Spherical Skinning with Dual-Quaternions and QTangents

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Goals

#1 Improve performance by reducing the shader constant requirements for joint transformations

30% shader constants reduction

#2 Reduce the memory foot-print of skinned geometry

22% vertex memory reduction

29% for static geometry

Skinned Geometry

Goal #1

- Improve performance by reducing the shader constant requirements for joint transformations
  - Skinned geometry requires multiple passes
    - Motion Blur requires twice the transformations
  - The amount of required shader constants affects the performance of a single pass

Skinning with Quaternions

- ~30% less shader constants consumption compared to 4x3 packed matrices

- Quaternion Linear Skinning
  - Accumulated transformations don’t work for positions
    - Explosion of vertex instructions
- Quaternion Spherical Skinning [HEIJL04]
  - Extra vertex attribute required
  - Doesn’t handle well more than 2 influences per vertex
- Dual-Quaternion Skinning [KCO06] [KCZO08]
  - Increase in vertex instructions

Dual-Quaternion Skinning [KSO06] [KCZO08]

- Compared to Linear Skinning with matrices
  - Accumulation of transformations is faster
  - Applying the transformation is slower
  - With enough influences per vertex it becomes overall faster
- The reduction of shader constants was a win over the extra vertex instructions cost

From Linear to Spherical

- Geometry needs to be rigged differently
  - And you will still need your helper joints
- Riggers and Animators need to get used to it
  - Some will love it, others will hate it
    Most will keep changing their mind
- You might have to write skinning plug-ins for third party authoring software
  - Some recent authoring packages have adopted
    Dual-Quaternion Skinning out of the box

Goal #2

- Reduce the memory foot-print of skinned geometry
  - We are now developing on consoles, every byte counts!
  - More compact vertex format will also lead to better performance
- Do not sacrifice quality in the process!

Tangent Frames

Tangent Frames were the biggest vertex attribute after our trivial memory optimizations

In further optimizing them we need to ensure that

- They keep begin efficiently transformed by Dual-Quaternions
- All our Normal Maps keep working as they are

About Tangent Frames

- Please make them orthogonal!
- If they are not, you are introducing skewing
  - You can't use a transpose to invert the frame matrix
    - You need a full matrix inversion
  - This will also prevent you from using some compression techniques!

Compressed Matrix Format

Vertex attributes contain two of the frame's vectors and a reflection scalar

Tangent			BiTangent			Reflection
x	y	z	x	y	z	s

The third frame's vector is rebuild from a cross product of the given vectors and a multiplication with the reflection scalar

```
normal = cross(tangent, biTangent) * s
```

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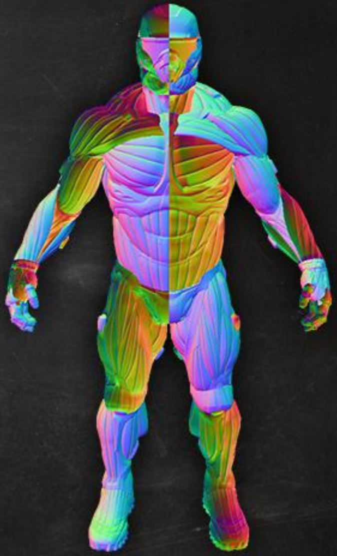
Tangent Frames With Quaternions

Quaternion to Matrix conversion

```
t = transform(q, vec3(1, 0, 0))
b = transform(q, vec3(0, 1, 0))
n = transform(q, vec3(0, 0, 1))
```

Quaternions don't natively contain reflection information



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Bringing Reflection Into the Equation

Similarly to the compressed matrix format, we can introduce reflection with a scalar value

```
t = transform(q, vec3(1, 0, 0))
b = transform(q, vec3(0, 1, 0))
n = transform(q, vec3(0, 0, 1)) * s
```

