CS380: Computer Graphics
3D Transformation

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Course URL:
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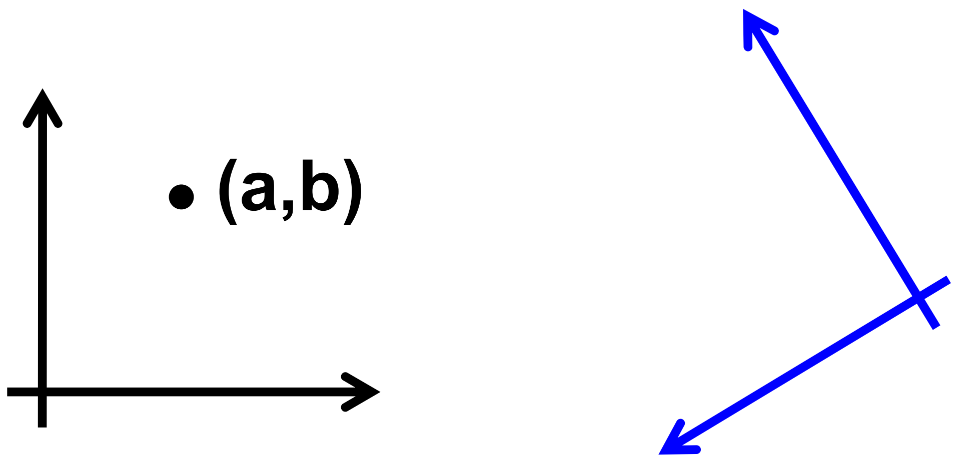
Class Objectives

- Understand the diff. between points and vectors
- Understand the frame
- Represent transformations in local and global frames

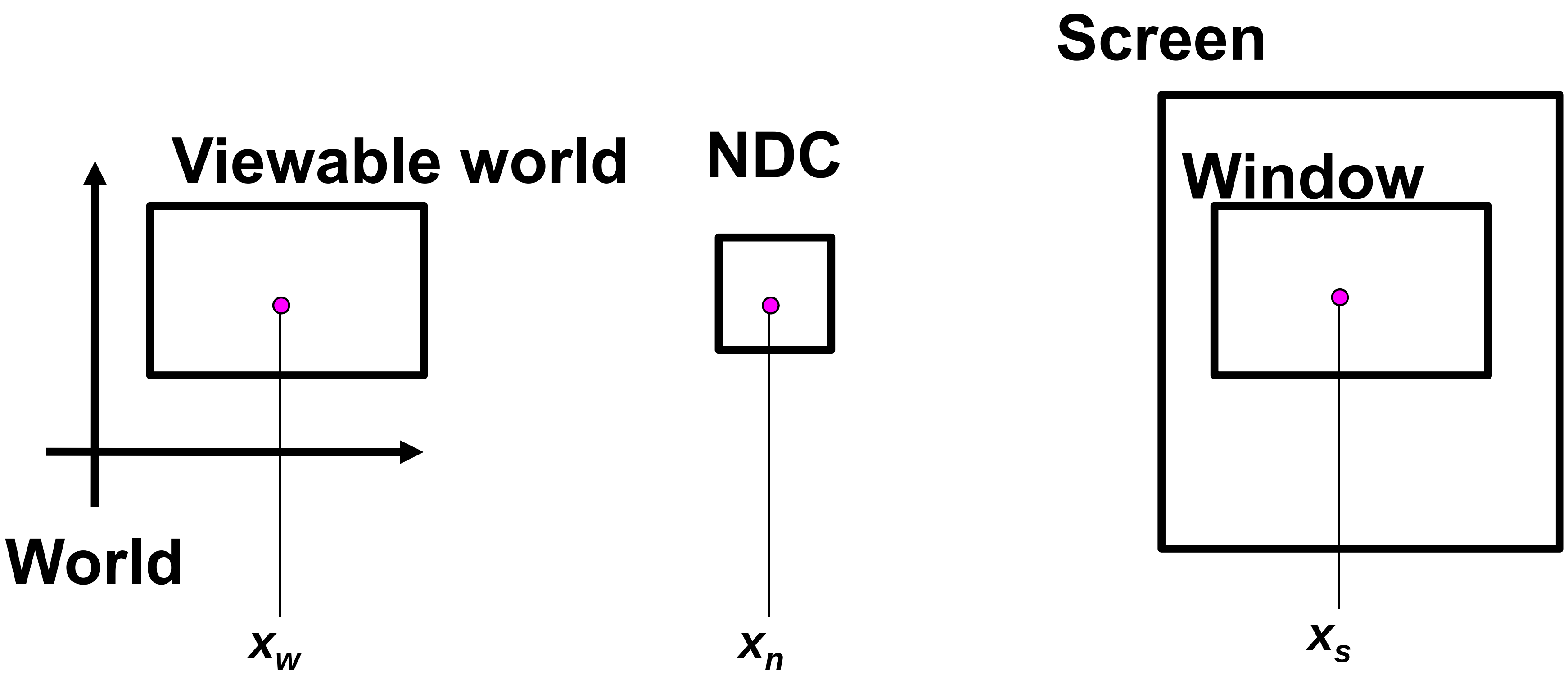
- Related chapters of my draft
  - Ch. 3.3 Affine frame
  - Ch. 3.4 Local and global frames
- At the last class:
  - 2D transformation and homogeneous coordinate
  - Idle-based animation

