CS 380 - GPU and GPGPU Programming
Lecture 15: GPU Compute APIs, Pt. 4; GPU Texturing, Pt. 1

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Reading Assignment #9 (until Oct 30)

Read (required):

- Interpolation for Polygon Texture Mapping and Shading,
  Paul Heckbert and Henry Moreton

  `https://www.ri.cmu.edu/publications/interpolation-for-polygon-texture-mapping-and-shading/`

- Homogeneous Coordinates

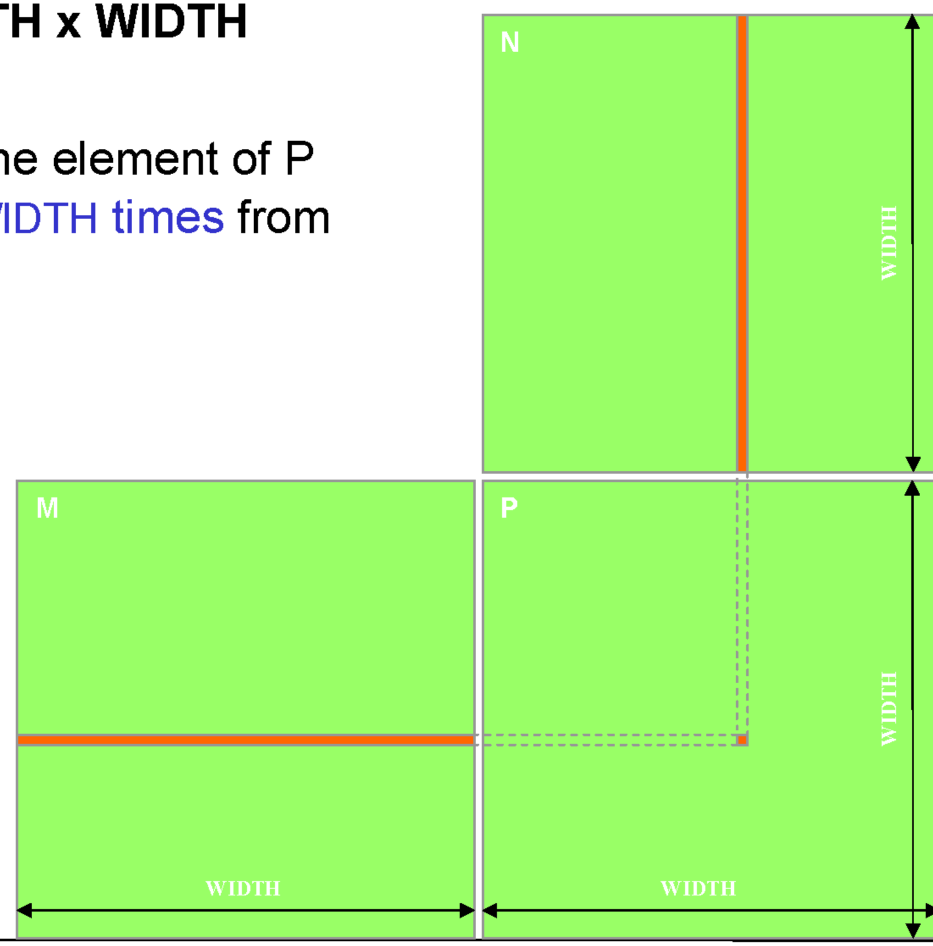
  `https://en.wikipedia.org/wiki/Homogeneous_coordinates`

Code Examples

Example #2: Matrix Multiply

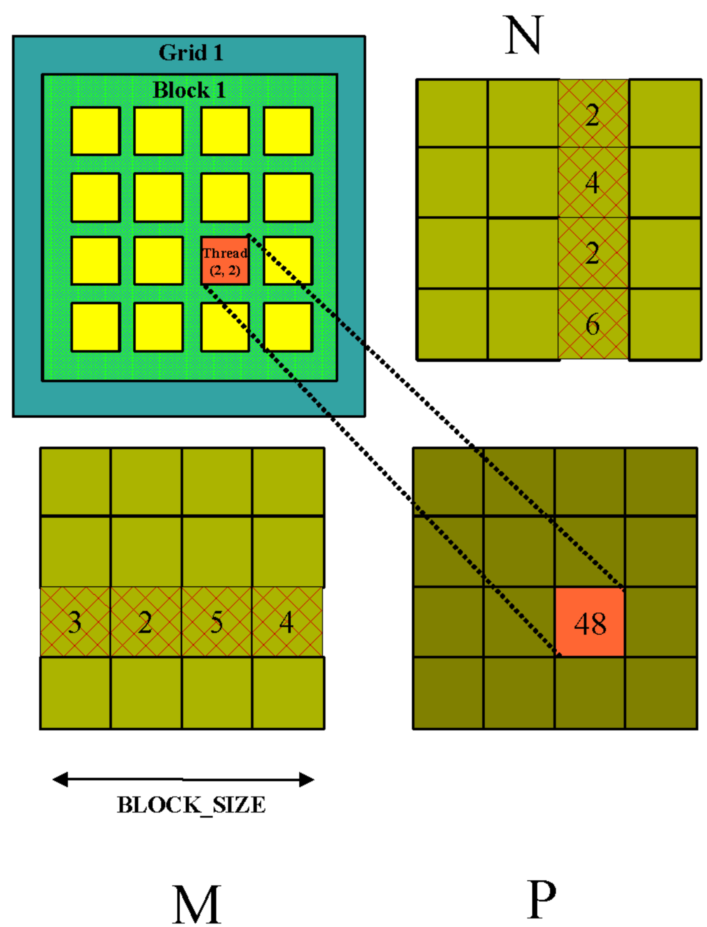
Programming Model: Square Matrix Multiplication

- **P = M * N of size WIDTH x WIDTH**
- **Without tiling:**
  - One thread handles one element of P
  - M and N are loaded WIDTH times from global memory



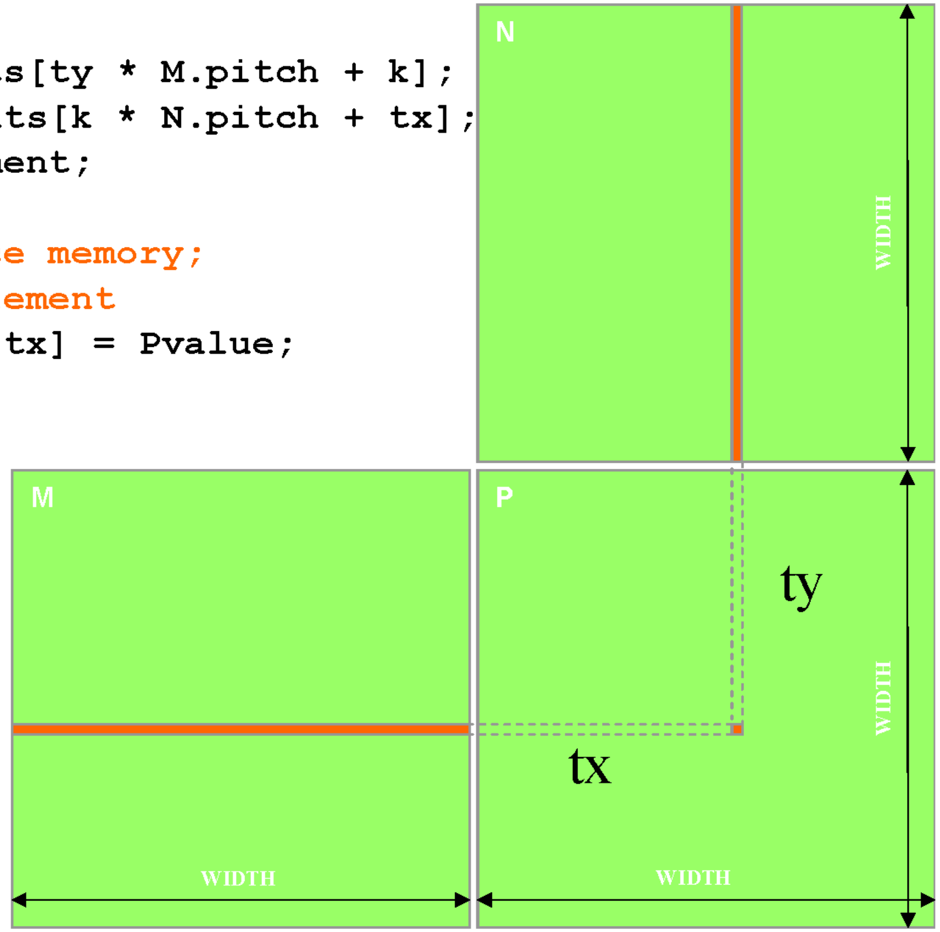
Multiply Using One Thread Block

- **One block of threads computes matrix P**
  - Each thread computes one element of P
- **Each thread**
  - Loads a row of matrix M
  - Loads a column of matrix N
  - Perform one multiply and addition for each pair of M and N elements
  - Compute to off-chip memory access ratio close to 1:1 (not very high)
- **Size of matrix limited by the number of threads allowed in a thread block**



Matrix Multiplication Device-Side Kernel Function (cont.)