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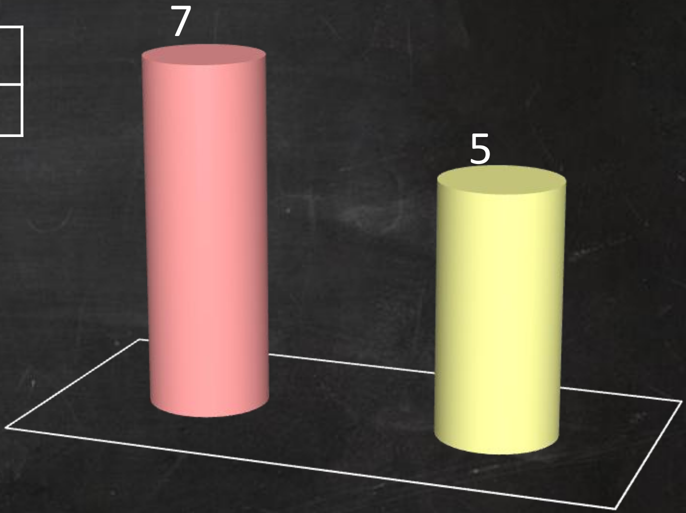
Tangent Frame Format Memory Comparison

Compressed Matrix

Tangent			BiTangent			Reflection
x	y	z	x	y	z	s

Quaternion

Quaternion				Reflection
x	y	z	w	s



Our Quaternion Properties

They are normalized

```
length(q) == 1
```

And they are sign invariant

```
q == -q
```

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Quaternion Compression

We can compress a Quaternion down to three elements by making sure one of the them is greater than or equal to zero

```
if (q.w < 0)
    q = -q
```

We can then rebuild the missing element with

```
q.w = sqrt(1 - dot(q.xyz, q.xyz))
```

Tangent Frame Format Memory Comparison

Compressed Matrix

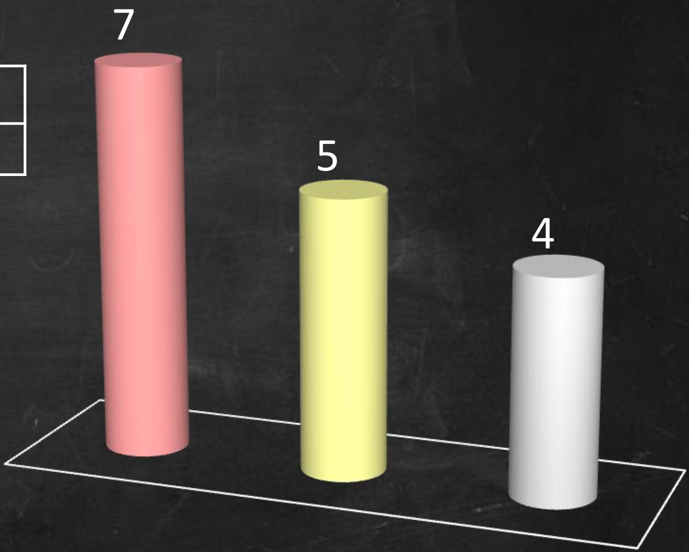
Tangent			BiTangent			Reflection
x	y	z	x	y	z	s

Quaternion

Quaternion				Reflection
x	y	z	w	s

Compressed Quaternion

Quaternion			Reflection
x	y	z	s



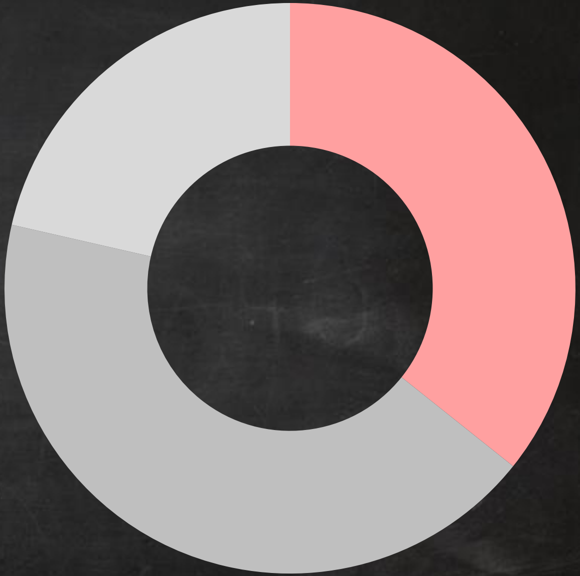
Instruction Cost

Quaternion decompression
5 `mov, dp3, add, rsq, rcp`

Quaternion to Tangent and BiTangent
6 `add, mul, mad, mad, mad, mad`

Normal and Reflection computation
3 `mul, mad, mul`

Total
11 for Tangent, BiTangent and Reflection
14 for full Tangent Frame



Avoiding Quaternion Compression

Isn't there a way to encode the reflection scalar in the Quaternion, instead of compressing it?