A Question?

- Suppose you have 2 frames and you know the coordinates of a point relative in one frame
  - How would you compute the coordinate of your point relative to the other frame?
  - (Generalized question to the mapping problem that we went over in the class)



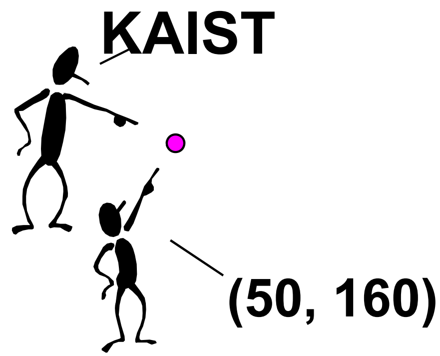
Revisit: Mapping from World to Screen



Geometry

- **A part of mathematics concerned with questions of size, shape, and relative positions of figures**

- **Coordinates are used to represent points and vectors**
  - **We will learn that they are just a naming scheme**
  - **The same point can be described by different coordinates**
  - **Both vectors and points expressed by coordinates, but they are very different**



Vector Spaces

- A vector (or linear) space V over a scalar field S consists of a set on which the following two operators are defined and the following conditions hold:
- Two operators for vectors:
  - Vector-vector addition

$$\forall \vec{u}, \vec{v} \in V \quad \vec{u} + \vec{v} \in V$$

  - Scalar-vector multiplication

$$\forall \vec{u} \in V, \forall a \in S \quad a\vec{u} \in V$$

- Notation:
  - Vector

$$\vec{v} = \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} a & b & c \end{bmatrix}^t$$

Vector Spaces

- **Vector-vector addition**
  - **Commutes and associates**

$$\vec{u} + \vec{v} = \vec{v} + \vec{u} \quad \vec{u} + (\vec{v} + \vec{w}) = (\vec{u} + \vec{v}) + \vec{w}$$

  - **An additive identity and an additive inverse for each vector**

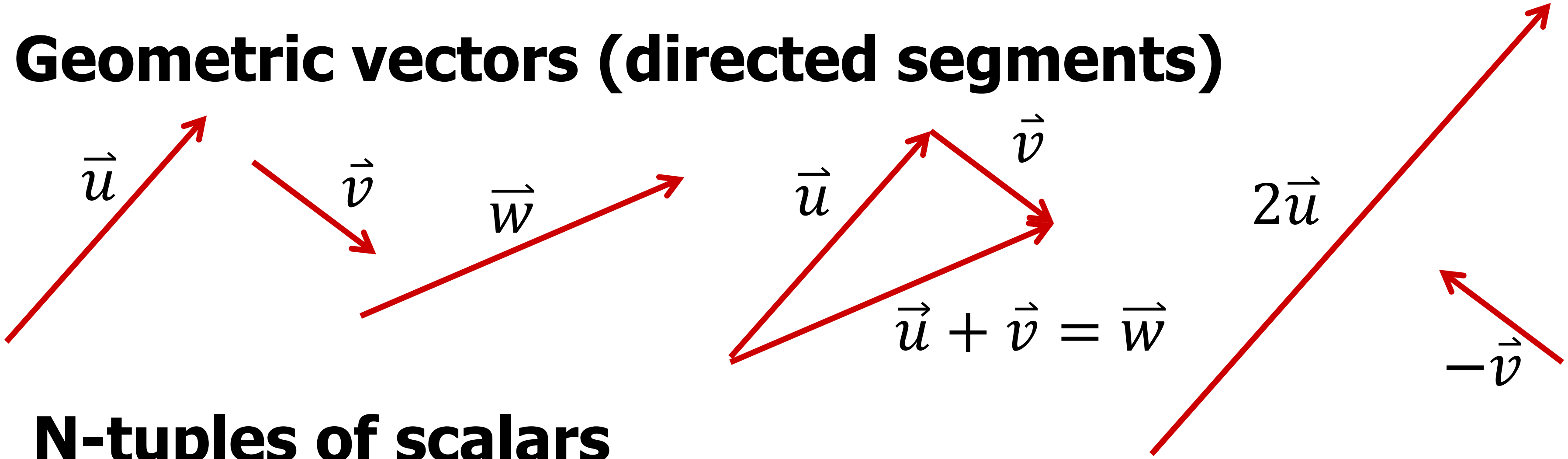
$$\vec{u} + \vec{\mathbf{0}} = \vec{u} \qquad \vec{u} + (-\vec{u}) = \vec{\mathbf{0}}$$

