance Between Two Circles in 3D*)  
[DistanceCircle3Disk3.pdf](#) (*Distance Between a Circle and a Disk in 3D*)

Apple LLVM 6.1.0 complained yet once again that “std::abs is ambiguous”, this time in the minimum-area and minimum-volume box code when running our tool to trap compiler problems with template instantiation. The relevant verification code is

```
#include <GteMinimumAreaBox2.h>
// Has line of code
// ComputeType cmax = std::max(std::abs(axis[0]), std::abs(axis[1]));

#include <GteBSRational.h>
// Has lines of code
// namespace std
// {
//     template <typename UIntegerType> inline
//     gte::BSRational<UIntegerType> abs(gte::BSRational<UIntegerType> const& number)
//     {
//         return (number.GetSign() >= 0 ? number : -number);
//     }
// }

#include <GteUIntegerAP32.h>

namespace gte
{
    // ComputeType for this instantiation is BSRational<UIntegerAP32>.
    template class MinimumAreaBox2<float, BSRational<UIntegerAP32>>;
}
```

The compiler complains that [std::abs](#) is ambiguous in the line of code that computes [cmax](#). However, it has no complaints about the code

```
#include <GteBSRational.h>
#include <GteUIntegerAP32.h>
#include <GteMinimumAreaBox2.h>
namespace gte
{
    template class MinimumAreaBox2<float, BSRational<UIntegerAP32>>;
}
```

In the listing with `GteMinimumAreaBox2.h` included first, the implied behavior is the following. LLVM attempts to instantiate class `MinimumAreaBox2` with `ComputeType` equal to `BSRational<UIntegerAP32>`. For LLVM to complain about the `std::abs` in the line of code for `cmax`, it has not yet processed the definition of `std::abs` in the file `GteBSRational.h` even though it should have read the contents of this file before encountering the explicit instantiation code. Using the template code for the Standard C++ Library, it tries to find a match for `std::abs` with type `BSRational<UIntegerAP32>` but fails. In the listing with `GteMinimumAreaBox2.h` included last, the implied behavior is that LLVM processes the definition of `std::abs` in the file `GteBSRational.h` before attempting to instantiate class `MinimumAreaBox2`. During the instantiation, it finds a match for `std::abs` for the type `BSRational<UIntegerAP32>`.

Is this an Apple LLVM bug? Or is the header file order dependency required because of some C++ 11 specification? Removing the const reference in the `std::abs` input for `BSRational<UIntegerAP32>` did not eliminate the problem. The Xcode symbol navigator actually shows the various definitions of `abs` in `<cmath>`, `<cstdlib>`, `stdlib.h`, `GteBSNumber.h`, and `GteBSRational.h`. For the latter two files, the symbol navigator shows `abs<>()`. For the other occurrences, the symbol navigator shows `abs()`. Perhaps the Standard C++ Library just has too many occurrences of `abs` wrapped with layers of “Is this C code? C++ 0X code or C++ 11 code? Inside or outside namespace std?”

## 76 Updates to Version 1.11

**April 11, 2015.** The Apple LLVM 6.1.0 compiler generated an error, stating that declarations of the specializations for `oppositeFace` must occur before the definitions (in the cpp file). Added the declarations in the h file, but in a conditional compilation block to prevent exposing them to Microsoft Visual Studio 2013. The Microsoft compiler incorrectly generates an error about a redefinition of `oppositeFace`. A comment in the code states what the C++ specification says about explicit instantiation of static members of a template class. [This is the main change that led to shipping a new version of GTEngine so quickly after the previous version.](#)

`TetrahedronKey.h`

**April 11, 2015.** Added functions `GetRootInfo*` to count the number of real-valued roots and their multiplicities without actually computing the roots.

`RootsPolynomial.h`

**April 20, 2015.** Two blocks of code were returning `true` rather than an integer representing number of bisections used in the code, a carry-over from when the functions used to return Boolean values. Modified the functions to return meaningful integers in all cases.

`RootsBisection.h`

Added significant improvements to (1) the document for the test-intersection and find-intersection queries for ellipses and (2) the document for computing the area of intersection of ellipses. The source code implementation for the test-intersection and find-intersection queries were updated to use the details described

in the document. Implemented the query for area of intersection of ellipses. Unit tests for the queries were added internally. The area queries were also computed numerically using Mathematica 10.1 to verify that the GTEngine code is producing correct results.

[IntrEllipse2Ellipse2.h](#)  
[IntersectionOfEllipses.pdf](#) (*Intersection of Ellipses*)  
[AreaIntersectingEllipses.pdf](#) (*The Area of Intersecting Ellipses*)

## 77 Updates to Version 1.10

**March 11, 2015.** Added new distance queries for points and cylinders.

[GTEngine.{h,vcxproj,vcxproj.filters}](#)  
[DistPoint3Cylinder3.{h,cpp}](#)

**March 13, 2015.** Added tag-dispatch-based type traits class [Arithmetic](#). Added a class [Function](#) that provides math wrapper functions with implementations based on the tag types. The wrappers are for [float](#), [double](#), and [long double](#) (floating-point types); for [IEEEBinary16](#) (16-bit floating-point type); and for [BSNumber](#) and [BSRational](#) (exact types, but the functions return approximations because the results cannot be represented exactly). Removed the previous support for square roots from the distance query header. Removed the min and max implementations from the exact types, because [std::min](#) and [std::max](#) work as-is due to the existence of comparison operators in the binary scientific classes. Modified the segment-segment distance query to use the new system.

[GTEngine.{h,vcxproj,vcxproj.filters}](#)  
[Constants.h](#)  
[Functions.h](#)  
[IEEEBinary16.{h,cpp}](#)  
[DCPQuery.h](#)  
[DistSegmentSegment.h](#)  
[BSNumber.h](#)  
[BSRational.h](#)  
[Arithmetic.h](#)

**March 29, 2015.** Added some definitions for variables used in the equations in the section *Separation Tests Involving Other Directions*. Converted the verbatim pseudocode to use `lstlisting` format.

[IntersectionOfCylinders.pdf](#) (*Intersection of Cylinders*)

**April 2, 2015.** Moved the debug members [mValue](#) to be the first members of the classes. This allows one to see the converted values in the MSVS debugger variable summary; thus, you do not have to open tree controls

to drill down to the converted value. Added adjustments to [BSRational](#) to enforce a constraint that when the numerator is 0, the denominator should be 1. Fixed a bug in the conversion from [BSRational](#) to a floating-point type. When the round-up step causes a carry-out, so to speak, from the trailing significand, a block of code was executed to set  $w$  to 1 and adjust  $p - q$ . This was incorrect and, in fact, not necessary because  $w$  is not used as the trailing significand in the conversion. The documentation was updated accordingly.

[BSNumber.h](#)

[BSRational.h](#)

[ArbitraryPrecision.pdf](#) (*GTEngine: Arbitrary Precision Arithmetic*)

**April 4, 2015.** Rewrote the document for computing the roots of low-degree polynomials. The new document goes into great detail about the classification of roots (real or non-real, multiplicities) and how to use exact rational arithmetic to correctly classify the roots in a program. This leads to more robust root finding using the closed-form expressions for polynomials of degrees 2, 3, and 4. Implementations of this replace the old code in [RootsPolynomial](#). Unit tests were added (in-house) that provide 100 % code coverage for the robust root finders. The motivation for the revisions was based on trying to compute intersections of ellipses, and the nonrobust root finder for quartic polynomials created many problems numerically.

[LowDegreePolynomialRoots.pdf](#) (*Low-Degree Polynomial Roots*)

[RootsPolynomial.h](#)

## 78 Updates to Version 1.9

**February 10, 2015.** Added [Distance](#) functions that are controlled by the *tag-dispatch pattern* in order to provide a single interface to the square root function for numerical types ([float](#), [double](#)) and for exact types ([BSNumber](#), [BSRational](#)).

[DCPQuery.h](#)

[DistSegmentSegment.h](#)

**February 11, 2015.** In the else clause at the end of [operator\(\)](#), the  $2 \times 2$  matrix needs to be a rotation, not a reflection.

[SymmetricEigensolver2x2.h](#)

**February 19, 2015.** A new tool to compile an HLSL shader and store it as bytecode embedded in a C++ array. This is useful if you do not want to expose an algorithm by an embedded human-readable string in the source code and executable.

[GTBuildAll.sln](#)

[HLSLShaderFactory.{h,cpp}](#)

[ShaderFactory.{h,cpp}](#)

Tools/HLSLToByteCode/HLSLToByteCode.sln  
Tools/HLSLToByteCode/HLSLToByteCode.vcxproj  
Tools/HLSLToByteCode/HLSLToByteCode.vcxproj.filters  
Tools/HLSLToByteCode/HLSLToByteCode.cpp

**February 23, 2015.** The general symmetric eigensolver had an incorrect algorithm for tracking the number of reflections in order to determine whether the product of Householder reflections, Givens rotations, and sorting of eigenvalues leads to a rotation or a reflection. The other changes involving replacing the general eigensolver with solvers specific to 2D and 3D.

SymmetricEigensolver.h  
ApprGaussian2.h  
ApprGaussian3.h  
ApprGreatCircle.h  
ApprOrthogonalLine2.h  
ApprOrthogonalLine3.h  
ApprOrthogonalPlane3.h  
Hyperellipsoid.h  
IntrEllipse2Ellipse2.h  
IntrEllipsoid3Ellipsoid3.h

**February 24, 2015.** [MinimumVolumeBox3](#) no longer uses the code in [MinimumAreaBox2](#), so the latter code is now private to the class. [MinimumVolumeBox3](#) now uses exact rational arithmetic for all phases, avoiding the floating-point rounding problems of the old code that projected the extreme polyline to the supporting plane of the hull face.

MinimumAreaBox2.h  
MinimumVolumeBox3.h

The box vertex order changed for [OrientedBox2](#) and [OrientedBox3](#), so the drawing code needed modification.

Samples/Geometries/MinimumAreaBox2D/MinimumAreaBox2DWindow.cpp  
Samples/Geometries/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp

Made [TransformBy](#) a `const` function.

BoundingSphere.{h,cpp}

**February 26, 2015.** Replaced the  $O(n^2)$  algorithm for computing the minimum-area rectangle derived from a hull-face normal and its corresponding extreme polyline. The replacement uses the  $O(n)$  Rotating Calipers algorithm extended to 3D boxes that are extrusions of a 2D rectangle.

MinimumVolumeBox3.h

**February 28, 2015.** Added CPU multithreading support to [ConvexHull3](#) and [MinimumVolumeBox3](#). Improved the performance of the comparison operators for [BSRational](#) by early-out testing of the signs of numerators. Extended [BSPrecision](#) to measure precision for [BSRational](#) expressions. Added comments to header files about the choice of [N](#) for [UIntegerFP<N>](#).

ConvexHull3.h  
MinimumVolumeBox3.h  
BSRational.h  
BSPrecision.{h,cpp}  
ConvexHull2.h  
PrimalQuery2.h  
PrimalQuery3.h

**March 3, 2015.** The conversion from the rational minimum-volume box to floating-point box had a loss of precision too early in the conversion. This led to divisions by zero in the extents and to zero-valued axes. Some preconditioning was added to defer the precision loss until the very last step.

MinimumVolumeBox3.h

Added support for disk input/output.

BSNumber.h  
BSRational.h  
UIntegerAP32.{h,cpp}  
UIntegerFP32.h

**March 4, 2015.** Fixed a subtle error in the minimum-volume bounding box code when rotating calipers is used. The starting rectangle needed axes that satisfied a particular scaling constraint in order to properly compare scaled areas. The 2D code was rewritten to be similar in structure to the 3D code.

MinimumVolumeBox3.h  
MinimumAreaBox2.h  
Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.{h,cpp}

Fixed the coefficients in [b\[\]](#) in the ChebyshevRatio file. Modified the slerp code in the SlerpEstimate file to compile on Playstation 4 clang compiler.

ChebyshevRatio.h  
SlerpEstimate.h

**March 10, 2015.** Based on data sets provided in bug reports, we decided to do a *deep dive* into the rotating calipers algorithm and code. The convex polygon must be ordered counterclockwise. The loop of the algorithm has two invariants:

1. the edges emanating from the current supporting points of the box must not be coincident with a box edge, and
2. of all consecutive polygon points that support a box edge, the chosen support point must be right-most on the edge (as the box is traversed counterclockwise).