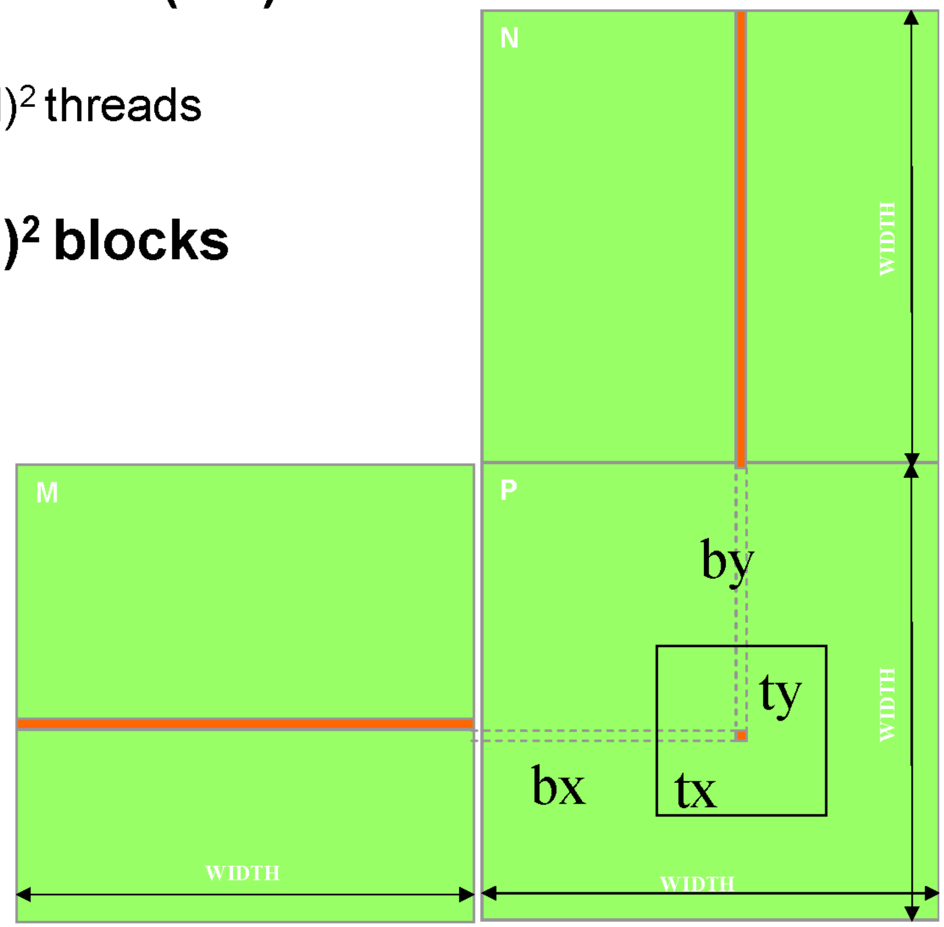
```
…
    for (int k = 0; k < M.width; ++k)
    {
      float Melement = M.elements[ty * M.pitch + k];
      float Nelement = Nd.elements[k * N.pitch + tx];
      Pvalue += Melement * Nelement;
    }
    // Write the matrix to device memory;
    // each thread writes one element
    P.elements[ty * blockDim.x+ tx] = Pvalue;
}
```



Handling Arbitrary Sized Square Matrices

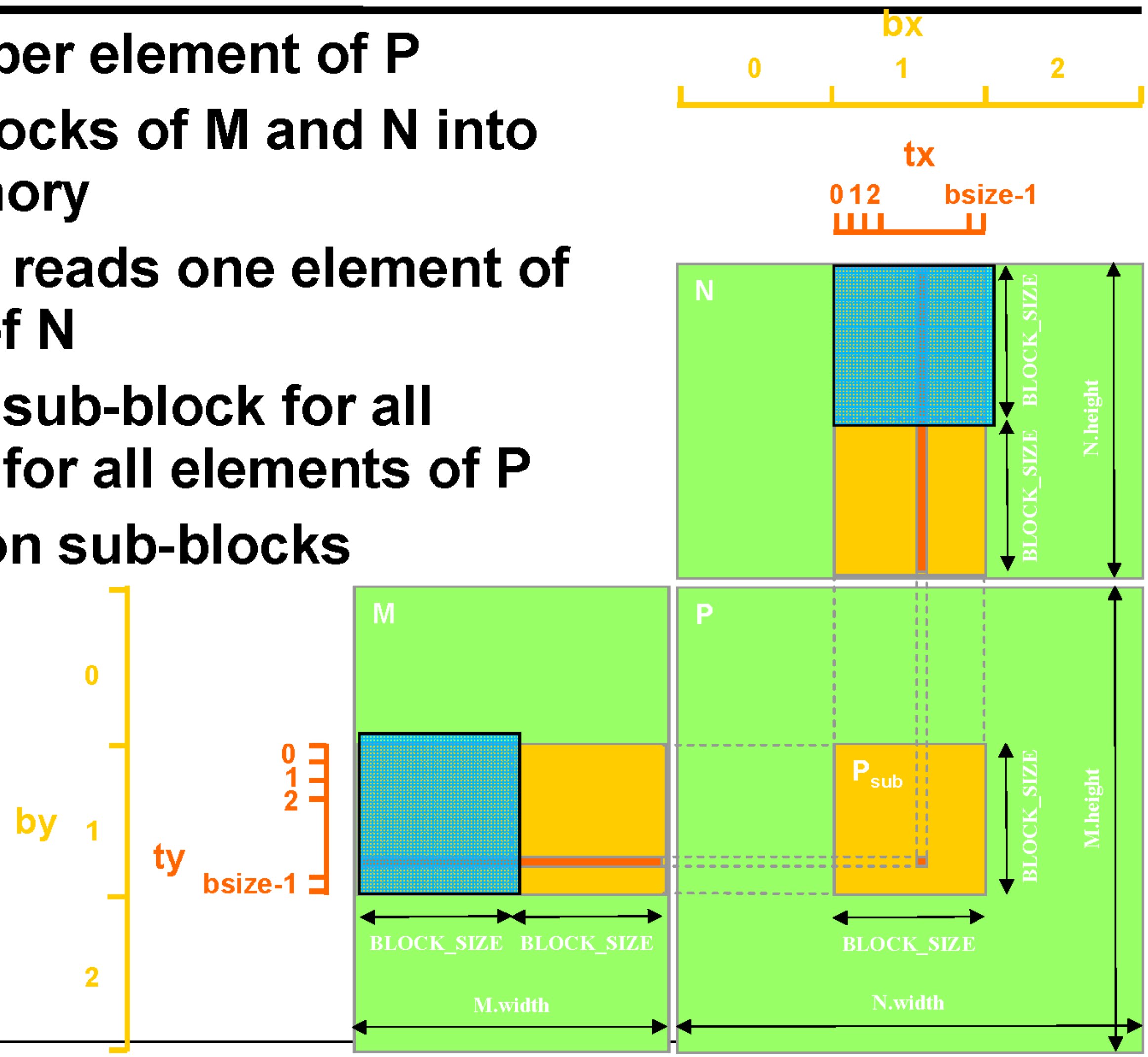
- **Have each 2D thread block to compute a $(BLOCK\_WIDTH)^2$ sub-matrix (tile) of the result matrix**
  - Each has $(BLOCK\_WIDTH)^2$ threads
- **Generate a 2D Grid of $(WIDTH/BLOCK\_WIDTH)^2$ blocks**

You still need to put a loop around the kernel call for cases where WIDTH is greater than Max grid size!



