CS 4204 Computer Graphics

Channel Data and Keyframing Animation

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Animation

- ***When we speak of an 'animation', we refer to the data required to pose a skeleton over some range of time***
- ***This should include information to specify all necessary DOF values over the entire time range***
- ***Sometimes, this is referred to as a 'clip' or even a 'move' (as 'animation' can be ambiguous)***

Pose Space

- *If a character has N DOFs, then a pose can be thought of as a point in N-dimensional pose space*

$$\mathbf{\Phi} = \begin{bmatrix} \phi_1 & \phi_2 & \dots & \phi_N \end{bmatrix}$$

- *An animation can be thought of as a point moving through pose space, or alternately as a fixed curve in pose space*

$$\mathbf{\Phi} = \mathbf{\Phi}(t)$$

- *'One-shot' animations are an open curve, while 'loop' animations form a closed loop*
- *Generally, we think of an individual 'animation' as being a continuous curve, but there's no strict reason why we couldn't have discontinuities (cuts)*

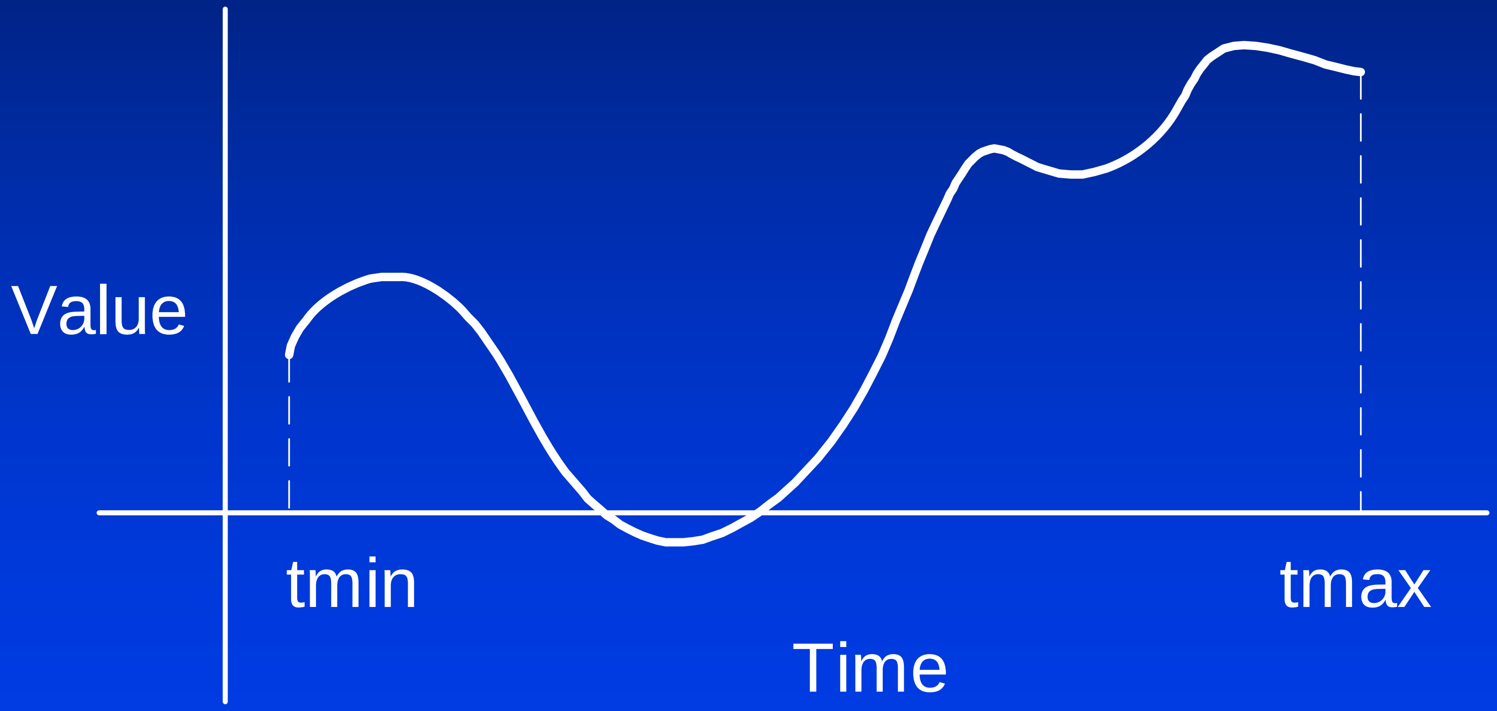
Channels

- ***If the entire animation is an N-dimensional curve in pose space, we can separate that into N 1-dimensional curves, one for each DOF***

$$\phi_i = \phi_i(t)$$

- ***We call these 'channels'***
- ***A channel stores the value of a scalar function over some 1D domain (either finite or infinite)***
- ***A channel will refer to pre-recorded or pre-animated data for a DOF, and does not refer to the more general case of a DOF changing over time (which includes physics, procedural animation…)***

Channels



Channels

- ***As a channel represents pre-recorded data, evaluating the channel for a particular value of* t *should always return the same result***
- ***We allow channels to be discontinuous in value, but not in time***
- ***Most of the time, a channel will be used to represent a DOF changing over time, but occasionally, we will use the same technology to relate some arbitrary variable to some other arbitrary variable (i.e., torque vs. RPM curve of an engine…)***

Array of Channels

- ***An animation can be stored as an array of channels***
- ***A simple means of storing a channel is as an array of regularly spaced samples in time***
- ***Using this idea, one can store an animation as a 2D array of floats (NumDOFs x NumFrames)***
- ***However, if one wanted to use some other means of storing a channel, they could still store an animation as an array of channels, where each channel is responsible for storing data however it wants***

Array of Poses

An alternative way to store an animation is as an array of poses

This also forms a 2D array of floats (NumFrames x NumDOFs)

Which is better, poses or channels?