To satisfy the first invariant, collinear vertices must be removed from the convex polygon; otherwise, an box edge might contain three or more support points. To satisfy the second invariant, the new bottom support point for a minimum-angle polygon edge is trivial to select and the new support points are a subset of the old support points. However, two (or more) emanating edges that tie for the minimum angle with box edges can cause a new support point *not* to be right-most on an edge. We revised the minimum-area and minimum-volume box code to ensure the invariants are satisfied. The 3D problem is somewhat more complicated because projecting a polyline that supports a box with face coincident with a convex hull face is not possible when using exact rational arithmetic.

MinimumVolumeBox3.h  
MinimumAreaBox2.h  
Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.{h,cpp}  
Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.{h,cpp}

Added a conditional define so that one may view double-precision values of **BSNumber** and **BSRational** when debugging code that uses exact rational arithmetic. Be aware that this can be very slow because of the conversion to double-precision whenever new objects are created by arithmetic operations.

BSNumber.h  
BSRational.h

Increased the integer template parameter of **UIntegerFP32** in the sample algorithm so that it supports any **float** input.

Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow.cpp

Some traps are placed in the edge-insertion code to avoid crashing when the constrained triangulation failed due to use of floating-point **ComputeType**. Two additional tests were needed to verify that the **item** iterator was valid before dereferencing it.

ConstrainedDelaunay2.h



## 79 Updates to Version 1.8

**January 14, 2015.** Added DX11.1 formats to the `DF_*` enumeration.

`DataFormat.{h,cpp}`

**January 22, 2015.** Fixed bugs in the line-rectangle distance query. The last block of code used `result.lsParameter[0]` when it should have used `result.lsParameter[1]`. The indexing for `result.rectangleParameter[1]` was incorrect.

`DistLine3Rectangle3.h`

**January 22, 2015.** Added a template wrapper for the square root function in order to overload `float`, `double`, `BSNumber`, and `BSRational` implementations. The wrapper is named `Sqrt` and will replace any calls to `sqrt` where the programmer has the option to use an exact arithmetic type instead of a standard floating-point type.

`Functions.h`  
`BSNumber.h`  
`BSRational.h`

**January 22, 2015.** Converted the point-triangle distance query to a template that has the dimension as a parameter.

`DistPoint3Tetrahedron3.h`  
`DistRay3Triangle3.h`  
`DistSegment3Tetrahedron3.h`  
`DistPointTriangle.h`  
`DistPoint3Triangle3.h`

**January 25, 2015.** Added a function to count the number of active graphics objects and the system memory they are using.

`DX11Engine.{h,cpp}`

**January 26, 2015.** Fixed an error in the description for region 2 and added some clarification about the sign tests for the partial derivatives of  $R(s, t)$ .

`DistanceLine3Line3.pdf` (*Robust Computation of Distance Between Line Segments*)

Implemented a robust version of point-triangle distance that avoids the problems when a nearly degenerate triangle causes the numerical determinant to be zero. The previous version is now written for exact arithmetic, because it uses fewer arithmetic operations than the robust version.

[DistPointTriangleExact.h](#)  
[DistPointTriangle.h](#)

**January 31, 2015.** Fixed an error in the logic for handling the directional derivative of the quadratic function  $R(s, t)$  along the segment of intersection where  $\partial R(s, t)/\partial s = 0$ .

[DistSegmentSegment.h](#)  
[Samples/Mathematics/Geometrics/DistanceSegments3/DistanceSeg3Segs.hsl](#)

Fixed an error in the computation of the  $t$ -parameter.

[DistPointSegment.h](#)

Added an include of [<cstdlib>](#) to resolve an Xcode compiler complaint about ambiguous use of [std::abs](#).

[IntrAlignedBox3Cone3.h](#)

## 80 Updates to Version 1.7

**December 14, 2014.** Moved the INL file content into the H files and deleted all the INL files. The number of INL files was on the order of over 400, so they are not listed here.

**December 16, 2014.** Replaced 3D-specific [Rectangle3](#) with  $n$ -dimensional [Rectangle](#).

[GTEngine.{h,vcxproj,vcxproj.filters}](#)  
[DistPoint3Rectangle3.h](#)  
[DistLine3Rectangle3.h](#)  
[Rectangle.h](#)  
[Rectangle3.h](#)

Converted distance and intersection code to use new [Line](#), [Ray](#), and [Segment](#) objects.

[DistLineLine.h](#)  
[DistLineRay.h](#)  
[DistLineSegment.h](#)

DistRayRay.h  
DistRaySegment.h  
DistLine3Triangle3.h  
DistIntrLine3Capsule3.h  
DistIntrRay3Capsule3.h  
Picker.cpp  
DistLine{2,3}Line{2,3}.h  
DistLine{2,3}Ray{2,3}.h  
DistLine{2,3}Segment{2,3}.h  
DistRay{2,3}Ray{2,3}.h  
DistRay{2,3}Segment{2,3}.h

Added convenient template aliases.

DistPointAlignedBox.h  
DistPointHyperellipsoid.h  
DistPointLine.h  
DistPointOrientedBox.h  
DistPointRay.h  
DistPointSegment.h  
DistSegmentSegment.h

Renamed the source file to match the header file name.

GenerateMeshUV.cpp  
GenerateMeshUVs.cpp

**December 17, 2014.** Replaced 3D-specific [Cone3](#) with  $n$ -dimensional [Cone](#).

GTEngine.{h,vcxproj,vcxproj.filters}  
IntrLine3Cone3.h  
IntrSphere3Cone3.h  
Cone.h  
Cone3.h

Replaced 3D-specific [Capsule3](#) with  $n$ -dimensional [Capsule](#).

GTEngine.{h,vcxproj,vcxproj.filters}  
ContCapsule3.h  
IntrCapsule3Capsule3.h  
IntrHalfspace3Capsule3.h  
IntrLine3Capsule3.h

IntrPlane3Capsule3.h  
Capsule.h  
Capsule3.h

Added intersection testing for 2D oriented box and cone.

GTEngine.{h,vcxproj,vcxproj.filters}  
IntrOrientedBox2Cone2.h

**December 17, 2014.** The constructor initialization for `mTextColor` in the project generation needed to have braces based on the recent change to support `std::initialize`.

Tools/GenerateProject/ProjectTemplate.cpp

**December 19, 2014.** The `GetVertices` function needed to initialize the mask to 1, not to 0.

OrientedBox.h

**December 26, 2014.** Added intersection testing for 3D oriented box and cone, including a sample to illustrate visually that the tests work correctly.

GTEngine.{h,vcxproj,vcxproj.filters}  
GTBuildAll.sln  
IntrOrientedBox3Cone3.h  
Samples/Geometrics/IntersectBoxCone/IntersectBoxConeWindow.{h,cpp}  
Samples/Geometrics/IntersectBoxCone/IntersectBoxCone.{sln,vcxproj,vcxproj.filters,cpp}

Moved the inline function bodies to the header files and removed the inline files from the distribution (to reduce file count).

Tools/GenerateApproximations/GteAMDPerformance.{vcxproj,vcxproj.filters}  
Tools/GPUPerfAPI-2.1.739.0/GteAMDPerformance.h  
Tools/GenerateApproximations/FitASin.h  
Tools/GenerateApproximations/FitATan.h  
Tools/GenerateApproximations/FitCos.h  
Tools/GenerateApproximations/FitExp2.h  
Tools/GenerateApproximations/FitASin.h  
Tools/GenerateApproximations/FitInvSqrt.h  
Tools/GenerateApproximations/FitLog2.h  
Tools/GenerateApproximations/FitReciprocal.h  
Tools/GenerateApproximations/FitSin.h

Tools/GenerateApproximations/FitTan.h  
Tools/GPUPerfAPI-2.1.739.0/GteAMDPerformance.inl  
Tools/GenerateApproximations/FitASin.inl  
Tools/GenerateApproximations/FitATan.inl  
Tools/GenerateApproximations/FitCos.inl  
Tools/GenerateApproximations/FitExp2.inl  
Tools/GenerateApproximations/FitASin.inl  
Tools/GenerateApproximations/FitInvSqrt.inl  
Tools/GenerateApproximations/FitLog2.inl  
Tools/GenerateApproximations/FitReciprocal.inl  
Tools/GenerateApproximations/FitSin.inl  
Tools/GenerateApproximations/FitTan.inl

Fixed a build break in the AMD performance sample. The sample needed updating because of several recent changes in GTEngine.

Samples/Basics/PerformanceAMD/PerformanceAMDWindow.{h,cpp}  
Samples/Basics/PerformanceAMD/PerformanceAMD.{vcxproj,vcxproj.filters}

**December 28, 2014.** Added template aliases [TIntervalInterval](#) and [FIntervalInterval](#).

IntrIntervals.h

Modified the document on line-cone intersection and updated the code comments to match it.

IntersectionLineCone.pdf (*Intersection of a Line and a Cone*)  
IntrLine3Cone3.h  
IntrRay3Cone3.h  
IntrSegment3Cone3.h

**January 4, 2015.** Added test-intersection query for 3D aligned boxes and cones. Modified the test-intersection query for 3D oriented boxes to derive from the new query. Added template aliases [TAlignedBox3Cone3](#) and [TIOrientedBox3Cone3](#) for convenience. Modified the sample application for testing the code.

IntrOrientedBox3Cone3.h  
Samples/Geometrics/IntersectBoxCone/IntersectBoxConeWindow.{h,cpp}  
IntrAlignedBox3Cone3.h  
IntersectionBoxCone.pdf (*Intersection of a Box and a Cone*)

## 81 Updates to Version 1.6

**November 27, 2014.** The pseudocode for computing the fitted cylinder subtracted the input point average

for numerically stable computations. The returned center needed the average added to it.

[CylinderFitting.pdf](#) (*Fitting 3D Data with a Cylinder*)

**November 28, 2014.** The B-spline curve and surface fitting had problems when the matrix storage convention is `GTE_USE_COL_MAJOR`. The banded matrix system solver and inverter selected storage convention based on the macro setting. Instead, the convention must be selected by the user based on his knowledge of the storage used by the input matrices. The relevant functions in `BandedMatrix` are now templates with a Boolean parameter that specifies the storage convention. The fitter classes have always used row-major order, regardless of the `GTEngine` macro that is active.

[BandedMatrix.{h,inl}](#)  
[BSplineCurveFit.inl](#)  
[BSplineSurfaceFit.inl](#)

**December 1, 2014.** Added estimates for the SLERP of quaternions. Factored out the estimations into the class `ChebyshevRatio` so that they can be used for vectors of other dimensions. The error bounds for the Chebyshev ratios are now reported based on numerical experiments; the paper on which they were based had a flawed error analysis. Revised the `Quaternion` class to use the general formula for SLERP rather than the estimate it had been using. Added more SLERP functions that have restricted domains and allow for preprocessing of quaternions (as animation data). In particular the `EstimateRPH` is useful for preprocessed quaternions that allow the estimates to be applied for angles no larger than  $\pi/4$ , leading to very small errors.

[GTEngine.{h,vcxproj,vcxproj.filters}](#)  
[Quaternion.{h,inl}](#)  
[ChebyshevRatio.{h,inl}](#)  
[SlerpEstimate.{h,inl}](#)

**December 2, 2014.** The `Vector2`, `Vector3`, and `Vector4` classes derived from `Vector` existed solely to provide constructors for 2, 3, or 4 inputs, respectively. We added two constructors to `Vector`, one having an input `std::array<Real>` and one that has the input `std::initialize`, allowing an arbitrary number of inputs. We have removed the derived classes, but you can still use the class names because we have used template aliasing to define them properly. For example, the alias for 2D vectors is

```
template <typename Real>
using Vector2 = Vector<2,Real>;
```

We eliminated special static members and used instead `Vector` specials. The comparison operators now directly use the lexicographically based ones for `std::array`. Quite a large number of files have changed, both engine and application code.