Multiply Using Several Blocks - Idea

- One thread per element of P
- Load sub-blocks of M and N into shared memory
- Each thread reads one element of M and one of N
- Reuse each sub-block for all threads, i.e. for all elements of P
- Outer loop on sub-blocks



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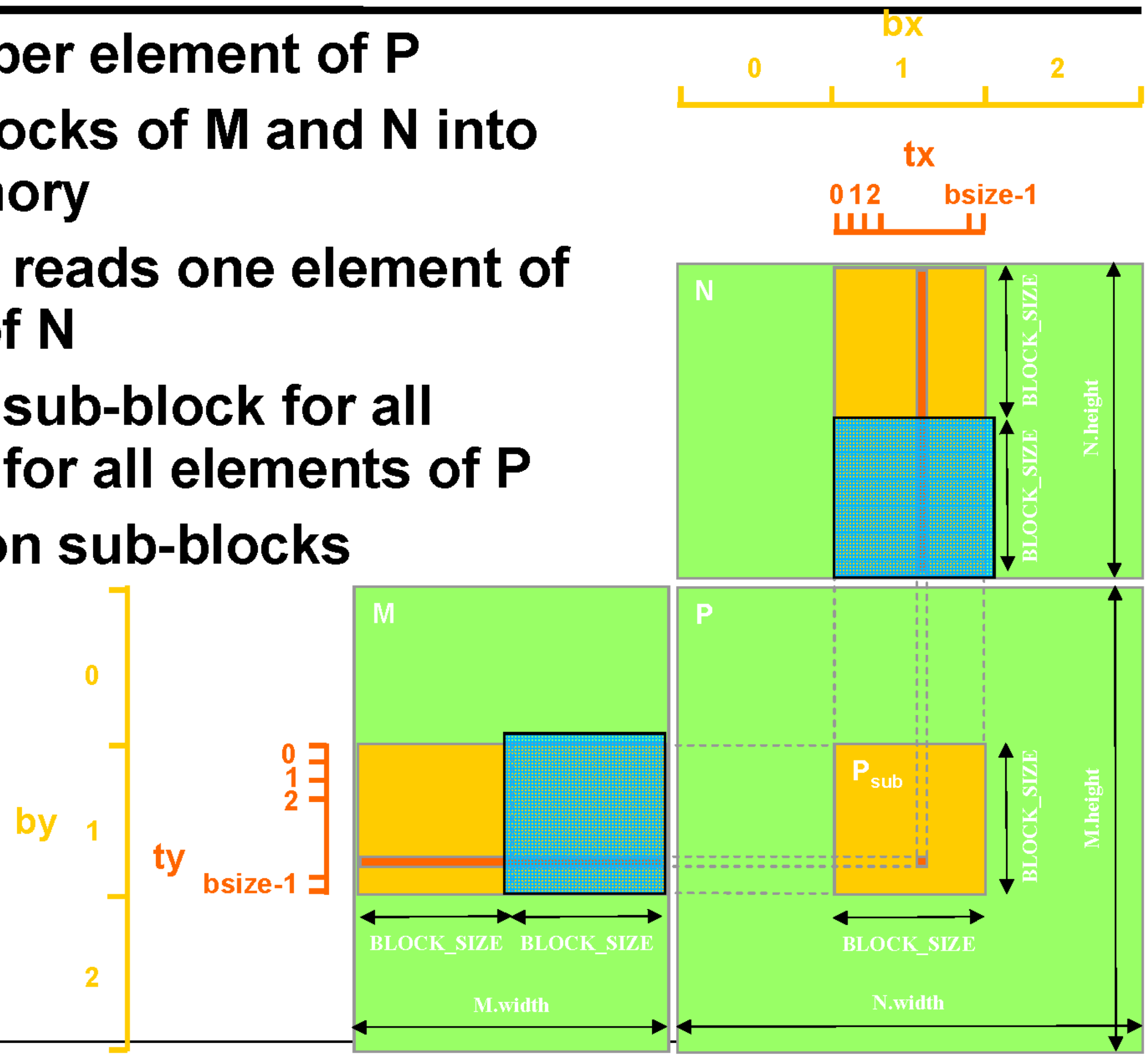


Example: Matrix Multiplication (1)

- Copy matrices to device; invoke kernel; copy result matrix back to host

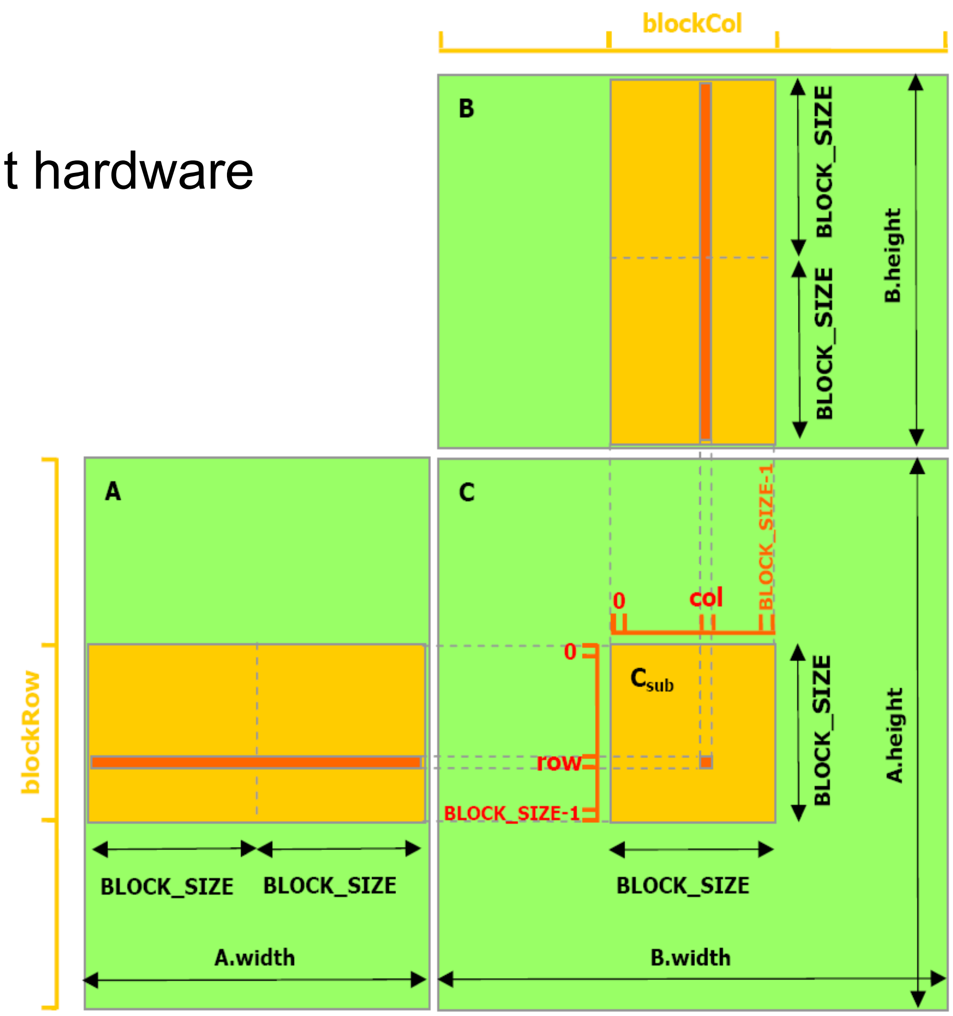
```
// Matrix multiplication - Host code
// Matrix dimensions are assumed to be multiples of BLOCK_SIZE
void MatMul(const Matrix A, const Matrix B, Matrix C)
{
    // Load A and B to device memory
    Matrix d_A;
    d_A.width = d_A.stride = A.width; d_A.height = A.height;
    size_t size = A.width * A.height * sizeof(float);
    cudaMalloc((void**)&d_A.elements, size);
    cudaMemcpy(d_A.elements, A.elements, size,
               cudaMemcpyHostToDevice);
    Matrix d_B;
    d_B.width = d_B.stride = B.width; d_B.height = B.height;
    size = B.width * B.height * sizeof(float);
    cudaMalloc((void**)&d_B.elements, size);
    cudaMemcpy(d_B.elements, B.elements, size,
               cudaMemcpyHostToDevice);
```