- **Scalar-vector multiplication distributes**

$$(a + b)\vec{u} = a\vec{u} + b\vec{u} \quad a(\vec{u} + \vec{v}) = a\vec{u} + a\vec{v}$$

Example Vector Spaces

- **Geometric vectors (directed segments)**



- **N-tuples of scalars**

$$\vec{u} = (1,3,7)^t \qquad \vec{u} + \vec{v} = (3,5,4)^t = \vec{w}$$
$$\vec{v} = (2,2,-3)^t \qquad 2\vec{u} = (2,6,14)^t$$
$$\vec{w} = (3,5,4)^t \qquad -\vec{v} = (-2,-2,3)^t$$

- **We can use N-tuples to represent vectors**

Basis Vectors

- **A vector basis is a subset of vectors from V that can be used to generate any other element in V, using just additions and scalar multiplications**
- **A basis set, $\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_n$, is linearly dependent if:**

$$\exists a_1, a_2, \ldots, a_n \neq 0 \quad \text{such that} \quad \sum_{\mathrm{i}=0}^{\mathrm{n}} \mathrm{a_i} \vec{v}_i = 0$$

- **Otherwise, the basis set is linearly independent**
  - **A linearly independent basis set with *i* elements is said to *span* an *i-dimensional* vector space**

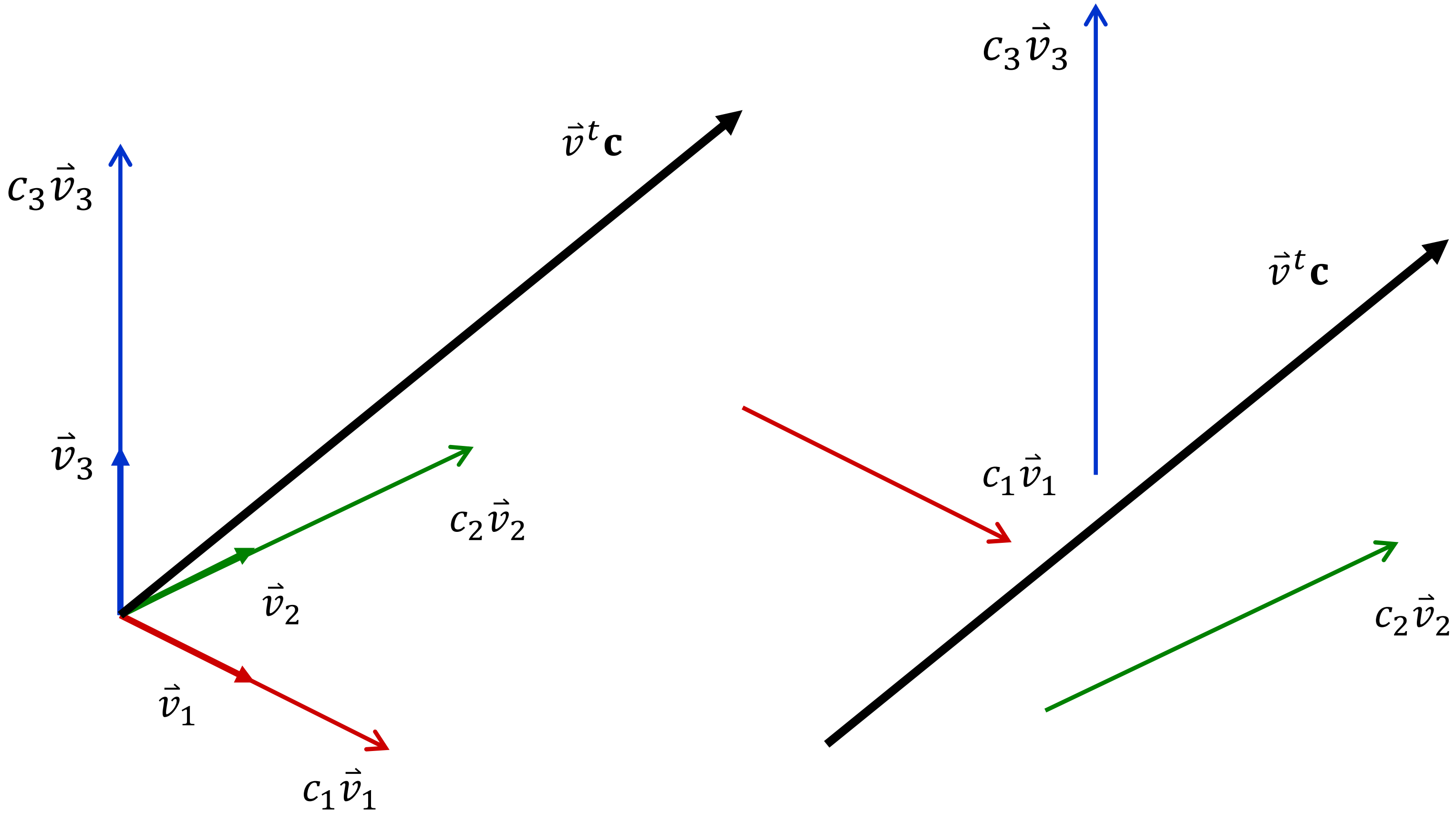
Vector Coordinates

- **A linearly independent basis set can be used to uniquely name or address a vector**