[Vector.{h,inl}](#)  
[Vector2.{h,inl}](#)  
[Vector3.{h,inl}](#)  
[Vector4.{h,inl}](#)

ApprEllipse2.inl  
 ApprEllipsoid3.inl  
 ApprGaussian{2,3}.inl  
 ApprOrthogonalLine{2,3}.inl  
 Arc2.inl  
 BoundingSphere.{inl,cpp}  
 Circle3.inl  
 Cone3.inl  
 ContEllipse2.inl  
 ContEllipsoid3.inl  
 ContOrientedBox{2,3}.inl  
 ContPointInPolyhedron3.inl  
 ContScribeCircle2.inl  
 ContScribeCircle3Sphere3.inl  
 Delanuay{2,3}.inl  
 Delaunay{2,3}Mesh.inl  
 DistPoint3Frustum3.inl  
 Ellipse2.inl  
 Ellipsoid3.inl  
 Frustum3.inl  
 GenerateMeshUV.inl  
 Halfspace3.inl  
 IntpSphere2.inl  
 IntrCircle2Circle2.inl  
 IntrLine{2,3}OrientedBox{2,3}.inl  
 IntrLine3Capsule3.inl  
 IntrLine3Cylinder3.inl  
 IntrRay{2,3}OrientedBox{2,3}.inl  
 IntrSegment{2,3}OrientedBox{2,3}.inl  
 Line{2,3}.inl  
 MinimumAreaBox2.inl  
 MinimumAreaCircle2.inl  
 MinimumVolumeBox3.inl  
 MinimumVolumeSphere3.inl  
 OrientedBox{2,3}.inl  
 PlanarMesh.{h,inl}  
 Plane3.inl  
 Polygon2.inl  
 PolyhedralMassProperties.inl  
 Polyhedron3.inl  
 Ray{2,3}.inl  
 Segment{2,3}.inl  
 Tetrahedron3.inl  
 Torus3.inl  
 Transform.inl  
 Triangle{2,3}.inl  
 TriangulateEC.inl  
 BlendState.cpp

Camera.cpp  
 CullingPlane.cpp  
 Fluid{2,3}.cpp  
 Fluid{2,3}InitializeSource.cpp  
 LightingConstants.cpp  
 MeshFactory.cpp  
 Node.cpp  
 OverlayEffect.cpp  
 Picker.cpp  
 SamplerState.cpp  
 TextEffect.cpp  
 Visual.cpp  
 Window.cpp  
 Samples/Basics/DirectionalLightTexture/DirectionalLightTextureWindow.cpp  
 Samples/Basics/GaussianBlurring/GaussianBlurringWindow.cpp  
 Samples/Basics/GeometryShaders/GeometryShadersWindow.cpp  
 Samples/Basics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp  
 Samples/Basics/SharedTextures/SharedTexturesWindow.cpp  
 Samples/Basics/StructuredBuffers/StructuredBuffersWindow.cpp  
 Samples/Basics/TextureArrays/TextureArraysWindow.cpp  
 Samples/Basics/Texturing/TexturingWindow.cpp  
 Samples/Basics/VertexColoring/VertexColoringWindow.cpp  
 Samples/Geometries/AllPairsTriangles/AllPairsTrianglesWindow.cpp  
 Samples/Geometries/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow.cpp  
 Samples/Geometries/ConvexHull2D/ConvexHull2DWindow.cpp  
 Samples/Geometries/ConvexHull3D/ConvexHull3DWindow.cpp  
 Samples/Geometries/Delaunay2D/Delaunay2DWindow.cpp  
 Samples/Geometries/Delaunay3D/Delaunay3DWindow.cpp  
 Samples/Geometries/DistanceSegments3/DistanceSegments3.cpp  
 Samples/Geometries/MinimumAreaBox2D/MinimumAreaBox2DWindow.cpp  
 Samples/Geometries/MinimumAreaCircle2D/MinimumAreaCircle2DWindow.cpp  
 Samples/Geometries/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp  
 Samples/Geometries/MinimumVolumeSphere3D/MinimumVolumeSphere3DWindow.cpp  
 Samples/Geometries/ShortestPath/ShortestPathWindow.cpp  
 Samples/Geometries/TriangulationCDT/TriangulationCDTWindow.cpp  
 Samples/Geometries/TriangulationEC/TriangulationECWindow.cpp  
 Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.cpp  
 Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp  
 Samples/Graphics/BlownGlass/BlownGlassWindow.cpp  
 Samples/Graphics/Lights/LightsWindow.cpp  
 Samples/Graphics/Picking/PickingWindow.cpp  
 Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersectionWindow.cpp  
 Samples/Graphics/VideoStreams/VideoStreamsWindow.cpp  
 Samples/Graphics/WireMesh/WireMeshWindow.cpp  
 Samples/Imagics/Convolution/ConvolutionWindow.cpp  
 Samples/Imagics/MedianFiltering/MedianFilteringWindow.cpp  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp  
 Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.cpp



Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.cpp  
 Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp  
 Samples/Mathematics/Interpolation2D/Interpolation2DWindow.cpp  
 Samples/Mathematics/PlaneEstimation/PlaneEstimationWindow.cpp  
 Samples/Physics/Cloth/ClothWindow.cpp  
 Samples/Physics/Fluids2D/Fluids2DWindow.cpp  
 Samples/Physics/Fluids3D/Fluids3DWindow.cpp  
 Samples/Physics/MassSprings3D/MassSprings3DWindow.cpp  
 Samples/Physics/Rope/RopeWindow.cpp

Modified files to have uniformity in using `#if defined(symbol)` rather than `#ifdef symbol`.

GMatrix.inl  
 GVector.inl  
 GaussianElimination.inl  
 IntelSSE.inl  
 LinearSystem.inl  
 Logger.h  
 MinimizeN.inl  
 SingularValueDecomposition.inl  
 SymmetricEigensolver.inl  
 DX11DrawTarget.cpp  
 DX11Engine.cpp  
 DX11InputLayoutManager.cpp  
 HLSLDefiner.cpp  
 HLSLShaderFactory.cpp  
 Samples/Basics/DirectionalLightTexture/DirectionalLightTextureEffect.cpp  
 Samples/Basics/GaussianBlurring/GaussianBlurringWindow.{h,cpp}  
 Samples/Basics/GeometryShaders/GeometryShadersWindow.{h,cpp}  
 Samples/Basics/LowLevelD3D11/Application.cpp  
 Samples/Basics/Texturing/TexturingWindow.{h,cpp}  
 Samples/Basics/VertexColoring/VertexColoringWindow.{h,cpp}  
 Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.{h,cpp}  
 Samples/Geometrics/ShortestPath/ShortestPathWindow.{h,cpp}  
 Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.{h,cpp}  
 Samples/Physics/MassSprings3D/MassSprings3DWindow.{h,cpp}

The file had a template parameter hard-coded as `float` when it should have been `Real`.

IntrSphere3Frustum3.inl

**December 3, 2014.** The `Matrix2x2`, `Matrix3x3`, and `Matrix4x4` classes derived from `Matrix` existed solely to provide constructors for  $2 \times 2$ ,  $3 \times 3$ , and  $4 \times 4$  matrices. We added two constructors to `Matrix`, one having an input `std::array<Real, NumRows*NumCols>` and one that has the input `std::initialize`, allowing an arbitrary

number of inputs. We have removed the derived classes, but you can still use the class names because we have added template aliasing to define them properly. For example, the alias for  $2 \times 2$  matrices is

```
template <typename Real>
using Matrix2x2 = Matrix <2,2,Real>;
```

We also eliminated special static members and used instead **Matrix** specials. The comparison operators now use the lexicographically based ones for `std::array`.

```
Matrix.{h,inl}
Matrix2x2.{h,inl}
Matrix3x3.{h,inl}
Matrix4x4.{h,inl}
GMatrix.{h,inl}
ApprEllipse2.inl
ApprEllipsoid3.inl
ContOrientedBox3.inl
ContScribeCircle2.inl
ContScribeCircle3Sphere3.inl
IntrEllipse2Ellipse2.inl
IntrEllipsoid3Ellipsoid3.inl
OdeImplicitEuler.inl
Rotation.inl
Camera.cpp
Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp
```

Fixed a comment about the static member required by the class when you expose a conditional define.

```
UIntegerFP32.inl
```

The **UpdateConstants** function needed conditional compilation to handle either matrix-vector multiplication convention.

```
DirectionalLightTextureWindow.cpp
```

The general vector and matrix classes were modified to have the same interfaces as their template-based counterparts.

```
GMatrix.{h,inl}
GVector.{h,inl}
Matrix.{h,inl}
Vector.{h,inl}
```

**December 4, 2014.** Removed the macro **GTE.MAKE.HLSL.STRING**. This macro was handy, allowing you to embed HLSL code in a CPP file, view it, and modify it as if it were regular C++ code. The macro builds

a string that is sent to the HLSL compiler, but before doing so we used `<regex>` to substitute matches in regular expressions involving preprocess macros such as `#if` and `#ifdef`. Unfortunately, the macro does not work on Linux or Macintosh machines as a general string building mechanism using gcc compilers. Our built-in effects such as `Texture2Effect` all had preprocessor defines involving `#ifdef GTE_USE_MAT_VEC` to control whether the shader should use the matrix-vector or vector-matrix multiplication convention. The C++ syntax highlighting made it appear as if the correct code blocks were exposed. The Microsoft Visual Studio 2013 compiler builds the string first, so in fact the code blocks that appeared to be active were actually not. The `HLSLDefiner` class has a mechanism for setting macro names in HLSL files before compilation; for example, it sets the string `"GTE_USE_MAT_VEC"` to the string `"1"` or `"0"` according to the convention active in the C++ code. It turns out this is incorrect, because you would instead need `#if GTE_USE_MAT_VEC` in the HLSL files. As soon as you switch to using the vector-matrix convention in C++ code, the HLSL files are incorrectly compiled and some sample applications no longer work. We also sometimes had to rewrite some HLSL lines of code because the macro was confused by the content of that code that interfered with the preprocessor's interpretation of the macro. In the end, this turned out to be a bad idea. After removal of the macro, the embedded shader code was replaced with quoted strings. Other shaders in HLSL files had to be modified to produce the correct code for vector-matrix convention. The samples have now all been tested using either matrix-vector or vector-matrix multiplication convention and using either row-major or column-major storage of the matrices (4 possible configurations). We discovered one bug in the `Transform` class, where the translation of the underlying  $4 \times 4$  matrix needed to be built differently depending on the multiplication convention. It showed up only when you use the GTEngine scene graph support and some node in the graph has a local transform with a nonzero translation.

```

ShaderFactory.{h,cpp}
ConstColorEffect.cpp
Fluid{2,3}AdjustVelocity.cpp
Fluid{2,3}ComputeDivergence.cpp
Fluid{2,3}EnforceStateBoundary.cpp
Fluid{2,3}InitializeSource.cpp
Fluid{2,3}InitializeState.cpp
Fluid{2,3}SolvePoisson.cpp
Fluid{2,3}UpdateState.cpp
GenerateMeshUVs.cpp
LightAmbientEffect.cpp
LightDirectionPerPixelEffect.cpp
LightDirectionPerVertexEffect.cpp
LightPointPerPixelEffect.cpp
LightPointPerVertexEffect.cpp
LightSpotPerPixelEffect.cpp
LightSpotPerVertexEffect.cpp
OverlayEffect.cpp
TextEffect.cpp
Texture{2,3}Effect.cpp
VertexColorEffect.cpp
Samples/Basics/DirectionalLightTexture/DirectionalLightTextureEffect.cpp
Samples/Basics/GeometryShaders/Shaders/RandomSquares.hlsl
Samples/Basics/GeometryShaders/Shaders/RandomSquaresIndirect.hlsl
Samples/Basics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp
Samples/Basics/MultipleRenderTargets/Shaders/MultipleRenderTargets.hlsl

```

Samples/Basics/ShaderReflection/TextureArrays.hlsl  
 Samples/Basics/ShaderReflection/Texturing.hlsl  
 Samples/Basics/ShaderReflection/VertexColoring.hlsl  
 Samples/Basics/StructuredBuffers/Shaders/StructuredBuffers.hlsl  
 Samples/Basics/TextureArrays/Shaders/TextureArrays.hlsl  
 Samples/Geometrics/AllPairsTriangles/Shaders/DrawUsingVertexID.hlsl  
 Samples/Geometrics/AllPairsTriangles/Shaders/TriangleIntersection.hlsl  
 Samples/Geometrics/AllPairsTriangles/Shaders/VertexColorIndexed.hlsl  
 Samples/Graphics/BlownGlass/Shaders/VolumeRender.hlsl  
 Samples/Graphics/PlaneMeshIntersection/Shaders/PlaneMeshIntersection.hlsl  
 Samples/Graphics/WireMesh/Shaders/WireMesh.hlsl  
 Samples/Imagics/SurfaceExtraction/Shaders/DrawSurfaceIndirect.hlsl  
 Samples/Physics/Fluids3D/Shaders/VolumeRender.hlsl  
 Samples/Physics/MassSprings3D/Shaders/DrawUsingVertexID.hlsl

As mentioned, we replaced the macroized embedded HLSL code in built-in effects with quoted strings. A new folder was added, **GeometricTools/GTEngine/Shaders** that contain HLSL files with this code (no quoted strings). These are just for reference and are not loaded from disk during engine/application run time. Other HLSL files used in specialized applications are loaded from disk, but the HLSL files are in the application project directory trees.