Example: Matrix Multiplication (2)

```
    // Allocate C in device memory
    Matrix d_C;
    d_C.width = d_C.stride = C.width; d_C.height = C.height;
    size = C.width * C.height * sizeof(float);
    cudaMalloc((void**)&d_C.elements, size);

    // Invoke kernel
    dim3 dimBlock(BLOCK_SIZE, BLOCK_SIZE);
    dim3 dimGrid(B.width / dimBlock.x, A.height / dimBlock.y);
    MatMulKernel<<<dimGrid, dimBlock>>>(d_A, d_B, d_C);

    // Read C from device memory
    cudaMemcpy(C.elements, d_C.elements, size,
               cudaMemcpyDeviceToHost);

    // Free device memory
    cudaFree(d_A.elements);
    cudaFree(d_B.elements);
    cudaFree(d_C.elements);
}
```

Example: Matrix Multiplication (3)

- Multiply matrix block-wise
- Set BLOCK_SIZE for efficient hardware use, e.g., to 16 on cc. 1.x or 16 or 32 on cc. 2.x +
- Maximize parallelism
  - Launch as many threads per block as block elements
  - Each thread fetches one element of block
  - Perform row * column dot products in parallel



Example: Matrix Multiplication (4)

```
__global__ void MatrixMul( float *matA, float *matB, float *matC, int w )
{
    __shared__ float blockA[ BLOCK_SIZE ][ BLOCK_SIZE ];
    __shared__ float blockB[ BLOCK_SIZE ][ BLOCK_SIZE ];

    int bx = blockIdx.x; int tx = threadIdx.x;
    int by = blockIdx.y; int ty = threadIdx.y;

    int col = bx * BLOCK_SIZE + tx;
    int row = by * BLOCK_SIZE + ty;

    float out = 0.0f;
    for ( int m = 0; m < w / BLOCK_SIZE; m++ ) {

        blockA[ ty ][ tx ] = matA[ row * w +   m * BLOCK_SIZE + tx       ];
        blockB[ ty ][ tx ] = matB[ col     + ( m * BLOCK_SIZE + ty ) * w ];
        __syncthreads();

        for ( int k = 0; k < BLOCK_SIZE; k++ ) {
            out += blockA[ ty ][ k ] * blockB[ k ][ tx ];
        }
        __syncthreads();
    }

    matC[ row * w + col ] = out;
}
```

Caveat: for brevity, this code assumes matrix sizes are a multiple of the block size (either because they really are, or because padding is used; otherwise guard code would need to be added)

What About Memory Performance?
(more to come later…)

Memory Layout of a Matrix in C

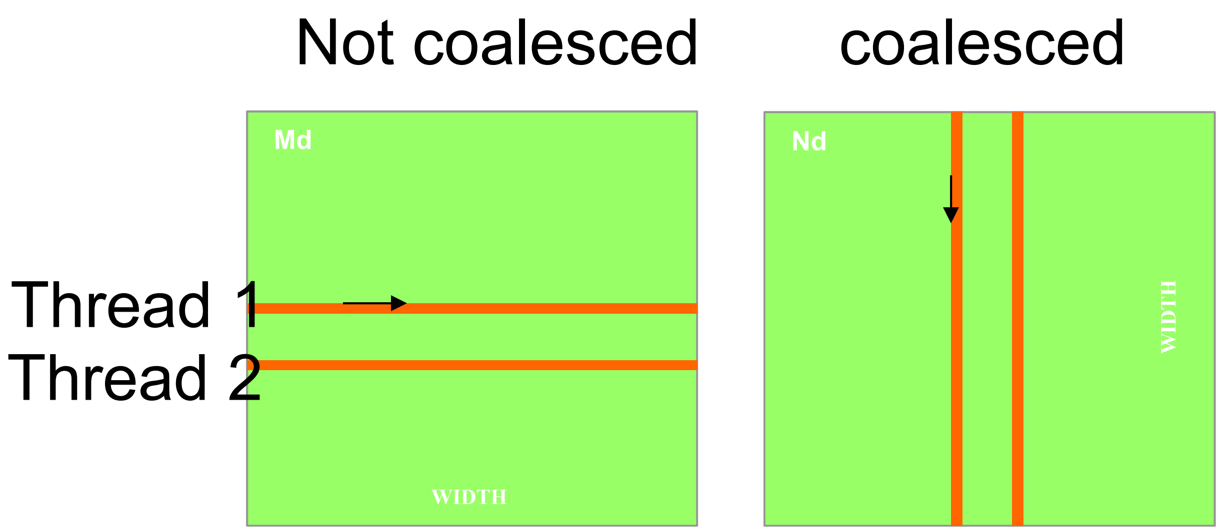
$M_{0,0}$	$M_{1,0}$	$M_{2,0}$	$M_{3,0}$
$M_{0,1}$	$M_{1,1}$	$M_{2,1}$	$M_{3,1}$
$M_{0,2}$	$M_{1,2}$	$M_{2,2}$	$M_{3,2}$
$M_{0,3}$	$M_{1,3}$	$M_{2,3}$	$M_{3,3}$

M

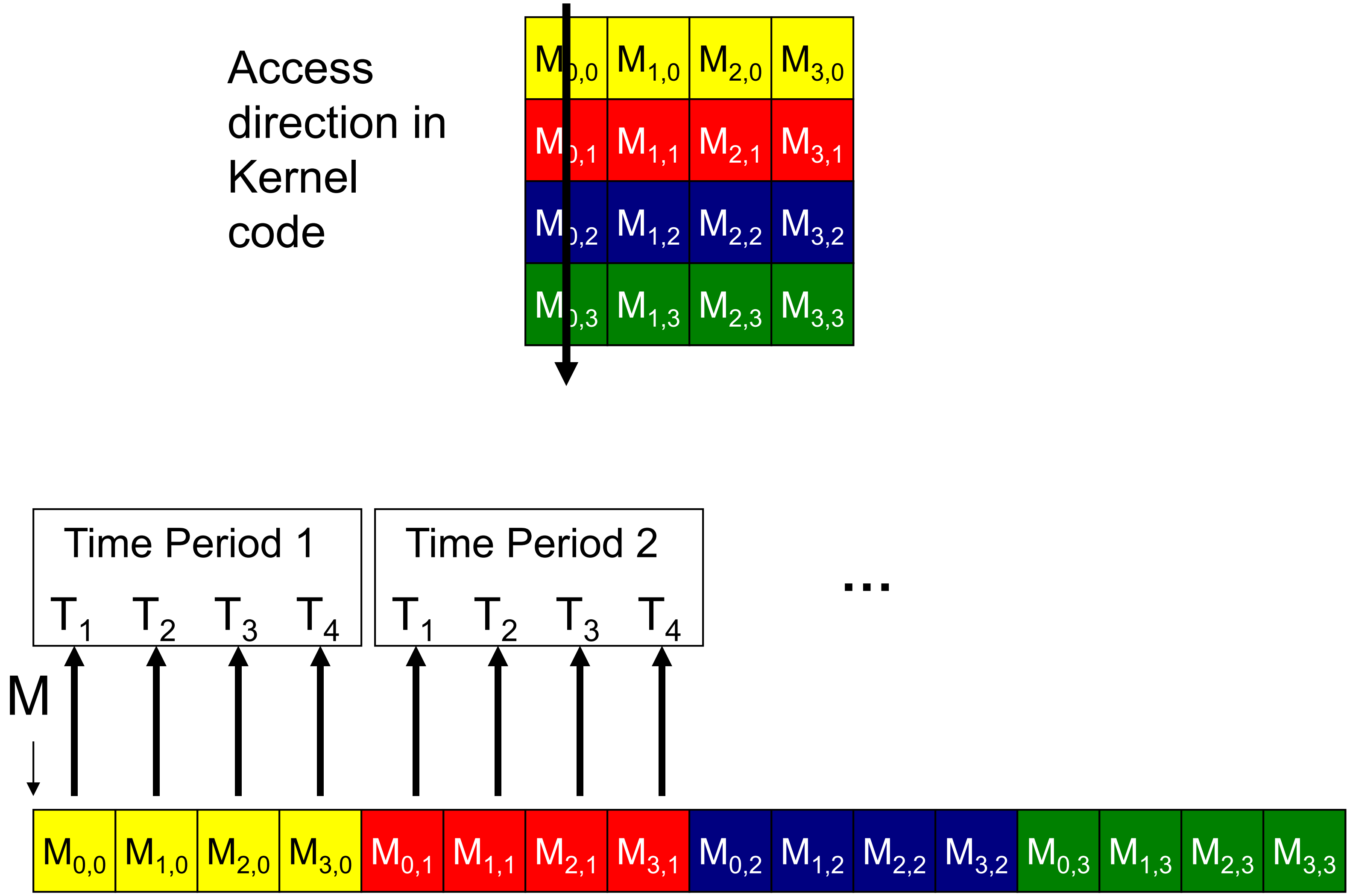
$M_{0,0}$	$M_{1,0}$	$M_{2,0}$	$M_{3,0}$	$M_{0,1}$	$M_{1,1}$	$M_{2,1}$	$M_{3,1}$	$M_{0,2}$	$M_{1,2}$	$M_{2,2}$	$M_{3,2}$	$M_{0,3}$	$M_{1,3}$	$M_{2,3}$	$M_{3,3}$