  - **This is the done by assigning the vector coordinates as follows:**

$$\vec{x} = \sum_{i=1}^{3} c_i \vec{v}_i = [\vec{v}_1 \quad \vec{v}_2 \quad \vec{v}_3] \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix}$$
$$= \vec{v}^t \mathbf{c}$$

- **Note: we'll use bold letters to indicate tuples of scalars that are interpreted as coordinates**
- **Our vectors are still abstract entities**
  - **So how do we interpret the equation above?**

Interpreting Vector Coordinates



Valid Interpretation **Equally Valid Interpretation**

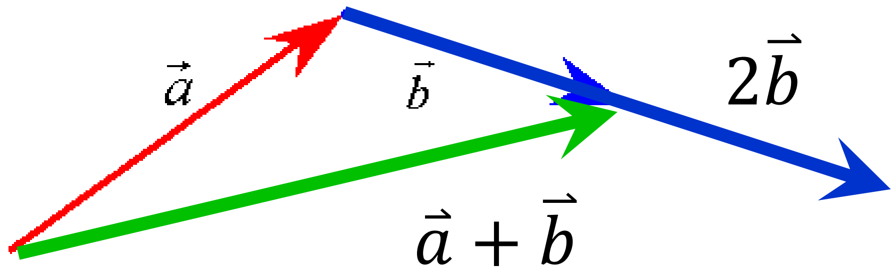
Remember, vectors don't have any notion of position

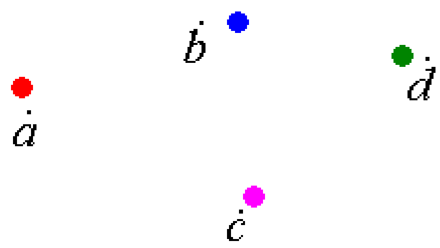
Points

- **Conceptually, points and vectors are very different**
  - **A point $\dot{p}$ is a place in space**
  - **A vector $\vec{v}$ describes a direction independent of position (pay attentions notations)**

How Vectors and Points Differ

- The operations of addition and multiplication by a scalar are well defined for vectors
  - Addition of 2 vectors expresses the concatenation of 2 “motions”
  - Multiplying a vector by some factor scales the motion
- These operations does not make sense for points