Shaders/ConstantColorEffect.hlsl  
 Shaders/DirectionalLightTextureEffect.hlsl  
 Shaders/Fluid{2,3}AdjustVelocity.hlsl  
 Shaders/Fluid{2,3}ComputeDivergence.hlsl  
 Shaders/Fluid{2,3}EnforcePoissonBoundary.hlsl  
 Shaders/Fluid{2,3}EnforceStateBoundary.hlsl  
 Shaders/Fluid{2,3}GenerateVortex.hlsl  
 Shaders/Fluid{2,3}InitializeSource.hlsl  
 Shaders/Fluid{2,3}InitializeState.hlsl  
 Shaders/Fluid{2,3}SolvePoisson.hlsl  
 Shaders/Fluid{2,3}UpdateState.hlsl  
 Shaders/Fluid{2,3}ZeroPoisson.hlsl  
 Shaders/GenerateMeshUVs.hlsl  
 Shaders/LightAmbientEffect.hlsl  
 Shaders/LightDirectionPerPixelEffect.hlsl  
 Shaders/LightDirectionPerVertexEffect.hlsl  
 Shaders/LightPointPerPixelEffect.hlsl  
 Shaders/LightPointPerVertexEffect.hlsl  
 Shaders/LightSpotPerPixelEffect.hlsl  
 Shaders/LightSpotPerVertexEffect.hlsl  
 Shaders/MultipleRenderTargetsPShader{0,1,2,3,4}.hlsl  
 Shaders/OverlayEffectColorPShader.hlsl  
 Shaders/OverlayEffectGrayPShader.hlsl  
 Shaders/OverlayEffectVShader.hlsl  
 Shaders/TextEffect.hlsl  
 Shaders/Texture{2,3}Effect.hlsl

Shaders/VertexColorEffect.hlsl

We discovered a bug in the `Transform` class, where the translation of the underlying  $4 \times 4$  matrix needed to be built differently depending on the multiplication convention. It showed up only when you use the GTEngine scene graph support and some node in the graph has a local transform with a nonzero translation.

`Transform.{h,inl}`

We had added the capability to select (`GTE_USE_MAT_VEC` or `GTE_USE_VEC_MAT`) and (`GTE_USE_ROW_MAJOR` or `GTE_USE_COL_MAJOR`). This capability has been removed because it has the potential to cause mismatches in CPP code. The comments in the file had indicated this. The conclusion is that if you want conventions different from our defaults, you will have to modify `GTEngineDEF.h` to select yours, and you will have to modify this file every time you grab a newer distribution.

`GTEngineDEF.h`

The points were not rotating with the trackball (the segments and sphere were). Subscribed the points up to the automatic update mechanism of class `Window`.

`Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3D.h`  
`Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3D.cpp`

Converted an `#ifdef` to `#if defined()`.

`Samples/Graphics/VideoStreams/VideoStreamsWindow.cpp`

**December 7, 2014.** Factored out the calls to `memcpy` and `memcpy_s` to a wrapper function `Memcpy` to encapsulate the platform differences in a single location.

`GTEngine.{h,vcxproj,vcxproj.filters}`  
`GaussianElimination.{h,inl}`  
`GenerateMeshUV.{h,inl}`  
`LinearSystem.{h,inl}`  
`MinimizeN.{h,inl}`  
`SingularValueDecomposition.{h,inl}`  
`SymmetricEigensolver.{h,inl}`  
`DX11Buffer.cpp`  
`DX11Texture.cpp`  
`HLSLShader.cpp`  
`HLSLShaderVariable.cpp`  
`Font.cpp`

```

MarchingCubes.cpp
Image.cpp
Samples/Basics/GeometryShaders", "GeometryShadersWindow.cpp
Samples/Basics/MultipleRenderTargets", "MultipleRenderTargetsWindow.cpp
Samples/Basics/TextureArrays", "TextureArraysWindow.cpp
Samples/Geometries/ConvexHull3D", "ConvexHull3DWindow.cpp
Samples/Geometries/MinimumVolumeBox3D", "MinimumVolumeBox3DWindow.cpp
Samples/Imagics/MedianFiltering", "MedianFilteringWindow.cpp
Wrapper.{h,cpp}

```

The function body for [Contain](#) was in the header file. Moved it to the inline file to be consistent with style.

```
PlanarMesh.h
```

A new document describing a variation of an iterative eigensolver for symmetric  $3 \times 3$  matrices. A source code implementation and a sample application are provided.

```

GTEngine.{h,vcxproj,vcxproj.filters}
GTBuildAll.sln
SymmetricEigensolver3x3.{h,inl}
Samples/Mathematics/SymmetricEigensolver3x3/SymmetricEigensolver3x3.{sln,vcxproj}
Samples/Mathematics/SymmetricEigensolver3x3/SymmetricEigensolver3x3.{vcxproj.filters,cpp}
RobustEigenSymmetric3x3.pdf (A Robust Eigensolver for 3x3 Symmetric Matrices)

```

**December 8, 2014.** Started the process of consolidating and sharing code for various geometric primitives by using templates for which the dimension is one of the parameters. This will occur in stages. The list of new files for the first stage is shown next.

```

GTEngine.{h,vcxproj,vcxproj.filters}
AlignedBox.{h,inl}
DistPointAlignedBox.{h,inl}
DistPointLine.{h,inl}
DistPointOrientedBox.{h,inl}
DistPointRay.{h,inl}
DistPointSegment.{h,inl}
DistSegmentSegment.{h,inl}
Hyperellipsoid.{h,inl}
Hypersphere.{h,inl}
Line.{h,inl}
OrientedBox.{h,inl}
Ray.{h,inl}
Segment.{h,inl}
ApprEllipse2.{h,inl}
ApprEllipsoid3.{h,inl}

```

ApprGaussian{2,3}.h  
 ApprQuadratic{2,3}.h  
 ApprOrthogonalLine{2,3}.h  
 Capsule3.h  
 ContCapsule3.h  
 ContCircle2.h  
 ContCylinder3.h  
 ContEllipse2.h  
 ContEllipsoid3.h  
 ContOrientedBox{2,3}.inl  
 ContOrientedBox3.inl  
 ContScribeCircle3Sphere3.h  
 ContScribeSphere3.h  
 ConvexHull{2,3}.h  
 Cylinder3.h  
 Delaunay{2,3}.h  
 DistLine{2,3}Line{2,3}.h  
 DistLine{2,3}Ray{2,3}.h  
 DistLine{2,3}Segment{2,3}.h  
 DistLine3AlignedBox3.h  
 DistPoint2Ellipse2.h  
 DistPoint3Ellipsoid3.h  
 DistRay{2,3}Ray{2,3}.h  
 DistRay{2,3}Segment{2,3}.h  
 DistRay3AlignedBox3.{h,inl}  
 DistRay3OrientedBox3.{h,inl}  
 DistRay3Rectangle3.h  
 DistRay3Triangle3.h  
 DistSegment3AlignedBox3.{h,inl}  
 DistSegment3OrientedBox3.{h,inl}  
 DistSegment3Rectangle3.h  
 DistSegment3Triangle3.h  
 IntpQuadraticNonuniform2.{h,inl}  
 IntrCircle2Circle2.h  
 IntrAlignedBox{2,3}AlignedBox{2,3}.h  
 IntrAlignedBox{2,3}OrientedBox{2,3}.{h,inl}  
 IntrCapsule3Capsule3.h  
 IntrEllipse2Ellipse2.{h,inl}  
 IntrHalfspace3Ellipsoid3.h  
 IntrHalfspace3OrientedBox3.h  
 IntrHalfspace3Segment3.h  
 IntrHalfspace3Sphere3.h  
 IntrLine2AlignedBox2.h  
 IntrLine2Circle2.h  
 IntrLine2Line2.h  
 IntrLine2OrientedBox2.h  
 IntrLine2Ray2.h  
 IntrLine2Segment2.h

IntrLine2Triangle2.h  
 IntrLine3AlignedBox3.h  
 IntrLine3Cone3.h  
 IntrLine3Cylinder3.h  
 IntrLine3Ellipsoid3.h  
 IntrLine3OrientedBox3.h  
 IntrLine3Plane3.h  
 IntrLine3Sphere3.h  
 IntrLine3Triangle3.h  
 IntrOrientedBox2Circle2.h  
 IntrOrientedBox{2,3}OrientedBox{2,3}.{h,inl}  
 IntrOrientedBox3Frustum3.{h,inl}  
 IntrOrientedBox3Sphere3.h  
 IntrPlane3Cylinder3.h  
 IntrPlane3Ellipsoid3.h  
 IntrPlane3OrientedBox3.h  
 IntrPlane3Plane3.h  
 IntrRay2AlignedBox2.h  
 IntrRay2Circle2.h  
 IntrRay2OrientedBox2.h  
 IntrRay2Ray2.h  
 IntrRay2Segment2.h  
 IntrRay2Triangle2.h  
 IntrRay3AlignedBox3.h  
 IntrRay3Cone3.h  
 IntrRay3Cylinder3.h  
 IntrRay3Ellipsoid3.h  
 IntrRay3OrientedBox3.h  
 IntrRay3Plane3.h  
 IntrRay3Sphere3.h  
 IntrRay3Triangle3.h  
 IntrSegment{2,3}AlignedBox{2,3}.h  
 IntrSegment2Circle2.h  
 IntrSegment{2,3}OrientedBox{2,3}.h  
 IntrSegment2Segment2.h  
 IntrSegment2Triangle2.h  
 IntrSegment3Capsule3.h  
 IntrSegment3Cone3.h  
 IntrSegment3Cylinder3.h  
 IntrSegment3Ellipsoid3.h  
 IntrSegment3Plane3.h  
 IntrSegment3Sphere3.h  
 IntrSegment3Triangle3.h  
 IntrSphere3Cone3.h  
 MinimumAreaBox2.h  
 MinimumAreaCircle2.h  
 MinimumVolumeBox3.{h,inl}  
 MinimumVolumeSphere3.h



```

Picker.{h,cpp}
Projection.h
Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp
Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2DWindow.cpp
Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.cpp
AlignedBox{2,3}.{h,inl}
Circle2.{h,inl}
Ellipse2.{h,inl}
Ellipsoid3.{h,inl}
Point{2,3}AlignedBox{2,3}.{h,inl}
Point{2,3}Line{2,3}.{h,inl}
Point{2,3}OrientedBox{2,3}.{h,inl}
Point{2,3}Ray{2,3}.{h,inl}
Point{2,3}Segment{2,3}.{h,inl}
DistSegment{2,3}Segment{2,3}.{h,inl}
Line{2,3}.{h,inl}
OrientedBox{2,3}.{h,inl}
Ray{2,3}.{h,inl}
Segment{2,3}.{h,inl}
Sphere3.{h,inl}

```

Implemented separate code for segment-segment intersection using exact rational arithmetic.

```

DistSegmentSegmentExact.{h,inl}
Samples/Geometrics/DistanceSegments3/DistanceSegments3.cpp
DistanceSegmentsRobust.{h,inl}

```

Implemented the special case symmetric eigensolver for  $2 \times 2$  matrices.

```

SymmetricEigensolver2x2.{h,inl}

```

**December 9, 2014.** Another stage of consolidating code to support objects of multiple dimension, classes [Hyperplane](#), [Halfspace](#), and [Triangle](#).

```

GTEngine.{h,vcxproj,vcxproj.filters}
Halfspace.{h,inl}
Hyperplane.{h,inl}
Triangle.{h,inl}
ConvexHull3.h
Delaunay3.h
DistLine3Triangle3.h
DistPoint3Triangle3.h
DistPoint3Plane3.h
IntrHalfspace3Capsule3.h

```

```

IntrHalfspace3Cylinder3.h
IntrHalfspace3Ellipsoid3.h
IntrHalfspace3OrientedBox3.h
IntrHalfspace3Segment3.h
IntrHalfspace3Sphere3.h
IntrHalfspace3Triangle3.h
IntrLine{2,3}Triangle{2,3}.h
IntrPlane3Plane3.h
IntrPlane3Triangle3.h
IntrRay3Triangle3.h
IntrSegment3Triangle3.h
SeparatePoints3.inl
Tetrahedron.h
Halfspace3.{h,inl}
Plane3.{h,inl}
Triangle2.{h,inl}

```

Removed the class [GeometricPrimitive](#). We thought it would store more information per object type, but given it is a fancy base class for comparison operators, it is not necessary.

```

GTEngine.{h,vcxproj,vcxproj.filters}
Arc2.{h,inl}
Capsule3.{h,inl}
Circle3.{h,inl}
Cone3.{h,inl}
Cylinder3.{h,inl}
Ellipse3.{h,inl}
Frustum3.{h,inl}
Polygon2.h
Polyhedron3.h
Rectangle3.{h,inl}
Tetrahedron3.{h,inl}
Torus3.{h,inl}
GeometricPrimitive.{h,inl}

```

In [SymmetricEigensolver](#), the test for a sort request in the function to get a single eigenvector was incorrect. Added functions to [SingularValueDecomposition](#) to get one singular value or one column of an orthogonal matrix. This is useful when you do not need an entire matrix.

```

SymmetricEigensolver.inl
SingularValueDecomposition.{h,inl}

```

**December 12, 2014.** Replaced the code for distance queries point-ellipse and point-ellipsoid with point-hyperellipsoid, where the dimension of the hyperellipsoid is now a template parameter. Added unit tests

for the code to compute the point-ellipse and point-ellipsoid distance. The tests provide 100 percent code coverage. Updated the PDF that describes the algorithm to reflect some modifications made in the code.