Remember, Quaternions are sign invariant

```
q == -q
```

We can arbitrarily decide whether one of its elements has to be negative or positive!

Encoding Reflection

First we initialize the Quaternion
by making sure **`q.w`** is always positive

```
if (q.w < 0)
    q = -q
```

If then we require reflection, we make **`q.w`** negative
by negating the entire Quaternion

```
if (reflection < 0)
    q = -q
```

Decoding Reflection

All we have to do in order to decode our reflection scalar is to check for the sign of `q.w`

```
reflection = q.w < 0 ? -1 : +1
```

As for the Quaternion itself, we can use it as it is!

```
q = q
```

Instruction Cost

Reflection decoding

2 `slt, mad`

Quaternion to Tangent and BiTangent

6 `add, mul, mad, mad, mad, mad`

Normal and Reflection computation

3 `mul, mad, mul`

Total

8 for Tangent, BiTangent and Reflection

11 for full Tangent Frame

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Tangent Frame Transformation with Dual-Quaternion

Quaternion-Vector transformation

```
  |
  |  float3x3 frame;
6 |  frame[0] = transform_quat_vec(
  |      skinningQuat, vertex.tangent.xyz);
  |
6 |  frame[1] = transform_quat_vec(
  |      skinningQuat, vertex.biTangent.xyz);
  |
2 |  frame[2] = cross(frame[0], frame[1]);
1 |  frame[2] *= vertex.tangent.w;
  |
```

15 instructions

Quaternion-Quaternion transformation

```
  |
5 |  float4 q = transform_quat_quat(
  |      skinningQuat, vertex.qTangent)
  |
8 |  float3x3 frame = quat_to_mat(q);
  |
3 |  frame[2] *= vertex.qTangent.w < 0 ? -1 : +1;
  |
  |
  |
  |
```

16 instructions

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QTangent Definition

A Quaternion of which the sign of
the scalar element encodes the Reflection

Stress-Testing QTangents

By making sure we throw at it
our most complex geometry!

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MAJOR US CITIES DESTROYED


China
BELOW6.2
06.05.2024
HORIZONT
PASS QUARANTIN

Singularity Found!

Singularity Found!

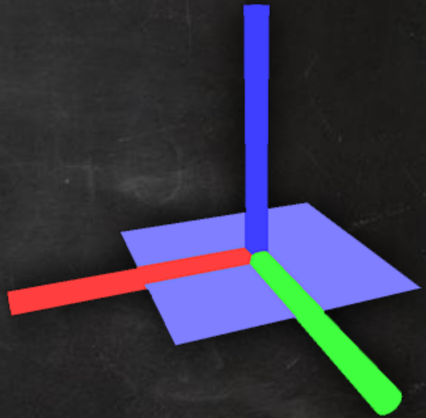
At times the most complex cases pass,
while the simplest fail!

Singularity

Our singularities manifest themselves when the Quaternion’s scalar element is equal to zero

```
     Matrix
-1,  0,  0
 0, -1,  0
 0,  0,  1
```

```
Quaternion
0, 0, 1, 0
```



This means the Tangent Frame’s surface is perpendicular to one of the identity’s axis

Floating-Point Standards

- So what happens when the Quaternion's scalar element is 0?
- The IEEE Standard for Floating-Point Arithmetic does differentiate between -0 and +0, so we should be fine!
- However GPUs don't exactly always comply to this standard, at times for good reasons

GPUs Floating-Point "Standards"

- GPUs allow vertex attributes to be specified as integers representing normalized unit scalars
- They are then resolved into Floating-Point values
- Integers don't differentiate between -0 and +0, thus this information is lost in the process

Handling Singularities

- In order to use integers to encode reflection, we need to ensure that **`q.w`** is never zero
- When we find **`q.w`** to be zero, we need to apply a bias