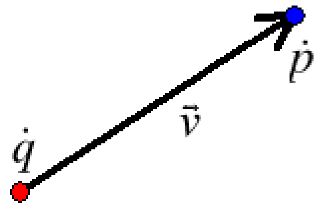




Making Sense of Points

- Some operations do make sense for points
  - Compute a vector that describes the motion from one point to another:

$$\dot{p} - \dot{q} = \vec{v}$$



  - Find a new point that is some vector away from a given point:

$$\dot{q} + \vec{v} = \dot{p}$$

A Basis for Points

- **Key distinction between vectors and points:**
  points are *absolute*, vectors are *relative*
- **Vector space is completely defined by a set of basis vectors**
- **The space that points live in requires the specification of an absolute origin**

$$\dot{p} = \dot{o} + \sum_i \vec{v}_i c_i = \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \vec{v}_3 & \dot{o} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ 1 \end{bmatrix}$$

Notice how 4 scalars (one of which is 1) are required to identify a 3D point

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Frames

- **Points live in *Affine* spaces**
- **Affine-basis-sets are called *frames or Special Euclidean group of three, SE (3)***

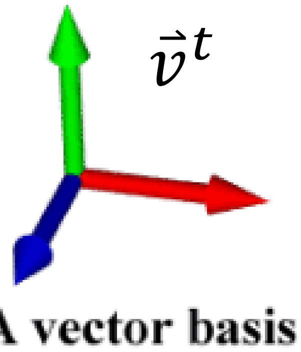
$$\dot{f}^t = \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \vec{v}_3 & \dot{o} \end{bmatrix}$$

- **Frames can describe vectors as well as points**

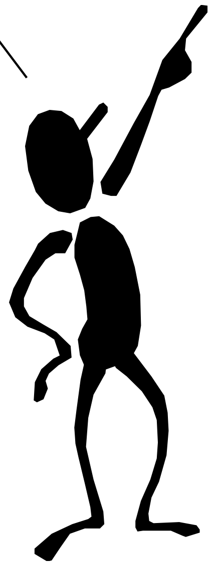
$$\dot{p} = \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \vec{v}_3 & \dot{o} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ 1 \end{bmatrix} \qquad \vec{x} = \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \vec{v}_3 & \dot{o} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ 0 \end{bmatrix}$$

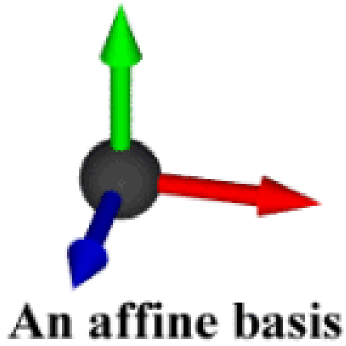
Pictures of Frames

- **Graphically, we will distinguish between vector bases and affine bases (frames) using the following convention**

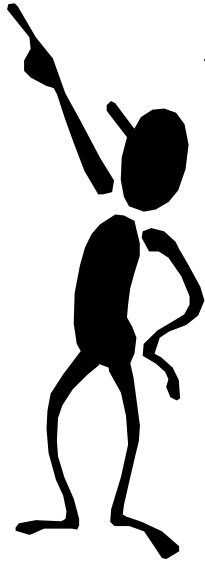


Three vectors





Three vectors and a point



A Consistent Model

- **Behavior of affine frame coordinates is completely consistent with our intuition**
  - **Subtracting two points yields a vector**
  - **Adding a vector to a point produces a point**
  - **If you multiply a vector by a scalar you still get a vector**
  - **Scaling points gives a nonsense 4th coordinate element in most cases**

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ 1 \end{bmatrix} - \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ 1 \end{bmatrix} = \begin{bmatrix} a_1 - b_1 \\ a_2 - b_2 \\ a_3 - b_3 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ 1 \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ 0 \end{bmatrix} = \begin{bmatrix} a_1 + v_1 \\ a_2 + v_2 \\ a_3 + v_3 \\ 1 \end{bmatrix}$$

Homogeneous Coordinates

- **Notice why we introduce homogeneous coordinates, based on simple logical arguments**
  - **Remember that coordinates are not geometric; they are just scales for basis elements**
  - **Thus, you should not be bothered by the fact that our coordinates suddenly have 4 numbers**

- **3D homogeneous coordinates refer to an affine frame with its 3 basis vectors and origin point**
  - **4 coordinates make sense in this aspect**
  - **4th coordinate can have one of two values, [0,1], indicating if whether the coordinates name a vector or a point**