[DistancePointEllipseEllipsoid.pdf](#) (*Distance from a Point to an Ellipse, an Ellipsoid, or a Hyperellipsoid*)  
[GTEngine.{h,vcxproj,vcxproj.filters}](#)  
[ApprEllipse2.h](#)  
[ApprEllipsoid3.h](#)  
[DistPointHyperellipsoid.{h,inl}](#)  
[DistPoint2Ellipse2.{h,inl}](#)  
[DistPoint3Ellipsoid3.{h,inl}](#)

Fixed a porting bug in [IntrLine2Line2](#) that had the cases swapped between parallel-and-equal and parallel-and-not-equal lines.

[IntrLine2Line2.inl](#)

Removed unused variables (LLVM on Macintosh complained).

[ContCapsule3.inl](#)

Return type of [SetMaxSizeToZero](#) needed to be void (LLVM on Macintosh complained).

[UIntegerAP32.h](#)  
[UIntegerFP32.h](#)

LLVM on Macintosh complained about the [SolveSystem<Real>](#) function call, requiring the [template](#) keyword to modify the function call. The fitter classes have a non-templated [SolveSystem](#) and a templated [SolveSystem](#), but they have different numbers of inputs. Perhaps C++ 11 requires the disambiguation anyway.

[BSplineCurveFit.inl](#)  
[BSplineSurfaceFit.inl](#)

## 82 Updates to Version 1.5

**November 6, 2014.** Implemented a robust algorithm for computing the distance between line segments in any dimension. Revised the PDF for computing distance between segments in 3D to describe the new algorithm. A GPU implementation is available in the sample application.

[GTEngine.{h,vcxproj,vcxproj.filters}](#)  
[GTBuildAll.sln](#)

DistanceSegmentsRobust.{h,inl}  
Samples/Geometrics/DistanceSegments3/DistanceSegments3.{sln,vcxproj,vcxproj.filters,cpp}  
Samples/Geometrics/DistanceSegments3/DistanceSeg3Seg3.hsl  
DistanceLine3Line3.pdf (*Distance Between Two Line Segments in 3D*)

Added a class to simplify counting how many bits of precision are needed by a sequence of expressions. This is useful to determine how large **N** must be in the template class **BSUInteger<N>** for **BSRational** to work properly in a geometric algorithm.

GTEngine.{h,vcxproj,vcxproj.filters}  
BSPrecision.{h,cpp}

Added a copy constructor and assignment operator.

MinHeap.{h,inl}

Added an equality comparison operator.

FeatureKey.{h,inl}

**November 7, 2014.** Implemented the TODO items in **BSRational**, adding conversions to **float** or **double** that produce correctly rounded results using round-to-nearest-ties-to-even. Added **std::min** and **std::max** functions for **BSNumber** and **BSRational**.

BSNumber.h  
BSRational.{h,inl}

**November 8, 2014.** Added **static\_assert** statements to ensure that the templates are instantiated only for dimensions 3 or 4.

Vector3.inl  
AxisAngle.{h,inl}  
Rotation.inl

Fixed a build break in the explicit instantiation tests for the **IsValid** debug support function.

MinHeap.inl

**November 9, 2014.** Modified an accessor to return the actual **UIntegerType** object rather than a pointer to the array it manages. This allows you to query how many unsigned integers are stored by the object.

BSNumber.{h,inl}

**November 18, 2014.** Removed the division of `delta` by `WHEEL_DELTA` in the message handler for the message `WM.MOUSEWHEEL`. The documentation indicates the `delta` is supposed to be in multiples of `WHEEL_DELTA`, but finer-resolution mouse wheels can send values smaller than `WHEEL_DELTA`. The `delta` passed to `Window::OnMouseWheel(delta,x,y,modifiers)` is now whatever the message has stored in the `WPARAM` value.

Window.h  
WindowSystem.cpp

**November 25, 2014.** Overhauled the arbitrary precision library to improve the performance and to improve readability. The unsigned integer arithmetic was factored out of `BSNumber` into two classes, one for arbitrary precision with storage of type `std::vector` and one for user-selected fixed precision with storage of type `std::array`. Both classes share code for the arithmetic logic unit. Many computations are now performed in-place to avoid expensive allocation, deallocation, and memory copies. A new PDF is posted that greatly expands on the library compared to the discussion in the *GPGPU Programming for Games and Science* book. The document serves as a discussion about the design of the library and a reference for how to use it. Examples are provided for using `BSPrecision` to determine the template parameter of `UIntegerFP<N>` that represents the maximum number of bits required to compute the exact results for a sequence of expressions.

GTEngine.{h,vcxproj,vcxproj.filters}  
BSNumber.{h,inl}  
BSRational.{h,inl}  
BSPrecision.{h,cpp}  
Samples/Geometries/ConstrainedDelaunay2D/ConstrainedDelaunay2DWindow.h  
Samples/Geometries/ConvexHull2D/ConvexHull2DWindow.h  
Samples/Geometries/ConvexHull3D/ConvexHull3DWindow.cpp  
Samples/Geometries/Delaunay2D/Delaunay2DWindow.h  
Samples/Geometries/Delaunay3D/Delaunay3DWindow.h  
Samples/Geometries/DistanceSegments3/DistanceSegments3.cpp  
Samples/Geometries/MinimumAreaBox2D/MinimumAreaBox2DWindow.h  
Samples/Geometries/MinimumAreaCircle2D/MinimumAreaCircle2DWindow.h  
Samples/Geometries/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.h  
Samples/Geometries/MinimumVolumeSphere3D/MinimumVolumeSphere3DWindow.h  
Samples/Geometries/TriangulationCDT/TriangulationCDTWindow.h  
Samples/Geometries/TriangulationEC/TriangulationECWindow.h  
Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp  
Samples/Mathematics/Interpolation2D/Interpolation2DWindow.h  
UIntegerALU32.{h,inl}  
UIntegerAP32.{h,inl,cpp}  
UIntegerFP32.{h,inl}  
ArbitraryPrecision.pdf (*GTEngine: Arbitrary Precision Arithmetic*)

## 83 Updates to Version 1.4

**September 27, 2014.** Removed the include of `atlcomcli.h` and added a simple wrapper for the COM objects. This eliminates the dependency of GTEngine on Microsoft's Active Template Library (ATL) so that the engine compiles using Microsoft Visual Studio 2013 Express Edition (which does not ship with MFC or ATL).

`WICFileIO.{h,cpp}`

**September 28, 2014.** The engine was designed to allow you to run versions of DirectX 10 and previous. However, the default target strings to the `ShaderFactory::Create*` compilation functions were hard-coded to use Shader Model 5 (DirectX 11). A static member was added, `std::string ShaderFactory::defaultShaderModel`, whose default is `"5_0"`. If you want to use DirectX 10.0 in any of our samples, you must add two lines of code in the `main` function. For example, in the sample file `GTEngine/Basics/VertexColoring/VertexColoring.cpp` there is a block of code that sets members of `parameters`. Add two more lines,

```
parameters.featureLevel = D3D_FEATURE_LEVEL_10_0;  
ShaderFactory::defaultShaderModel = "4_0";
```

DirectX 10.0 corresponds to Shader Model 4.0. If instead you want to run the sample with DirectX 10.1, then use

```
parameters.featureLevel = D3D_FEATURE_LEVEL_10_1;  
ShaderFactory::defaultShaderModel = "4_1";
```

You may select a default shader model that is less powerful than what the feature level supports. For example, you can select feature level 11.0 yet have a default shader model of `"4_1"` for compiling the shaders. The sample file for blended terrain had hard-coded targets provided explicitly in the calls to the shader factory; these were replaced by strings using `defaultShaderModel`.

`ShaderFactory.{h,cpp}`  
`Samples/Graphics/BlendedTerrain/BlendedTerrainEffect.cpp`

During drag-resize of the window boundary, `Window::OnResize` needed to trigger a redraw. Added a call to `Window::OnIdle` to allow the application to redraw.

`Window.cpp`

**October 2, 2014.** Added a new sample that illustrates shaders that combine texturing and per-pixel directional lighting.

`GTBuildAll.sln`  
`Samples/Basics/DirectionalLightTexture/DirectionalLightTexture.{sln,vcxproj,vcxproj.filters,cpp}`  
`Samples/Basics/DirectionalLightTexture/DirectionalLightTextureWindow.{h,cpp}`  
`Samples/Basics/DirectionalLightTexture/DirectionalLightTextureEffect.{h,cpp}`

**October 5, 2014.** Added a query `IsOriented()` to determine whether the mesh is orientable (all triangles in a connected component have the same topological orientation). Added a query `GetComponents(...)` to compute the connected components of the edge-triangle graph of the mesh.

`ETManifoldMesh.{h,cpp}`

Added a smaller helper class to generate a set of unique vertices from a triangle soup or from a collection of indexed triangles.

`GTEngine.{h,vcxproj,vcxproj.filters}`  
`UniqueVerticesTriangles.{h,inl}`

The file did not compile when `GTE.IMAGICS_ASSERT_ON_INVALID_INDEX` was exposed. Changed an index `i` to `d`. Moved the code contain this preprocessor symbol to the inline file so that our test framework will trap such problems. Made similar changes to test `GTE.VERIFY_PRIMITIVE_TYPE` in the `IndexBuffer` class. The inline file is new.

`Image.{h,inl,cpp}`  
`IndexBuffer.{h,inl,cpp}`

**October 6, 2014.** Revised the design of the sample application to be more clear about the concepts it illustrates. The original design had a  $512 \times 256$  application with the left subwindow showing the rendered square and the right subwindow showing the linearized depth of the rendering. The new design has a  $512 \times 512$  window and allows you to select any of 7 overlays. See the sample application webpage for details and screen captures.

`Samples/Basics/MultipleRenderTargets/MultipleRenderTargets.cpp`  
`Samples/Basics/MultipleRenderTargets/MultipleRenderTargetsWindow.{h,cpp}`  
`Samples/Basics/MultipleRenderTargets/Shaders/MultipleRenderTargets.hlsl`

**October 7, 2014.** Removed some of the flag testing in the `Initialize` call because they do not occur for structured buffers.

`HLSLStructuredBuffer.cpp`

Added `LogWarning` statements to the `TestIntersection` calls when a bounding sphere radius is zero. The picking system requires the bounding spheres to be computed, but the user is responsible for calling `UpdateModelBound` on a `Visual` object before passing it to the picking system. The `LogWarning`, when it occurs, is a hint that perhaps you did not call the update function.

`BoundingSphere.cpp`

The typecast of `mCounterStaging` in `GetNumActiveElements` is not necessary. In a previous version of the class, `mCounterStaging` was in a base class and declared as `ID3D11Resource*`, which at that time required the typecast.

`DX11StructuredBuffer.cpp`

The CPU copy of the power factor is modified in the application code but on each change the engine needed to update the GPU copy.

`Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp`

**October 8, 2014.** The `SetEnvironment` functions needed their search paths modified because of the merging of the old `Numerics` sample folder into `Mathematics`.

`Samples/Mathematics/PartialSums/PartialSums.cpp`  
`Samples/Mathematics/PlaneEstimation/PlaneEstimationWindow.cpp`  
`Samples/Mathematics/RootFinding/RootFinding.cpp`

**October 12, 2014.** Ported the Wild Magic code for triangulation of polygons, nested polygons, and trees of nested polygons using ear clipping.