Memory Coalescing

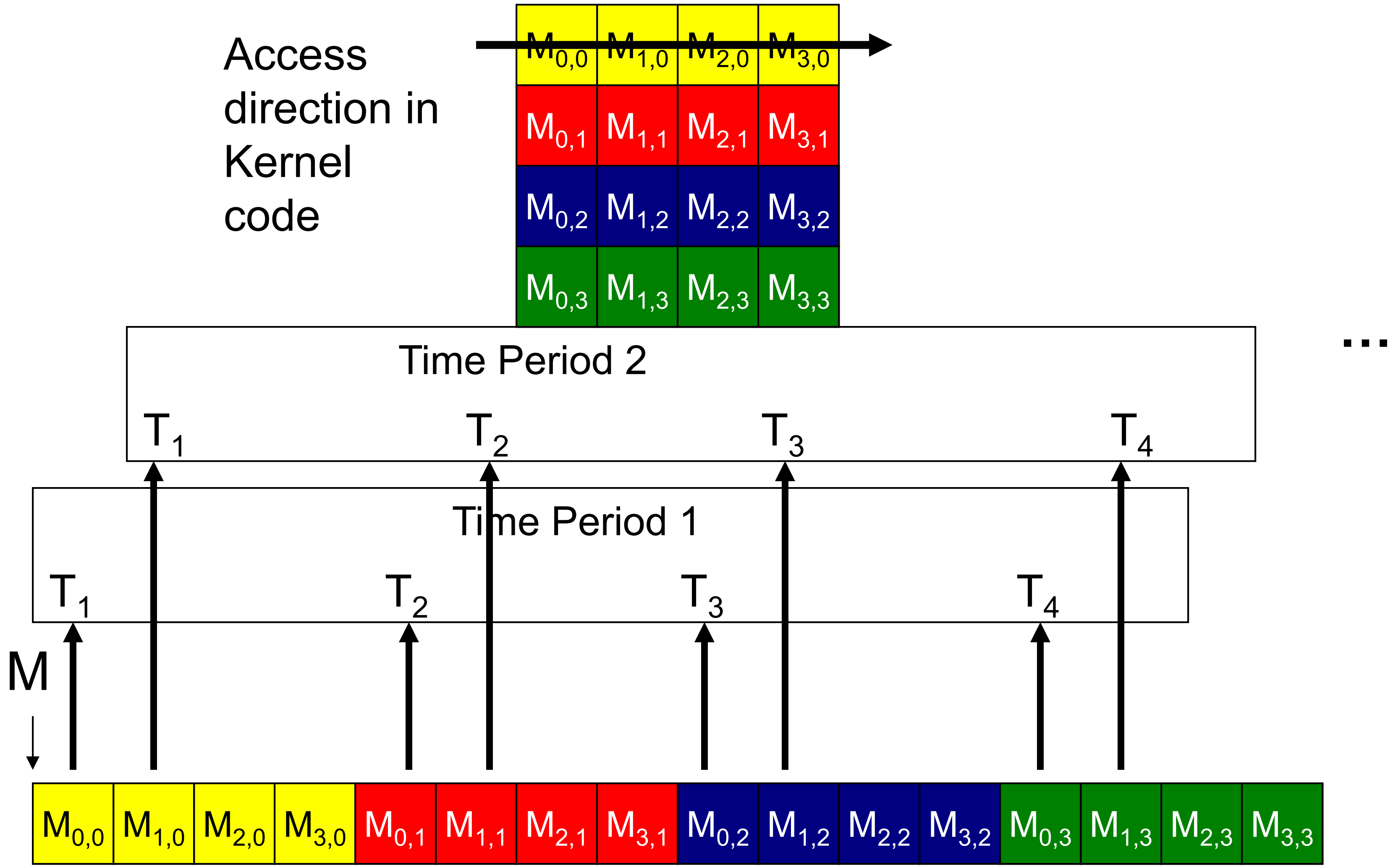
- When accessing global memory, peak performance utilization occurs when all threads in a half warp (full warp on Fermi) access continuous memory locations.
- Requirements relaxed on >=1.2 devices; L1 cache on Fermi!



Memory Layout of a Matrix in C



Memory Layout of a Matrix in C



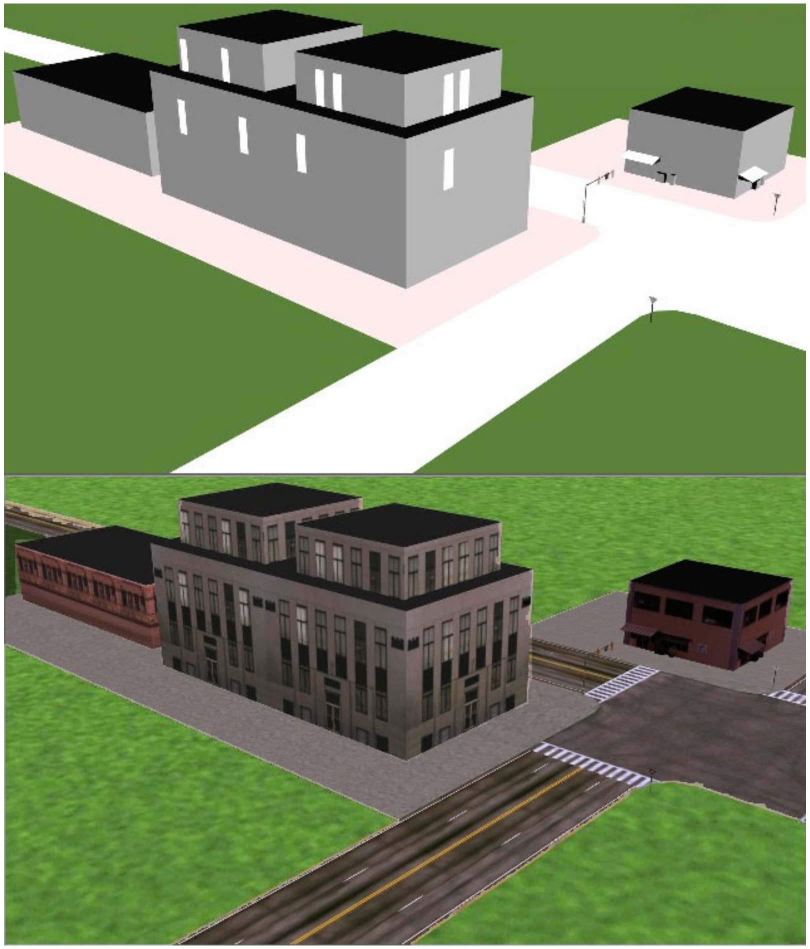
GPU Texturing

GPU Texturing

Rage / id Tech 5 (id Software)

Why Texturing?