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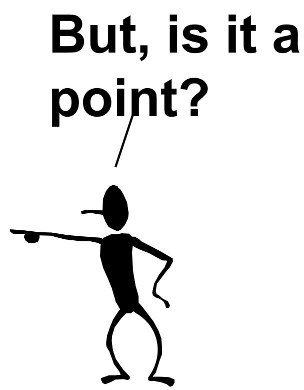
Affine Combinations

- **There are certain situations where it makes sense to scale and add points**
  - **Suppose you have two points, one scaled by α_1 and the other scaled by α_2**
  - **If we restrict the sum of these alphas, $\alpha_1 + \alpha_2 = 1$, we can assure that the result will have 1 as it's 4th coordinate value**

$$\alpha_1 \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ 1 \end{bmatrix} + \alpha_2 \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_1 a_1 + \alpha_2 b_1 \\ \alpha_1 a_2 + \alpha_2 b_2 \\ \alpha_1 a_3 + \alpha_2 b_3 \\ \alpha_1 + \alpha_2 \end{bmatrix} = \begin{bmatrix} \alpha_1 a_1 + \alpha_2 b_1 \\ \alpha_1 a_2 + \alpha_2 b_2 \\ \alpha_1 a_3 + \alpha_2 b_3 \\ 1 \end{bmatrix}$$



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Affine Combinations

- **Can be thought of as a constrained-scaled addition**
  - **Defines all points that share the line connecting our two initial points**

- **Can be extended to 3, 4, or any number of points (e.g., barycentric coordinates)**

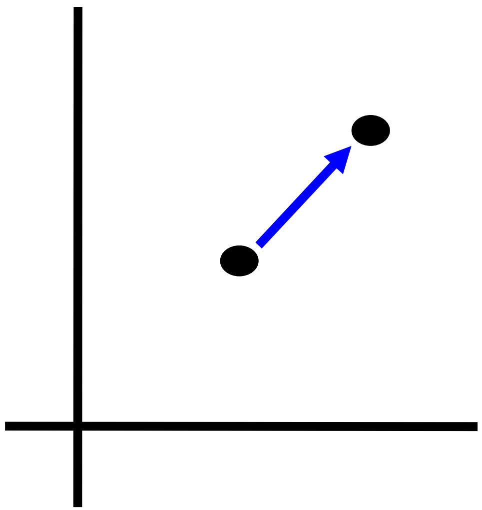
Affine Transformations

- **We can apply transformations to points using matrix**
  - **Need to use 4 by 4 matrices since our basis set has four components**
  - **Also, limit ourselves to transforms that preserve the integrity of our points and vectors; point to point, vector to vector**

$$\dot{p} = \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \vec{v}_3 & \dot{o} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ 1 \end{bmatrix} \Rightarrow \dot{p}' = \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \vec{v}_3 & \dot{o} \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ 1 \end{bmatrix}$$

  - **This subset of matrices is called the *affine* subset**

An Example



Composing Transformations

- **Represent a series of transformations**
  - **E.g., want to translate with T and, then, rotate with R**

- **Then, the series is represented by:**

$$\dot{p} = \dot{w}^t c \Rightarrow \dot{p}' = \dot{w}^t RTc = \dot{w}^t(R(Tc)) = \dot{w}^t(Rc') = \dot{w}^t c''$$