`GTBuildAll.sln`  
`GTEngine.{h,vcxproj,vcxproj.filters}`  
`TriangulationByEarClipping.pdf` (*Triangulation by Ear Clipping*)  
`TriangulateEC.{h,inl}`  
`Samples/Geometrics/TriangulationEC/TriangulationEC.{sln,vcxproj,vcxproj.filters,cpp}`  
`Samples/Geometrics/TriangulationEC/TriangulationECWindow.{h,cpp}`

**October 13, 2014.** The segment-object and ray-object tests use the line-object test to produce a t-interval of intersection corresponding to the line. The t-interval is then intersected with the segment t-interval or ray t-interval to determine the final intersection. The interval-interval test results needed to be used in the final determination. This was a porting error from Wild Magic to GTEngine.

`IntrRay3Capsule3.inl`  
`IntrRay3Cone3.inl`  
`IntrRay3Cylinder3.inl`  
`IntrRay3Ellipsoid3.inl`  
`IntrRay3Sphere3.inl`  
`IntrSegment3Capsule3.inl`  
`IntrSegment3Cone3.inl`  
`IntrSegment3Cylinder3.inl`  
`IntrSegment3Ellipsoid3.inl`  
`IntrSegment3Sphere3.inl`



**October 14, 2014.** Some code contained assignments of `ETManifoldMesh` objects, but the class does not have a copy constructor or assignment operator. The `std::map` members have dynamically allocated objects, so the assignments lead to memory leaks. Implemented a `Clear()` function, because the application code really wants to reset the mesh objects rather than copy them, but added a copy constructor and assignment operator in case other applications do require copies.

```
ETManifoldMesh.{h,cpp}  
GenerateMeshUV.inl  
ConvexHull3.inl  
Delaunay2.inl  
ConstrainedDelaunay2.inl
```

**October 15, 2014.** The `DoQuery` function had a case where `result.intersect` was uninitialized on return. Restructured the code to be clearer about setting members of `result` and removed the `Logger` code. Revised the test code for both line-capsule and line-cylinder and moved it into the formal unit test suite.

```
IntrLine3Capsule3.inl  
IntrLine3Cylinder3.{h,inl}
```

**October 16, 2014.** Added a convenient `GetComponents` function that returns `TriangleKey` objects rather than pointers from the containers of the calling `ETManifoldMesh` object. This allows you to clear or destroy the mesh before consuming the components.

```
ETManifoldMesh.{h,cpp}
```

Added tests for edges that have length zero and assigned reasonable weights. Such degeneracies can happen unexpectedly due to floating-point rounding errors; for example, you might start with a mesh with distinct vertices and run a smoothing filter that can lead to duplicate vertices.

```
GenerateMeshUV.inl
```

**October 18, 2014.** Added two member functions that can be used to address some practical problems that arise when working with planar meshes. The extensive comments in the header file explain what the problems can be and how to deal with them.

```
PlanarMesh.{h,inl}
```

**October 19, 2014.** Fixed the conversions from matrix or quaternion to axis-angle. The Wild Magic code had a wrapper `Math<Real>::ACos(z)` that tested for out-of-range `z`, clamping the input to `[-1,1]` by using if-then statements. This code was replaced by clamping using `std::min` and `std::max`, but was incorrectly implemented. Also, the implicit conversion from `Rotation<N,Real>` to Euler angles did not work because the caller needs to specify the order of axes. The implicit conversion was replaced by an `operator()` member that allows the user to specify the order. Our internal unit tests were updated accordingly.

Rotation.{h,inl}  
Transform.inl

**October 20, 2014.** The volume equation for a dodecahedron was in error.

PlatonicSolids.pdf (*Platonic Solids (parameters, vertices, mesh connectivity)*)

**October 23, 2014.** Ported the min-heap template class from Wild Magic. The class is intended to be a priority queue with the additional behavior that non-root heap nodes can have their weights modified followed by an update step that restores the heap to a min-heap. This is useful in several geometric algorithms. The comments in the header file provide more details and an example use in a geometric algorithm.

GTEngine.{h,vcxproj,vcxproj.filters}  
MinHeap.{h,inl}

These 2D sample applications were designed to illustrate computational geometry algorithms and draw the results in a fixed-size window. The lambda expressions used for drawing, however, require that the window not be resized because they access the screen texture whose size is determined by the initial window size. In the `main` function, we now set `parameters.allowResize = false`.

Samples/Geometrics/ConstrainedDelaunay2D/ConstrainedDelaunay2D.cpp  
Samples/Geometrics/ConvexHull2D/ConvexHull2D.cpp  
Samples/Geometrics/Delaunay2D/Delaunay2D.cpp  
Samples/Geometrics/Delaunay2D/Delaunay2DWindow.cpp  
Samples/Geometrics/MinimumAreaBox2D/MinimumAreaBox2D.cpp  
Samples/Geometrics/MinimumAreaCircle2D/MinimumAreaCircle2D.cpp  
Samples/Geometrics/TriangulationEC/TriangulationEC.cpp  
Samples/Geometrics/TriangulationEC/TriangulationECWindow.h  
Samples/Geometrics/TriangulationEC/TriangulationECWindow.cpp

Modified the `Load` functions to have a parameter that allows you to disable the pixel type check. This is useful when one application saves the file, another loads it, the pixel types are compatible, but the run-time type information does not match.

Image1.{h,inl}  
Image2.{h,inl}  
Image3.{h,inl}

Added an include command to ensure the file compiles if the pre-compiled header system is disabled.

GenerateMeshUVs.cpp

**October 24, 2014.** Added code for triangulation of a simple polygon, a polygon with holes, or a tree of nested polygons. The code uses constrained Delaunay triangulation. The sample application shows how you can take advantage of the convex hull that the code generates, where the triangles are classified as inside the polygon or outside the polygon.

```
GTEngine.{h,vcxproj,vcxproj.filters}  
GTBuildAll.sln  
TriangulateCDT.{h,inl}  
Samples/Geometrics/TriangulationCDT/TriangulationCDT.{sln,vcxproj,vcxproj.filters,cpp}  
Samples/Geometrics/TriangulationCDT/TriangulationCDTWindow.{h,cpp}
```

**October 25, 2014.** Added the ability to control `ITERATOR_DEBUG_LEVEL` globally by defining values for this in `GTEngineDEF.h`. The global exposure required some header files to have includes of `GTEngineDEF.h`. In debug configurations, the maximum amount of iterator debugging is enabled in Microsoft Visual Studio. This can often lead to very long debug times, which might be painful during development. Turning it off can speed up the times, but of course you will not have the benefit of trapping iterator problems or range checking. Three files needed the `GTE_IMPEXP` flag added (DLL configurations have not yet been added, however).

```
GTEngineDEF.h  
ApprQuery.h  
Array2.h  
AtomicMinMax.h  
Constants.h  
DCPQuery.h  
FeatureKey.h  
FIQuery.h  
GeometricPrimitive.h  
Histogram.h  
IEEEBinary.h  
LogToMessageBox.h  
LogToOutputWindow.h  
Memory.h  
RangeIteration.h  
RootsBisection.h  
RootsBrentsMethod.h  
RootsPolynomial.h  
SingularValueDecomposition.h  
ThreadSafeMap.h  
ThreadSafeQueue.h  
TIQuery.h  
UniqueVerticesTriangles.h  
Vector.h
```

On Linux and Macintosh, the file needed an include of `<cstring>` for `memset` to be defined. Microsoft Visual Studio implicitly allows this function without the include.

MassSpringArbitrary.h

## 84 Updates to Version 1.3

**September 14, 2014.** The `#Samples` and `#Tools` folder names are not friendly to Linux because of the leading hash mark. The folders were moved to the corresponding folders without the hash marks. The `#Data` subfolder of `Samples` was also renamed (to `Data`), which required changing the path handling in several sample applications. Also, the `Samples/Numerics` applications were moved to the `Samples/Mathematics` folder because there is really no important distinction between the two types (just as in Wild Magic).

GTBuildAll.sln  
Samples/Basics/GaussianBlurring/GaussianBlurringWindow.cpp  
Samples/Basics/MultipleRenderTargets/MultipleRenderTargetsWindow.cpp  
Samples/Basics/StructuredBuffers/StructuredBuffersWindow.cpp  
Samples/Basics/TextureArrays/TextureArraysWindow.cpp  
Samples/Basics/Texturing/TexturingWindow.cpp  
Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp  
Samples/Graphics/Picking/PickingWindow.cpp  
Samples/Imagics/Convolution/ConvolutionWindow.cpp  
Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.cpp  
Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp  
Samples/Mathematics/Interpolation2D/Interpolation2DWindow.cpp

Ported several Wild Magic physics library files to GTEngine.

GTEngine.{h,vcxproj,vcxproj.filters}  
MassSpringArbitrary.{h,inl}  
MassSpringCurve.{h,inl}  
MassSpringSurface.{h,inl}  
MassSpringVolume.{h,inl}  
ParticleSystem.{h,inl}  
PolyhedralMassProperties.{h,inl}  
RigidBody.{h,inl}

Changed the second `public` to `private`. This is a cosmetic change with no difference in the behavior of the application. In the constructor for `CpuMassSpringVolume`, reordered the initialization list according to C++ standards (initialization order is member order).

Samples/Physics/MassSprings3D/CpuMassSpringVolume.{h,cpp}  
Samples/Physics/MassSprings3D/GpuMassSpringVolume.h

**September 15, 2014.** Added a base class `ParametricCurve` for the various curve classes. This is effectively a port and consolidation of the Wild Magic `Curve{2,3}`, `SingleCurve{2,3}`, and `MultipleCurve{2,3}` classes. Added set/get accessors for individual control points and weights for the B-spline and NURBS curve classes. Unit tests have been written for the base class and the derived classes.

```
GTEngine.{h,vcxproj,vcxproj.filters}  
BezierCurve.{h,inl}  
BSplineCurve.{h,inl}  
NURBSCurve.{h,inl}  
NaturalSplineCurve.{h,inl}  
TCBSplineCurve.{h,inl}  
ParametricCurve.{h,inl}
```

**September 16, 2014.** Ported the Wild Magic physics sample named `Rope`, which illustrates 1-dimensional mass-spring systems.

```
GTBuildAll.sln  
Samples/Physics/Rope/Rope.{sln,vcxproj,vcxproj.filters,cpp}  
Samples/Physics/Rope/RopeWindow.{h,cpp}  
Samples/Physics/Rope/PhysicsModule.{h,cpp}  
Samples/Data/Rope.bmp
```

Added classes for computing the Frenet frame for a parametric curve. Added a class for representing tube surfaces with specified medial curve and radial function. Wild Magic had such a class, but it was tied to the graphics system. The `GTEngine` class is independent of the graphics system.

```
GTEngine.{h,vcxproj,vcxproj.filters}  
FrenetFrame.{h,inl}  
TubeSurface.{h,inl}
```

**September 17, 2014.** Fixed an error in the comments about which knots are equispaced for an open uniform curve.

```
BasisFunction.h
```

**September 18, 2014.** Added a base class `ParametricSurface` for several of the surface classes. Added a class for computing the Darboux frame for a parametric surface. These are effectively a port of the Wild Magic class `ParametricSurface`.

```
GTEngine.{h,vcxproj,vcxproj.filters}  
DarbouxFrame.{h,inl}  
BSplineSurface.{h,inl}
```

NURBSSurface.{h,inl}  
ParametricSurface.{h,inl}

The uv-coordinate generation is slow when the number of vertices is very large. The bottleneck was the iteration over the `std::map` objects that store the adjacent vertex information. The sparse linear system solver now creates a data structure that stores the relevant information in an array and performs much better.

GenerateMeshUV.{h,inl}

The implementation of slerp had one more term in its arrays than what the theory specifies in *D. Eberly, A fast and accurate algorithm for computing SLERP, The Journal of Graphics, GPU, and Game Tools, vol. 15, no. 3, pp. 161-176, October 21, 2011.*

Quaternion.inl

**September 19, 2014.** Ported the Wild Magic physics sample named `Cloth`, which illustrates 2-dimensional mass-spring systems.