- Idea: enhance visual appearance of surfaces by applying fine / high-resolution details



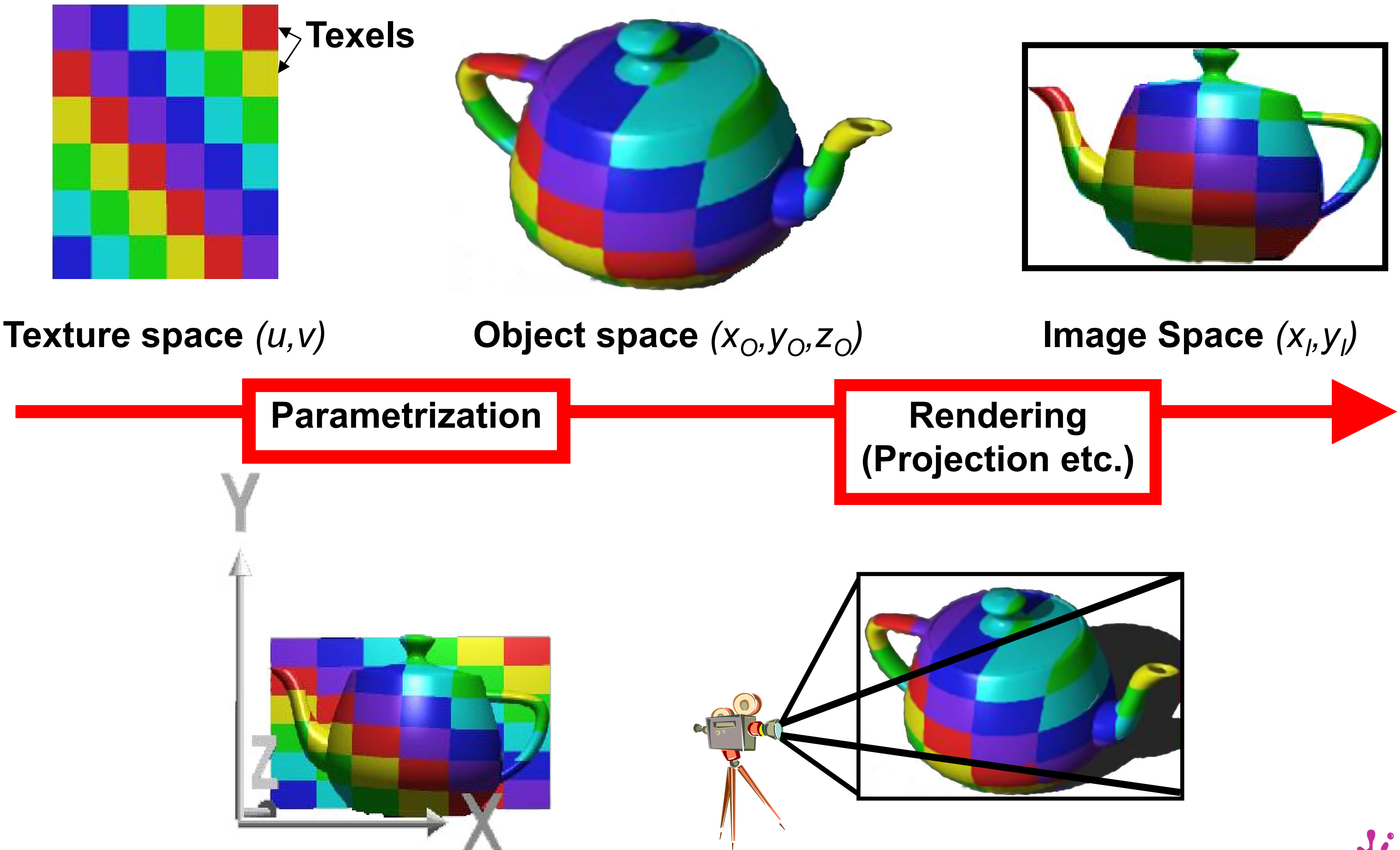
OpenGL Texture Mapping

- Basis for most real-time rendering effects
- Look and feel of a surface
- Definition:
  - A *regularly sampled function* that is mapped onto every *fragment* of a surface
  - Traditionally an image, but…
- Can hold arbitrary information
  - Textures become general data structures
  - Sampled and interpreted by fragment programs
  - Can render into textures → important!

Types of Textures

- Spatial layout
  - Cartesian grids: 1D, 2D, 3D, 2D_ARRAY, …
  - Cube maps, …
- Formats (too many), e.g. OpenGL
  - GL_LUMINANCE16_ALPHA16
  - GL_RGB8, GL_RGBA8, …: integer texture formats
  - GL_RGB16F, GL_RGBA32F, …: float texture formats
  - compressed formats, high dynamic range formats, …
- External (CPU) format vs. internal (GPU) format
  - OpenGL driver converts from external to internal

Texturing: General Approach



Texture Mapping

2D (3D) Texture Space

↓ Texture Transformation

2D Object Parameters

↓ Parameterization

3D Object Space

↓ Model Transformation

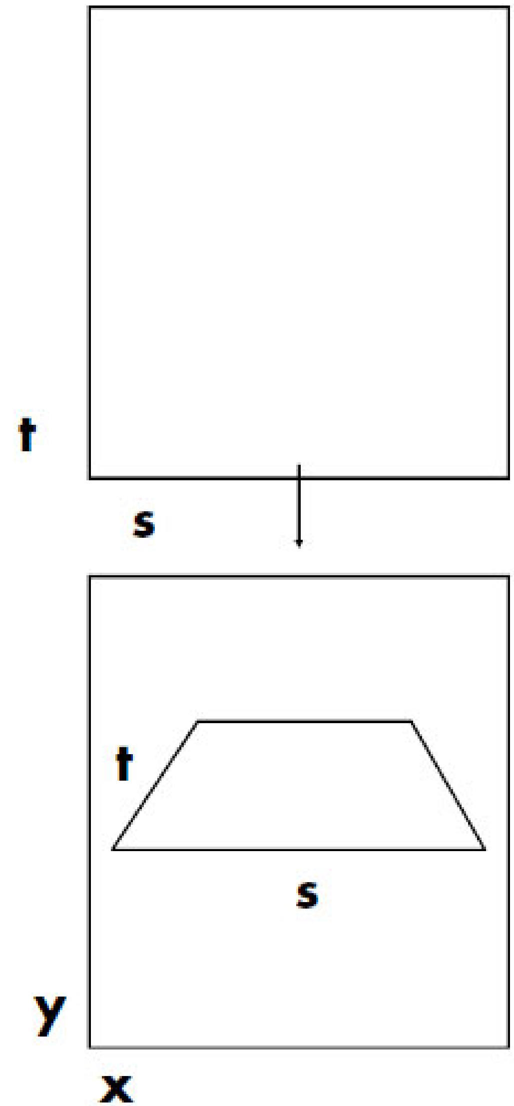
3D World Space

↓ Viewing Transformation

3D Camera Space

↓ Projection

2D Image Space



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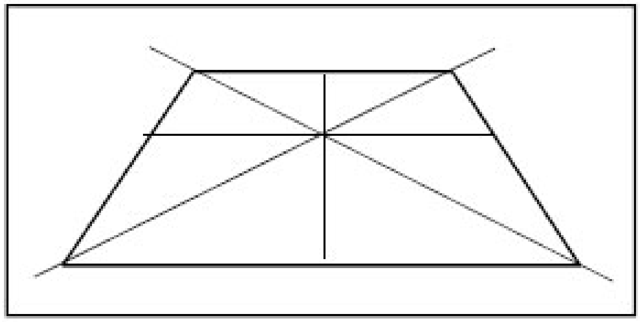
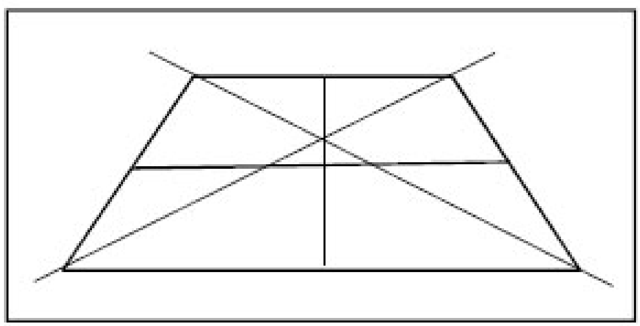
Linear Perspective