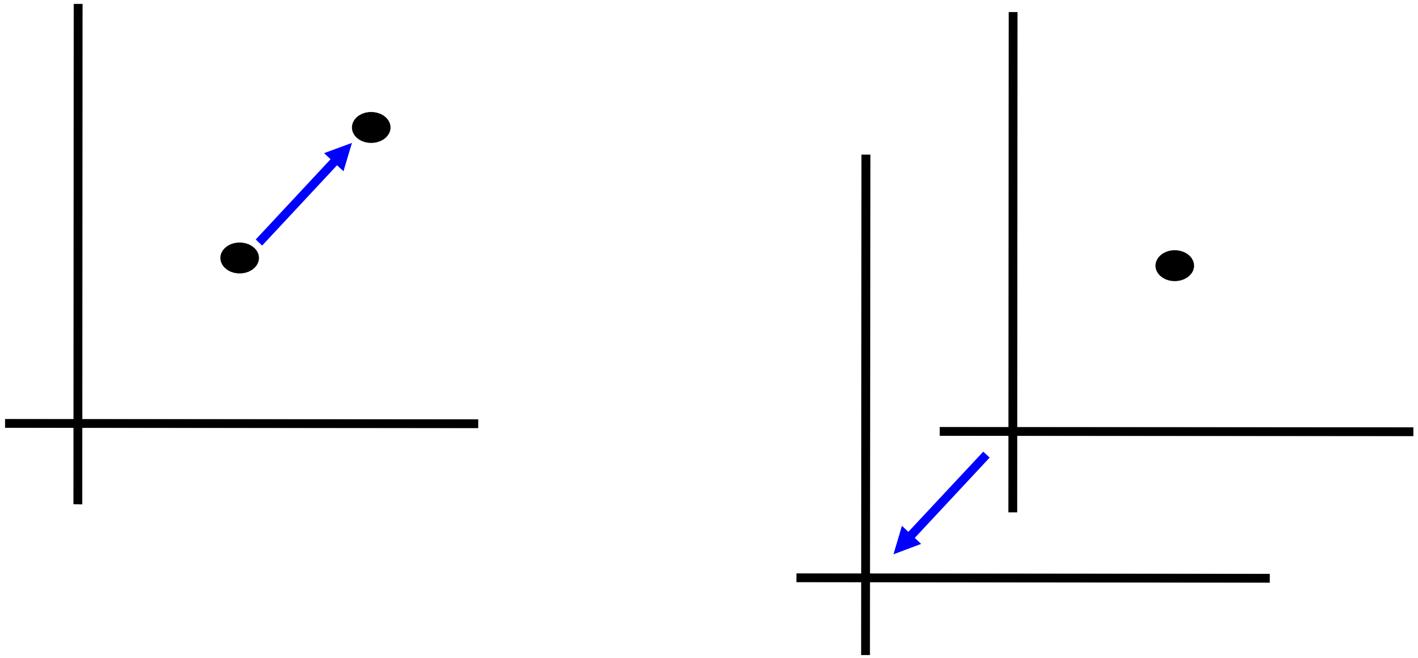
  - **Each step in the process can be considered as a change of coordinates**

- **Alternatively, we could have considered the same sequence of operations as:**

$$\dot{p} = \dot{w}^t c \Rightarrow \dot{p}' = \dot{w}^t RTc = \left((\dot{w}^t R)T\right)c = (\dot{m}^t T)c = \dot{e}^t c,$$

, where each step is considered as a change of basis

An Example



- **These are alternate interpretations of the same transformations**
  - **The left and right sequence are considered as a transformation about a *global frame and local* frames**

Same Point in Different Frames

- **Suppose you have 2 frames and you know the coordinates of a point relative in one frame**
  - **How would you compute the coordinate of your point relative to the other frame?**

$$\dot{p} = \dot{w}^t \mathbf{c} = \dot{z}^t \,?$$

  - **Suppose that my two frames are related by the transform *S* as shown below:**

$$\dot{z}^t = \dot{w}^t \mathbf{S} \quad and \quad \dot{w}^t = \dot{z}^t \mathbf{S}^{-1}$$