GTBuildAll.sln  
Samples/Physics/Cloth/Cloth.{sln,vcxproj,vcxproj.filters,cpp}  
Samples/Physics/Cloth/ClothWindow.{h,cpp}  
Samples/Physics/Cloth/PhysicsModule.{h,cpp}  
Samples/Data/Cloth.bmp

Added a class for representing rectangle surfaces with specified surface but used for sampling to build triangle meshes. Wild Magic had such a class, but it was tied to the graphics system. The `GTEngine` class is independent of the graphics system.

RectangleSurface.{h,inl}

The linear system solver used successive replacement rather than simultaneous replacement. Switched to simultaneous replacement, using ping-pong buffers, to allow for simple multithreading. The class now accepts a parameter that specifies how many threads are dedicated to the linear system solver. Added an include of `<string>` so that the file would compile by itself as the only include in a cpp file.

GenerateMeshUV.{h,inl}

**September 20, 2014.** The member `mNumBytes` was set twice in the else-clause in the constructor.

Resource.cpp

**September 22, 2014.** An include of `<iostream>` was needed to access `std::cout`.

`GenerateMeshUVsWindow.cpp`

Modified the functions to return the number of actual iterations used during bisection rather than just a Boolean result.

`RootsBisection.{h,inl}`  
`IntrEllipse2Ellipse2.inl`  
`IntrEllipsoid3Ellipsoid3.inl`

**September 24, 2014.** Added an explicit namespace scope on `ShaderFactory` in the `GTE_MAKE_HLSL_STRING` macro so that the macro can be used outside a `using namespace gte` block.

`ShaderFactory.h`

**September 25, 2014.** Added a new class `ComputeModel` that allows you to pass information to algorithm implementations whether to use the GPU, multiple threads on the CPU, or single threading on the CPU. Derived classes can provide additional behavior such as callbacks to report progress of an algorithm.

`GTEngine.{h,vcxproj,vcxproj.filters}`  
`ComputeModel.{h,cpp}`  
`GenerateMeshUV.{h,inl}`  
`GenerateMeshUVs.cpp`  
`Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.cpp`

The number of bytes for an image was stored as a 32-bit integer. This is a limitation for 64-bit processors that can allocate more than 2GB of memory. Modified several members to be `size_t`, which is a 32-bit unsigned integer on a 32-bit processor or a 64-bit unsigned integer on a 64-bit processor. Any functions that use `int` for 1-dimensional indices were modified to use `size_t`.

`Image.{h,inl,cpp}`  
`Image2.{h,inl}`  
`Image3.{h,inl}`  
`ImageUtility2.{h,inl,cpp}`  
`ImageUtility3.{h,inl,cpp}`

## 85 Updates to Version 1.2

**August 30, 2014.** Added the ability to specify the matrix storage convention and matrix-vector multiplication convention externally. The comments in the file explain the rationale and consequences of doing so.

GTEngineDEF.h

Added new template functions to allow conversions between N-tuples and (N+1)-tuples. These include [HLift](#), [HProject](#), [Lift](#), and [Project](#). The comments in the header file explain what each function does. The [HLift](#) and [HProject](#) functions are particularly useful for conversions between [Vector3<Real>](#) and [Vector4<Real>](#); objects.

Vector.{h,inl}

The [SetSegment](#) and [GetSegment](#) functions needed to distinguish between disjoint line segments and contiguous line segments.

IndexBuffer.cpp

**August 31, 2014.** Added support for picking point primitives and line segment primitives. The picking for triangles uses intersection tests. The picking for points and segments uses distance tests. The sample application was updated to show how this works. The line-segment distance code had a porting bug that was fixed; the returned distance was incorrectly set to zero when the segment closest point was an interior point.

Picker.{h,cpp}  
PickRecord.{h,inl,cpp}  
DistLine3Segment3.inl  
Samples/Graphics/Picking/PickingWindow.{h,cpp}

Modified our header dependency tool to trap problems when precompiled headers are disabled. The include of [GTEngine.h](#) in [GTEnginePCH.h](#) needed to be disabled to trap problems in cpp files. The following files had missing dependencies when we did this.

Camera.cpp  
Command.cpp  
ConstantBuffer.cpp  
DrawTarget.cpp  
DX11Engine.{h,cpp}  
Environment.cpp  
ETManifoldMesh.cpp  
Fluid2InitializeSource.cpp  
Fluid2InitializeState.cpp  
Fluid3InitializeSource.cpp  
Fluid3InitializeState.cpp  
Histogram.cpp  
HLSLBaseBuffer.h  
HLSLParameter.h



```

HLSLResource.h
HLSLShader.h
HLSLShader.cpp
HLSLShaderVariable.h
HLSLShaderType.h
IEEEBinary16.cpp
Image.cpp
IndexBuffer.cpp
LightingEffect.cpp
Logger.cpp
LogToMessageBox.cpp
LogToOutputWindow.cpp
MarchingCubes.cpp
OverlayEffect.cpp
Resource.cpp
Texture.cpp
TextEffect.cpp
Timer.cpp
TriangleKey.cpp
TSManifoldMesh.cpp
VertexFormat.cpp
VEManifoldMesh.cpp
WICFileIO.cpp
Window.cpp

```

**September 3, 2014.** Changed the `LogError` messages to `LogInformation` when an insertion will violate the manifold mesh requirement. Some applications might find it useful to attempt an insertion, using the returned null pointer as an indication to take an alternative action. You can set your Logger listeners to ignore `LogInformation` messages (or just ignore ones that are sent to `MessageBox` or `OutputWindow`); however, we also added the ability to turn off the `LogInformation` message specifically for these classes via a class member function.

```

VEManifoldMesh.{h,cpp}
ETManifoldMesh.{h,cpp}
TSManifoldMesh.{h,cpp}

```

Added class member function to get 1-dimensional indices or tuples for various neighborhood configurations of a pixel. Modified the image processing utilities to use these member functions. Added a static assertion to the image classes that requires the `PixelType` to be trivially copyable, a requirement of the design of the `Image` classes. Removed the `PixelRGBA8` and `PixelBGRA8` classes because the engine does not use them (nor are they that useful). Removed the `GteStandardImages.cpp` file that explicitly instantiated image classes. The engine design has been not to force explicit instantiation of template classes. The mass-spring system class used `Image3<Vector3<float>>`, but the template type is not trivially copyable. The code was easily modified to use `std::vector<Vector3<float>>`.

```

GTEngine.{vcxproj,vcxproj.filters}

```

```

GTEngineDEF.h
Image1.{h,inl}
Image2.{h,inl}
Image3.{h,inl}
ImageUtility2.{h,cpp}
ImageUtility3.{h,cpp}
Samples/Physics/MassSprings3D/CpuMassSpringVolume.{h,cpp}
Samples/Physics/MassSprings3D/MassSprings3DWindow.cpp

```

**September 11, 2014.** Ported the Wild Magic B-spline curve and surface code for least-squares fitting of data, including the sample applications.

```

GTEngine.{h,vcxproj,vcxproj.filters}
GTBuildAll.sln
BSplineCurveFit.{h,inl}
BSplineSurfaceFit.{h,inl}
Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitter.{sln,vcxproj,vcxproj.filters,cpp}
Samples/Mathematics/BSplineCurveFitter/BSplineCurveFitterWindow.{h,cpp}
Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitter.{sln,vcxproj,vcxproj.filters,cpp}
Samples/Mathematics/BSplineSurfaceFitter/BSplineSurfaceFitterWindow.{h,cpp}

```

The `mKeys` member of the class was a `std::vector` type and is used heavily in the range-iteration-based for-loop in `GetIndex`. Because of the checked iterators used in that loop, the performance in debug builds was horrific. Changed the type of `mKeys` to a native array to improve the performance for debugging.

```

BasisFunction.{h,inl}

```

In order to re-use a `MeshFactory` object with a different vertex format, the array that keeps track of whether texture coordinate channels occur had to be cleared when creating the vertex buffer.

```

MeshFactory.cpp

```

Added a new class that generates texture coordinates automatically for a mesh with rectangle or disk topology. The algorithm is based on barycentric mapping, mean-value weights, and Gauss-Seidel iteration for large sparse linear systems. Added a new class that manages a planar mesh and allows fast and exact point-in-triangle queries and computation of barycentric coordinates. This was added to support resampling of meshes with automatically generated texture coordinates.

```

GTEngine.{h,vcxproj,vcxproj.filters}
GenerateMeshUV.{h,inl}
PlanarMesh.{h,inl}

```

Fixed a comment that was cut-and-paste from another similar file.

[LightDirectionPerPixelEffect.h](#)

**September 13, 2014.** A new sample application that demonstrates using the class [GenerateMeshUV](#) to automatically generate texture coordinates for a mesh that has rectangle or disk topology. The sample also illustrates resampling using the class [PlanarMesh](#).

[GTBuildAll.sln](#)

[Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVs.{sln,vcxproj,vcxproj.filters,cpp}](#)

[Samples/Mathematics/GenerateMeshUVs/GenerateMeshUVsWindow.{h,cpp}](#)

## 86 Updates to Version 1.1

**August 26, 2014.** Refactored the basic lighting effects to share code, fixing several bugs in the process. Two new classes were added, [LightingConstants](#) and [LightingEffect](#). Added a new sample application to illustrate the effects; this is a port of the Wild Magic 5 Lights sample.

[GTEngine.{h,vcxproj,vcxproj.filters}](#)  
[GTBuildAll.sln](#)  
[VisualEffect.{h,cpp}](#)  
[LightAmbientEffect.{h,cpp}](#)  
[LightDirectionPerPixelEffect.{h,cpp}](#)  
[LightDirectionPerVertexEffect.{h,cpp}](#)  
[LightPointPerPixelEffect.{h,cpp}](#)  
[LightPointPerVertexEffect.{h,cpp}](#)  
[LightSpotPerPixelEffect.{h,cpp}](#)  
[LightSpotPerPixelEffect.{h,cpp}](#)  
[Samples/Graphics/Lights/Lights.{sln,vcxproj,vcxproj.filters,cpp}](#)  
[Samples/Graphics/Lights/LightsWindow.{h,cpp}](#)  
[LightingConstants.{h,cpp}](#)  
[LightingEffect.{h,inl,cpp}](#)  
[LightAmbientEffect.inl](#)  
[LightDirectionPerVertexEffect.inl](#)  
[LightDirectionPerPixelEffect.inl](#)  
[LightPointPerVertexEffect.inl](#)  
[LightPointPerPixelEffect.inl](#)  
[LightSpotPerVertexEffect.inl](#)  
[LightSpotPerPixelEffect.inl](#)

The MSDN documentation for [ID3D11DeviceContext::IASetVertexBuffers](#) and [ID3D11DeviceContext::Draw\(numVertices, startVertex\);](#) appears not to mention that [startVertex](#) is relative to the [offsets\[\]](#) passed to [IASetVertexBuffers](#). Fixed

the enabling of vertex buffers to set the offsets to zero. The `DX11Engine::DrawPrimitive` function passes the vertex buffer offset through the `startVertex` parameter.

`DX11VertexBuffer.cpp`

**August 29, 2014.** Added `HasMember` functions to test for the existence of member data with the specified name.

`ConstantBuffer.{h,cpp}`  
`TextureBuffer.{h,cpp}`

A small amount of refactoring of `Picker` to prepare for supporting point and line primitives (distance based). The triangle picking code was tested using a new sample application.

`GTBuildAll.sln`  
`Samples/Graphics/Picking/Picking.{sln,vcxproj,vcxproj.cpp}`  
`Samples/Graphics/Picking/PickingWindow.{h,cpp}`

Fixed a bug in the `Shader` constructor when generating the member layouts for constant buffers and texture buffers. The indices into the layout arrays were not incremented, which led to incorrect behavior for shaders with two or more such buffers.

`Shader.cpp`

Fixed a bug in the `GenerateLayout` member function. The shader type's offset was used to determine member offset in the structure, but the shader variable's offset has to be used instead (at the root of the recursion).

`HLSLBaseBuffer.cpp`

A change in the semantics for `Environment::GetPath` when no directories exist was not propagated to the append-consume buffer sample application, causing a bogus assertion when trying to find the HLSL file associated with the application.