Defining Our Bias Constant

We define our bias constant as the smallest value that will satisfy `q.w != 0`

If we are using an integer format, this value is given by

$$\texttt{bias} = 1 / (2^{\texttt{BITS}-1} - 1)$$

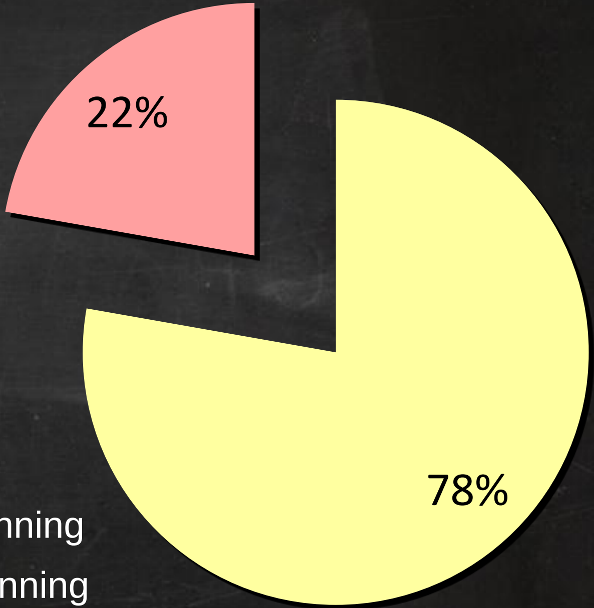
Applying the Bias Constant

We need to apply our bias for each Quaternion satisfying `q.w < bias`, and while doing so we make sure our Quaternion stays normalized

```
if (q.w < bias)
{
      q.xyz *= sqrt(1 - bias*bias)
      q.w = bias
}
```

QTangents with Skinned Geometry

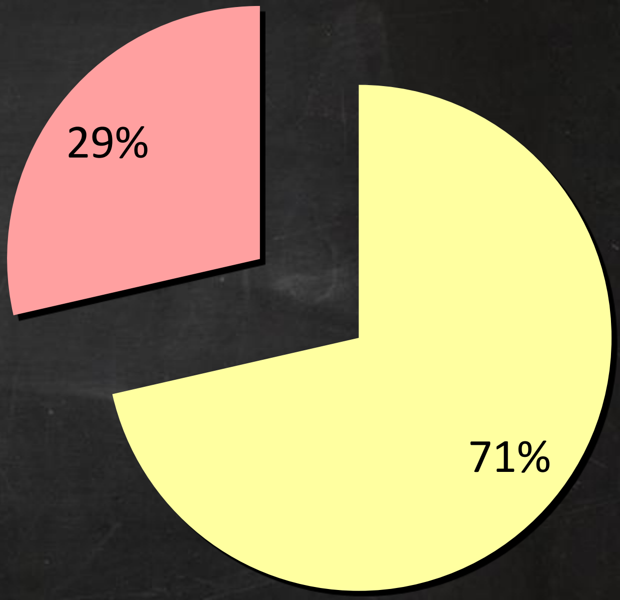
Position	4 float16	8 bytes
TexCoord	2 float16	4 bytes
Tangent	4 int16	8 bytes
BiTangent	4 int16	8 bytes
SkinIndices	4 uint8	4 bytes
SkinWeights	4 uint8	4 bytes



- From 36 bytes to 28 bytes per vertex
- ~22% memory saved
- No overhead with Dual-Quaternion Skinning
- ~8 instruction overhead with Linear Skinning

QTangents with Static Geometry

Position	4 float16	8 bytes
TexCoord	2 float16	4 bytes
Tangent	4 int16	8 bytes
BiTangent	4 int16	8 bytes



- From 28 bytes to 20 bytes per vertex
- ~29% memory saved
- ~8 instruction overhead

Future Developments

- Quaternions across polygons
  - Interpolating Quaternions across polygons and making use of them at the pixel level
- Quaternions in G-Buffers
  - Encoding the whole Tangent Frame instead of just Normals
  - Can open doors to more Deferred techniques
    - Anisotropic Shading
    - Directional blur along Tangents

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- Crytek

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Questions?

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