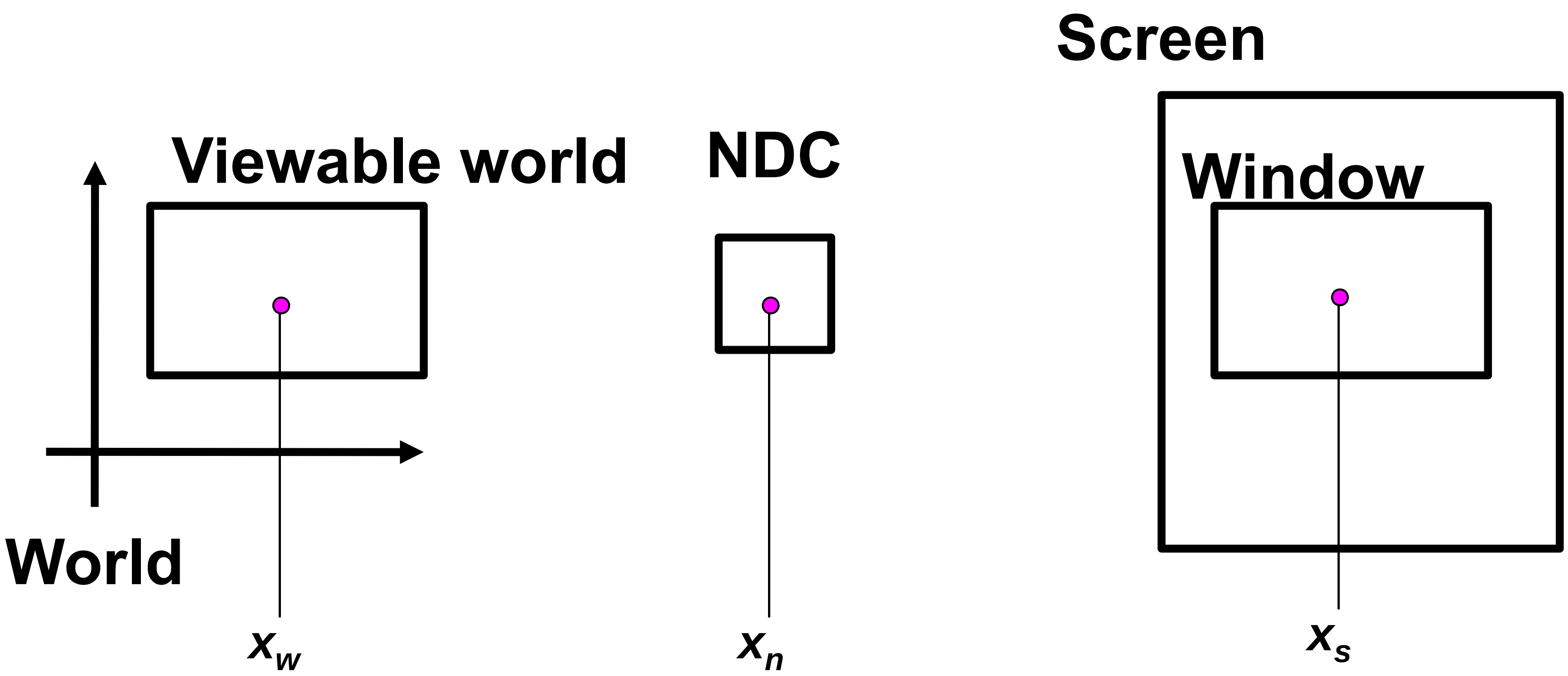
  - **Then, the coordinate for the point in second frame is simply:**

$$\dot{p} = \dot{w}^t \mathbf{c} = \dot{z}^t \mathbf{S}^{-1} \mathbf{c} = \dot{z}^t (\mathbf{S}^{-1} \mathbf{c}) = \dot{z}^t \mathbf{d}$$

Substitute for the frame

Reorganize & reinterpret

Revisit: Mapping from World to Screen



Class Objectives were:

- **Understand the diff. between points and vectors**
- **Understand the frame**
- **Represent transformations in local and global frames**

Quiz Assignment

- **Write down your answer on a paper and send its captured image**

Next Time

- **Modeling and viewing transformations**

Homework

- **Go over the next lecture slides before the class**
- **Watch 2 SIGGRAPH videos and submit your summaries before every Tue. class**

Any Questions?

- **Come up with one question on what we have discussed in the class and submit at the end of the class**
  - **1 for already answered or typical questions**
  - **2 for questions with thoughts or that surprised me**

- **Submit two times during the whole semester**

Additional slides

Scalar Fields

- **A scalar field S is a set on which addition (+) and multiplication (·) are defined and following conditions hold:**
  - **S is closed for addition and multiplication**

$$\forall a, b \in S \quad a + b \in S \quad a \cdot b \in S$$

  - **These operators commute, associate, and distribute**

$$\forall a, b, c \in S$$

$$a + b = b + a \quad a \cdot b = b \cdot a$$

$$a + (b + c) = (a + b) + c \quad a \cdot (b \cdot c) = (a \cdot b) \cdot c$$

$$a \cdot (b + c) = a \cdot b + a \cdot c$$

Scalar Fields – cont'd

- **A scalar field S is a set on which addition (+) and multiplication (·) are defined and following conditions hold:**
  - **Both operators have a unique identity element**

$$a + 0 = a, \qquad a \cdot 1 = a$$

  - **Each element has a unique inverse under both operators**

$$a + (-a) = 0, \qquad a \cdot a^{-1} = 1$$

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Examples of Scalar Fields

- **Real numbers**
- **Complex numbers (given the standard definitions for addition and multiplication)**
- **Rational numbers**
- **Notation: we will represent scalars by lower case letters**

    ***a*, *b*, *c*, … are scalar variables**