`Samples/Basics/AppendConsumeBuffers/AppendConsumeBuffers.cpp`

The hiding of the trackball rotation matrix inside the `Window` class prevented picking from working properly. The registration system that updated shader constants with projection-view-world transforms from the world transforms of associated objects needed a redesign. The trackball rotation is no longer applied implicitly. You can access it via a public member function. The `Register/Unregister` calls were replaced by two subscription

interfaces, one to subscribe to changes in the camera changes and have the pvw-matrices automatically updated—this is what the [Register/Unregister](#) system did. However, there is interaction between updating world transforms and pvw-matrices for effects, so a second subscription interface is used to have world transforms of objects automatically updated when the virtual trackball moves. The redesign led to many changes in sample applications. While we were in there, we cleaned up and refactored some of the samples to make the code more readable (consistent use of [bool SetEnvironment](#) and [bool CreateScene](#)). The `Windowi` class also has a new member function for computing a picking line for the current viewport and camera settings. This is used in conjunction with the [Picker](#) class.

```
Window.{h,inl,cpp}
Samples/Basics/GaussianBlurring/GaussianBlurringWindow.{h,cpp}
Samples/Basics/GeometryShaders/GeometryShadersWindow.{h,cpp}
Samples/Basics/MultipleRenderTargets/MultipleRenderTargetsWindow.{h,cpp}
Samples/Basics/StructuredBuffers/StructuredBuffersWindow.{h,cpp}
Samples/Basics/TextureArrays/TextureArraysWindow.{h,cpp}
Samples/Basics/Texturing/TexturingWindow.{h,cpp}
Samples/Basics/VertexColoring/VertexColoringWindow.{h,cpp}
Samples/Geometrics/AllPairsTriangles/AllPairsTrianglesWindow.cpp
Samples/Geometrics/ConvexHull3D/ConvexHull3DWindow.{h,cpp}
Samples/Geometrics/Delaunay3D/Delaunay3DWindow.{h,cpp}
Samples/Geometrics/MinimumVolumeBox3D/MinimumVolumeBox3DWindow.{h,cpp}
Samples/Geometrics/MinimumVolumeSphere3D/MinimumVolumeSphere3DWindow.cpp
Samples/Geometrics/ShortestPath/ShortestPathWindow.{h,cpp}
Samples/Graphics/BlendedTerrain/BlendedTerrainWindow.cpp
Samples/Graphics/BlownGlass/BlownGlassWindow.{h,cpp}
Samples/Graphics/Lights/LightsWindow.cpp
Samples/Graphics/PlaneMeshIntersection/PlaneMeshIntersectionWindow.{h,cpp}
Samples/Graphics/WireMesh/WireMeshWindow.{h,cpp}
Samples/Imagics/SurfaceExtraction/SurfaceExtractionWindow.cpp
Samples/Mathematics/Interpolation2D/Interpolation2DWindow.cpp
Samples/Physics/Fluids2D/Fluids2DWindow.{h,cpp}
Samples/Physics/Fluids3D/Fluids3DWindow.{h,cpp}
Samples/Physics/MassSprings3D/MassSprings3DWindow.{h,cpp}
```

## 87 Updates to Version 1.0

**August 13, 2014.** The files were missing the [#pragma once](#) guards against multiple inclusions.

```
Constants.h
MarchingCubesTable.h
SingularValueDecomposition.h
```

**August 15, 2014.** Fixed a typographical error in Equation (14). Replaced the  $\text{\LaTeX}$   $\varepsilon$  verbatim commands with `lstlisting` commands for more readable pseudocode.

[AreaIntersectingEllipses.pdf](#) (*The Area of Intersecting Ellipses*)

**August 17, 2014.** These modifications are related to the porting of the Wild Magic interpolation code to GTEngine.

Ported most of the Wild Magic interpolation code to GTEngine. A sample application illustrates use of the interpolators for 2D height-field data.

```
GTEngine.{h,vcxproj,vcxproj.filters}  
IntpAkima1.{h,inl}  
IntpAkimaUniform1.{h,inl}  
IntpAkimaUniform2.{h,inl}  
IntpAkimaUniform3.{h,inl}  
IntpBicubic2.{h,inl}  
IntpBilinear2.{h,inl}  
IntpLinearNonuniform2.{h,inl}  
IntpQuadraticNonuniform2.{h,inl}  
IntpSphere2.{h,inl}  
IntpThinPlateSpline2.{h,inl}  
IntpThinPlateSpline3.{h,inl}  
IntpTricubic3.{h,inl}  
IntpTrilinear3.{h,inl}  
IntpVectorField2.{h,inl}  
Samples/Mathematics/Interpolation2D/Interpolation2D.{sln,vcxproj,vcxproj.filters,cpp}  
Samples/Mathematics/Interpolation2D/Interpolation2DWindow.{h,cpp}  
Samples/Data/Checkerboard.png
```

Added wrappers for the meshes produced by Delaunay triangulation and tetrahedralization. Access to the input vertices of the DelaunayN classes was required to support this. The wrappers allow the interpolators to interact with general triangles mesh that are not produced by the Delaunay code. (Wild Magic forced you to use Delaunay meshes.)

```
Delaunay2.{h,inl}  
Delaunay3.{h,inl}  
Delaunay2Mesh.{h,inl}  
Delaunay3Mesh.{h,inl}
```

Added a mesh creator for regular triangle meshes ('half' a rectangle mesh).

```
MeshFactory.{h,cpp}
```

When computing barycentric coordinates, replaced the separate Dot and Cross functions by the single calls to DotCross.

Vector3.inl

Added functions `AllocateMapN` and `DeallocateMapN` for  $N = 2, 3, 4$ . This allows for wrapping an already existing 1-dimensional array with multidimensional array access.

Memory.{h,inl}

**August 19, 2014.** These modifications are related to getting the code, not including the Windows-specific graphics and application code, to compile on Linux and Macintosh OS X. The first batch of changes were consequences of trying to compile on Macintosh OS X. The second batch is due to Linux compilation, although changes in the first batch no doubt were needed anyway on Linux.

Hide the Windows-specific information from the other platforms.

GTEngine.h  
GTEngineDEF.h

The compiler did not like the `#pragma once` in the precompiled header file.

GTEnginePCH.h

The LLVM compiler successfully compiled `Delaunay2Mesh` and `Delaunay3Mesh` in our header verification tool when you compile in a single file. However, when a build-project is initiated, LLVM attempted to use the template parameter `Rational` as if it were an actual type and complained when trying to instantiate `Vector{2,3}::ComputeBarycentrics`. In particular, we had a line `if (std::abs(det) > epsilon)` for which LLVM said `std::abs` is ambiguous and that it did not match any of the standard functions for floating-point types. For now, we modified the code for `ComputeBarycentrics` to use `if (det < -epsilon || det > epsilon)`.

Vector2.inl  
Vector3.inl

LLVM does not have versions of the secure `memcpy_s` that Microsoft Visual Studio does. Added conditional compilation to handle this.

GaussianElimination.inl  
LinearSystem.inl  
MinimizeN.inl

Eliminated the typedef of `Function`. LLVM had difficulties with this in the derived classes. Removed the (WM5) `using` statements and added the explicit scoping by `this→`.

```
OdeSolver.{h,inl}  
OdeEuler.{h,inl}  
OdeImplicitEuler.{h,inl}  
OdeMidpoint.{h,inl}  
OdeRungeKutta4.{h,inl}
```

Removed the explicit last parameter to `ComputeBarycentrics`. The default parameter has the same value.

```
IntpQuadraticNonuniform2.inl
```

The file `<iterator>` needed to be included to access the definitions of `std::begin`, `std::end`, and `std::reverse_iterator`. Microsoft Visual Studio 2013 allowed the compilation without it, but not LLVM.

```
RangeIteration.h
```

The class had two member functions that required two implicit conversions to return values. One of them has to be explicit, and LLVM requires this.

```
Transform.inl
```

The definition of `size_t` appears to be built into Microsoft Visual Studio 2013. On LLVM, it is defined in `<cstddef>`, so this header file needed to be included.

```
Memory.h
```

The declaration for triangle barycentric coordinates was the incorrect size.

```
DistPoint3Triangle3.h  
DistTriangle3Triangle3.h
```

The header needed to include `<set>` because the class has a member using this container.

```
ConvexHull3.h
```

We have an internal tool that include each header file in a cpp file and tests whether it compiles. This is designed to expose a header file that might not include any dependencies it has. If the header is for template classes or functions, we also explicitly instantiate those in order to trap any compiler errors. Naturally, the tool has precompiled headers disabled. Surprisingly, some code passed the tests when compiling with Microsoft Visual Studio 2013 but the same code failed compilation on LLVM. For example, the `GetContainer` function in `GteContEllipsoid3.inl` incorrectly had a `Vector2` input when it should have been `Vector3`. This code passed the explicit instantiation compiler test using Microsoft Visual Studio 2013.



ContEllipsoid3.inl

Microsoft's compilers still violate the ANSI C++ standard that requires template derived classes to explicitly scope any access to template base class members or functions via `this→mBaseMember` and `this→BaseFunction`. In Wild Magic, we chose the `using` statement in the derived-class headers but decided against this in GTEngine because of the potential change in access rights (public, protected, private).

ConstrainedDelaunay2.inl  
DistPoint2OrientedBox2.inl  
DistPoint3OrientedBox3.inl  
IntrAkimaUniform1.inl  
IntrLine2OrientedBox2.inl  
IntrLine3OrientedBox3.inl  
IntrRay2OrientedBox2.inl  
IntrRay3OrientedBox3.inl  
IntrSegment2OrientedBox2.inl  
IntrSegment3OrientedBox3.inl  
Matrix2x2.inl  
Matrix3x3.inl  
Matrix4x4.inl  
Quaternion.inl  
Transform.inl  
Vector2.inl  
Vector3.inl  
Vector4.inl

Added typename modifiers to some variable declarations. Microsoft Visual Studio 2013 allowed the declarations without the modifiers, but not LLVM.

BSNumber.inl  
Delaunay2Mesh.inl  
Delaunay3Mesh.inl  
DistRectangle3Rectangle3.inl  
DistTriangle3Triangle3.inl

`BSNumber` had a declaration to make `BSRational` a friend. Microsoft Visual Studio 2013 allowed the original code, but not LLVM. Forward declared the `BSRational` template and modified the friend statement. The same mechanism had been used in Wild Magic to satisfy all compilers.

BSNumber.h

Microsoft Visual Studio 2013 allows you to make calls to math library functions such as `std::abs` and `sqrt` without including `<cmath>`. Added the include to satisfy LLVM.

```
BandedMatrix.h
GaussianElimination.h
GVector.h
IntpAkima1.h
IntpAkimaUniform2.h
IntpAkimaUniform3.h
Minimize1.h
RootsBrentsMethod.h
SingularValueDecomposition.h
SymmetricEigensolver.h
Vector.h
```

Removed an incorrect static cast of a 32-bit value to a 64-bit value when the return value of the function is in fact 32-bit.

```
BitHacks.cpp
```

The explicit instantiation of the oppositeFace array required a `template <>` modifier.

```
TetrahedronKey.cpp
```

The explicit instantiation of image classes needed to be inside a namespace block.

```
StandardImages.cpp
```

Removed the AlignedMemory class from the engine. It is not used, and the `_aligned_malloc` and `_aligned_free` calls do not exist on Macintosh OS X.

```
GTEngine.{h,vcxproj,vcxproj.filters}
AlignedMemory.{h,inl}
```

The changes below were necessary after the previous ones to get the code to compile on Linux.

The explicit instantiations had to occur inside a namespace block. A `using namespace gte` was not sufficient.

```
EdgeKey.cpp
TriangleKey.cpp
TetrahedronKey.cpp
```

The class uses the var-args system so we needed to include `<cstdarg>`.

Image.cpp

The files use `std::numeric_limits` and needed to include `<limits>`.

ImageUtility2.cpp  
DistLine3Rectangle3.h  
DistLine3Triangle3.h  
DistPoint3Circle3.h  
DistPoint3Tetrahedron3.h  
IntrIntervals.h  
IntrLine2AlignedBox2.h  
IntrLine2Line2.h  
IntrLine3AlignedBox3.h  
IntrLine3Plane3.h  
IntrCircle2Circle2.h  
NearestNeighborQuery.h

The files use `memcpy` or `memset` and needed to include `<cstring>`. The conditional compilation is now based on WIN32 (or not).

BasisFunction.h  
GaussianElimination.inl  
IntpAkimaUniform2.h  
IntpAkimaUniform3.h  
LinearSystem.inl  
MinimizeN.{h,inl}  
SurfaceExtractor.h  
SingularValueDecomposition.{h,inl}  
SymmetricEigensolver.{h,inl}

The files use `std::min`, `std::max`, `std::sort`, or `std::nth_element` and needed to include `<algorithm>`.

BSNumber.h  
ConvexHull2.h  
ContEllipse2MinCR.h  
MinimumAreaCircle2.h  
MinimumVolumeSphere3.h  
NearestNeighborQuery.h