Correct Linear Perspective



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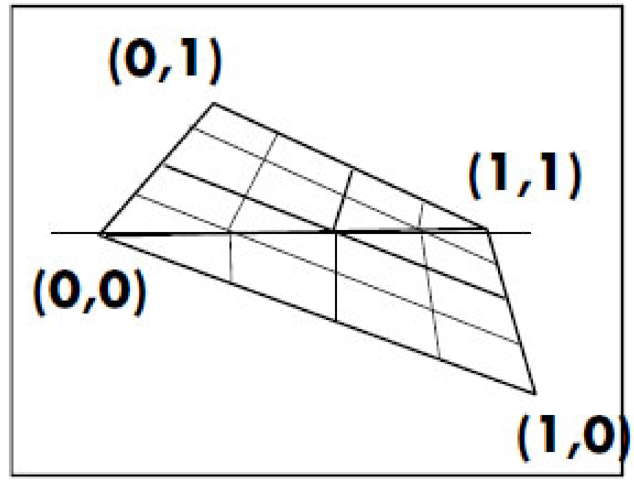

Linear Interpolation, *Bad*

Perspective Interpolation, *Good*

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Texture Mapping Polygons

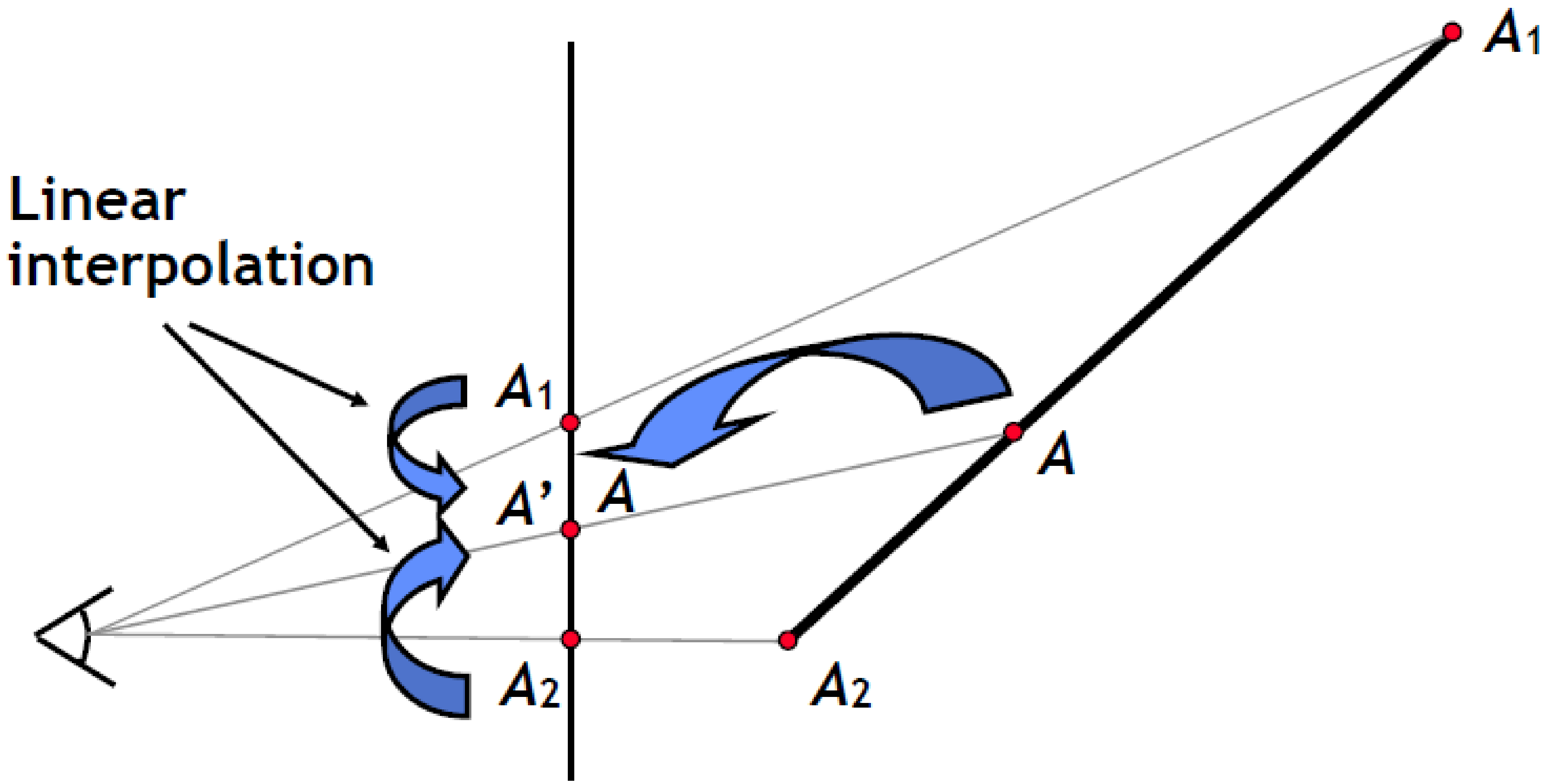
Forward transformation: linear projective map

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} s \\ t \\ r \end{bmatrix}$$

Backward transformation: linear projective map

$$\begin{bmatrix} s \\ t \\ r \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}^{-1} \begin{bmatrix} x \\ y \\ w \end{bmatrix}$$

Incorrect attribute interpolation



$A' \neq A$!

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Linear interpolation

Compute intermediate attribute value

- Along a line: $A = aA_1 + bA_2$, $a+b=1$
- On a plane: $A = aA_1 + bA_2 + cA_3$, $a+b+c=1$

Only projected values interpolate linearly in screen space (straight lines project to straight lines)

- x and y are projected (divided by w)
- Attribute values are not naturally projected

Choice for attribute interpolation in screen space

- Interpolate unprojected values
  - Cheap and easy to do, but gives wrong values
  - Sometimes OK for color, but
  - Never acceptable for texture coordinates
- Do it right

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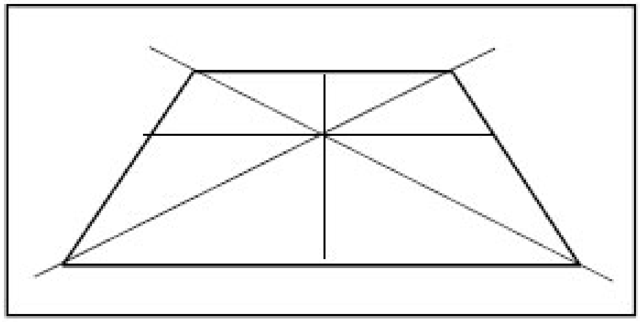
Linear Perspective



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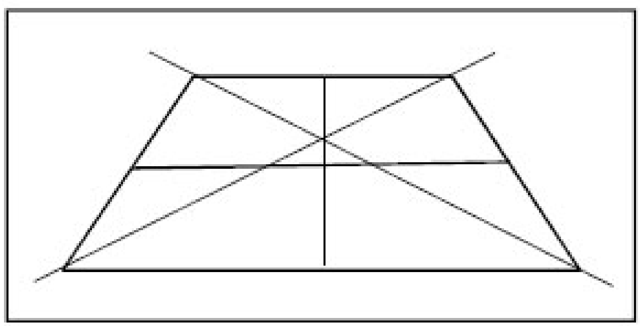

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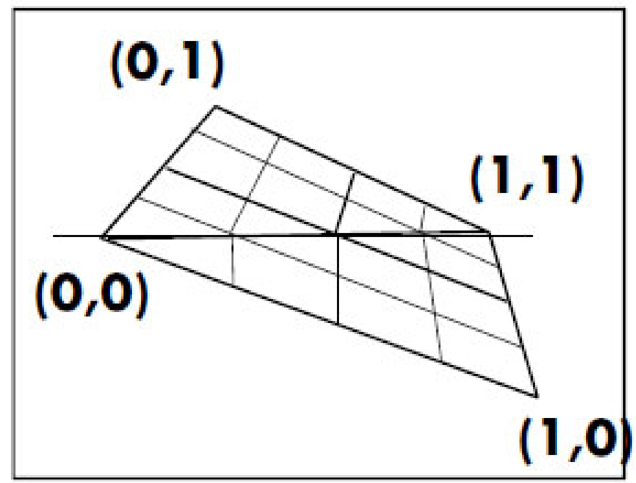

Linear Interpolation, *Bad*

Perspective Interpolation, *Good*

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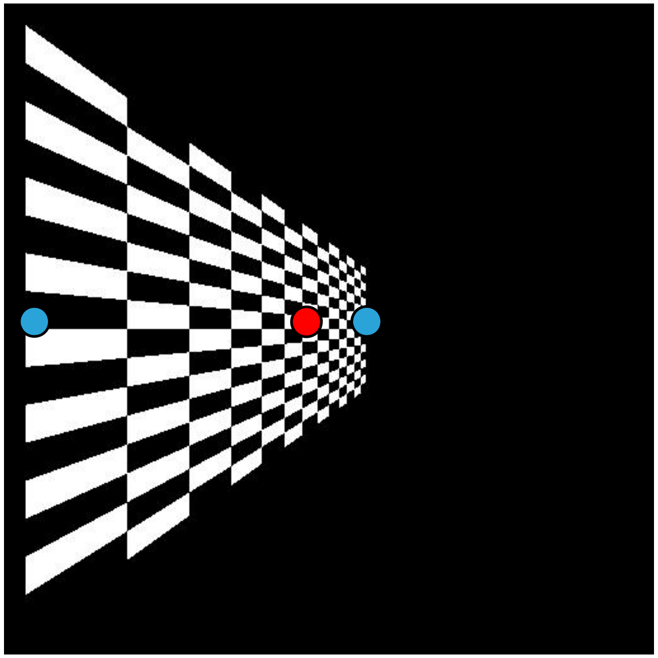
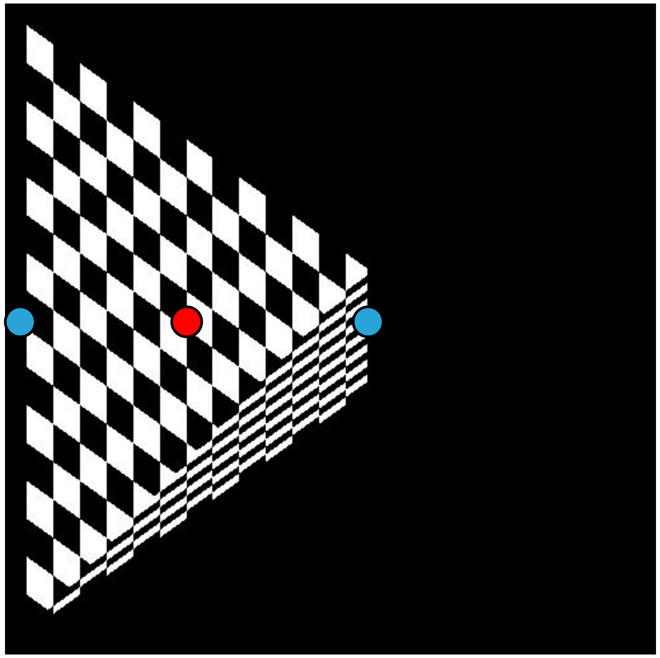
Perspective Texture Mapping

linear interpolation in object space

$$\frac{ax_1 + bx_2}{aw_1 + bw_2} \neq a\frac{x_1}{w_1} + b\frac{x_2}{w_2}$$

linear interpolation in screen space





$a = b = 0.5$

Homogeneous Coordinates (1)

Projective geometry

- (Real) projective spaces RP^n:

  Real projective line RP^1, real projective plane RP^2, ...
- A point in RP^n is a line through the origin (i.e., all the scalar multiples of the same vector) in an (n+1)-dimensional (real) vector space

Homogeneous coordinates of 2D projective point in RP^2

- Coordinates differing only by a non-zero factor λ map to the same point

  $(\lambda x, \lambda y, \lambda)$ dividing out the λ gives $(x, y, 1)$, corresponding to (x,y) in R^2
- Coordinates with last component = 0 map to “points at infinity”

  $(\lambda x, \lambda y, 0)$ division by last component not allowed; but again this is the same point if it only differs by a scalar factor, e.g., this is the same point as $(x, y, 0)$

Homogeneous Coordinates (2)

Examples of usage

- Translation (with translation vector $\vec{b}$)
- Affine transformations (linear transformation + translation)

$$\vec{y} = A\vec{x} + \vec{b}.$$

- With homogeneous coordinates:

$$\begin{bmatrix} \vec{y} \\ 1 \end{bmatrix} = \left[\begin{array}{ccc|c} & A & & \vec{b} \\ 0 & \dots & 0 & 1 \end{array}\right] \begin{bmatrix} \vec{x} \\ 1 \end{bmatrix}$$

- Setting the last coordinate = 1 and the last row of the matrix to [0, ..., 0, 1] results in translation of the point $\vec{x}$ (via addition of translation vector $\vec{b}$)
- The matrix above is a linear map, but because it is one dimension higher, it does not have to move the origin in the (n+1)-dimensional space for translation

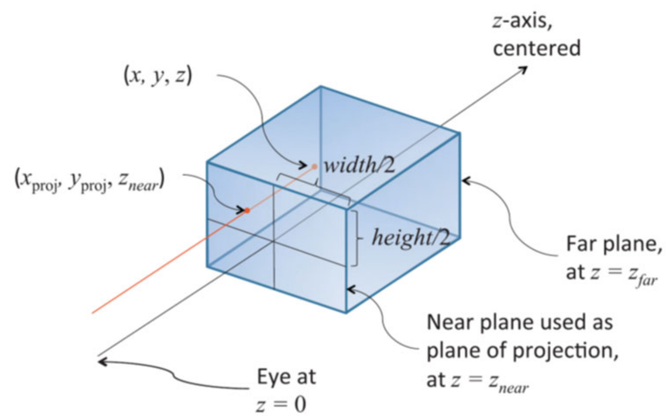
Homogeneous Coordinates (3)

Examples of usage

- Projection (e.g., OpenGL projection matrices)

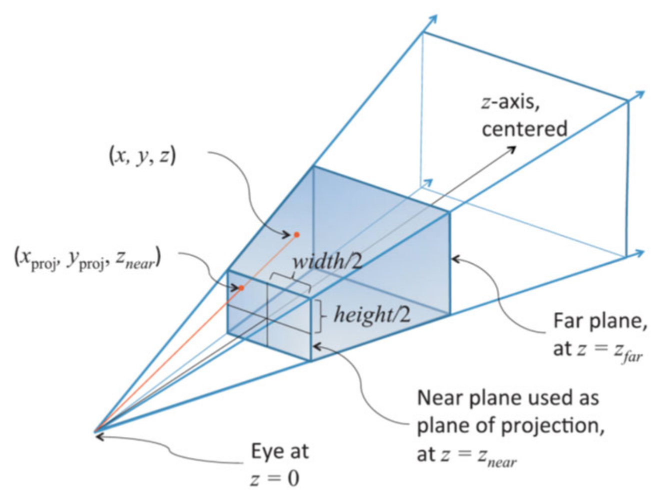
$$\begin{bmatrix} \frac{2}{\text{right}-\text{left}} & 0 & 0 & -\frac{\text{right}+\text{left}}{\text{right}-\text{left}} \\ 0 & \frac{2}{\text{top}-\text{bottom}} & 0 & -\frac{\text{top}+\text{bottom}}{\text{top}-\text{bottom}} \\ 0 & 0 & \frac{-2}{\text{far}-\text{near}} & -\frac{\text{far}+\text{near}}{\text{far}-\text{near}} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

orthographic



$$\begin{bmatrix} \frac{z_{near}}{width/2} & 0.0 & \frac{left+right}{width/2} & 0.0 \\ 0.0 & \frac{z_{near}}{height/2} & \frac{top+bottom}{height/2} & 0.0 \\ 0.0 & 0.0 & -\frac{z_{far}+z_{near}}{z_{far}-z_{near}} & \frac{2z_{far}z_{near}}{z_{far}-z_{near}} \\ 0.0 & 0.0 & -1.0 & 0.0 \end{bmatrix}$$

perspective



Thank you.