Poses vs. Channels

Which is better?

It depends on your requirements.

The bottom line:

- Poses are faster
- Channels are far more flexible and can potentially use less memory

Array of Poses

- ***The array of poses method is about the fastest possible way to playback animation data***
- ***A ‘pose’ (vector of floats) is exactly what one needs in order to pose a rig***
- ***Data is contiguous in memory, and can all be directly accessed from one address***

Array of Channels

- *As each channel is stored independently, they have the flexibility to take advantage of different storage options and maximize memory efficiency*
- *Also, in an interactive editing situation, new channels can be independently created and manipulated*
- *However, they need to be independently evaluated to access the ‘current frame’, which takes time and implies discontinuous memory access*

Poses vs. Channels

- ***Array of poses is great if you just need to play back some relatively simple animation and you need maximum performance. This corresponds to many video games***
- ***Array of channels is essential if you want flexibility for an animation system or are interested in generality over raw performance***
- ***Array of channels can also be useful in more sophisticated game situations or in cases where memory is more critical than CPU performance (which is not uncommon)***

Animation Class

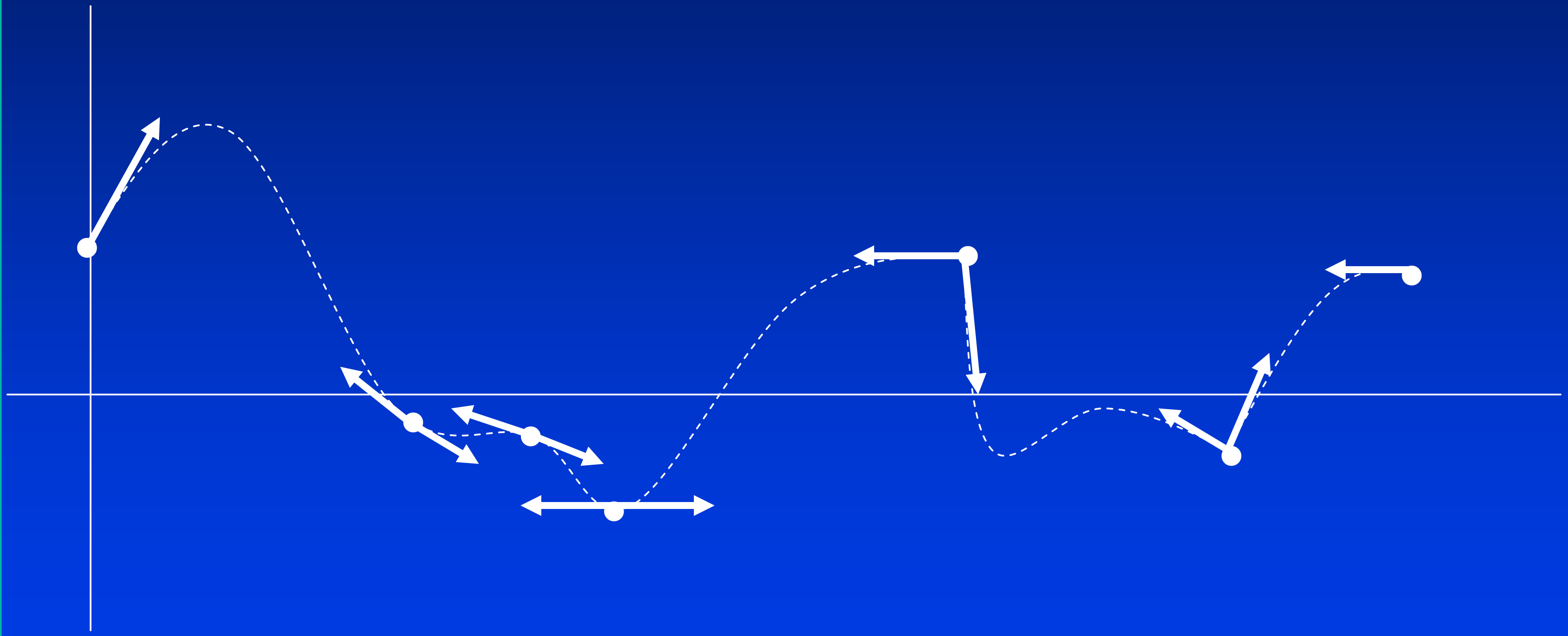
```
class AnimationClip {
        Channel *m_Array_of_Channels;
        void Evaluate(float time,Pose &p);
        bool Load(const char *filename);
};

class Channel {
        float *m_channel_data; // 1D array
        float Evaluate(float time);
        bool Load(FILE*);
};
```

Keyframe Channel

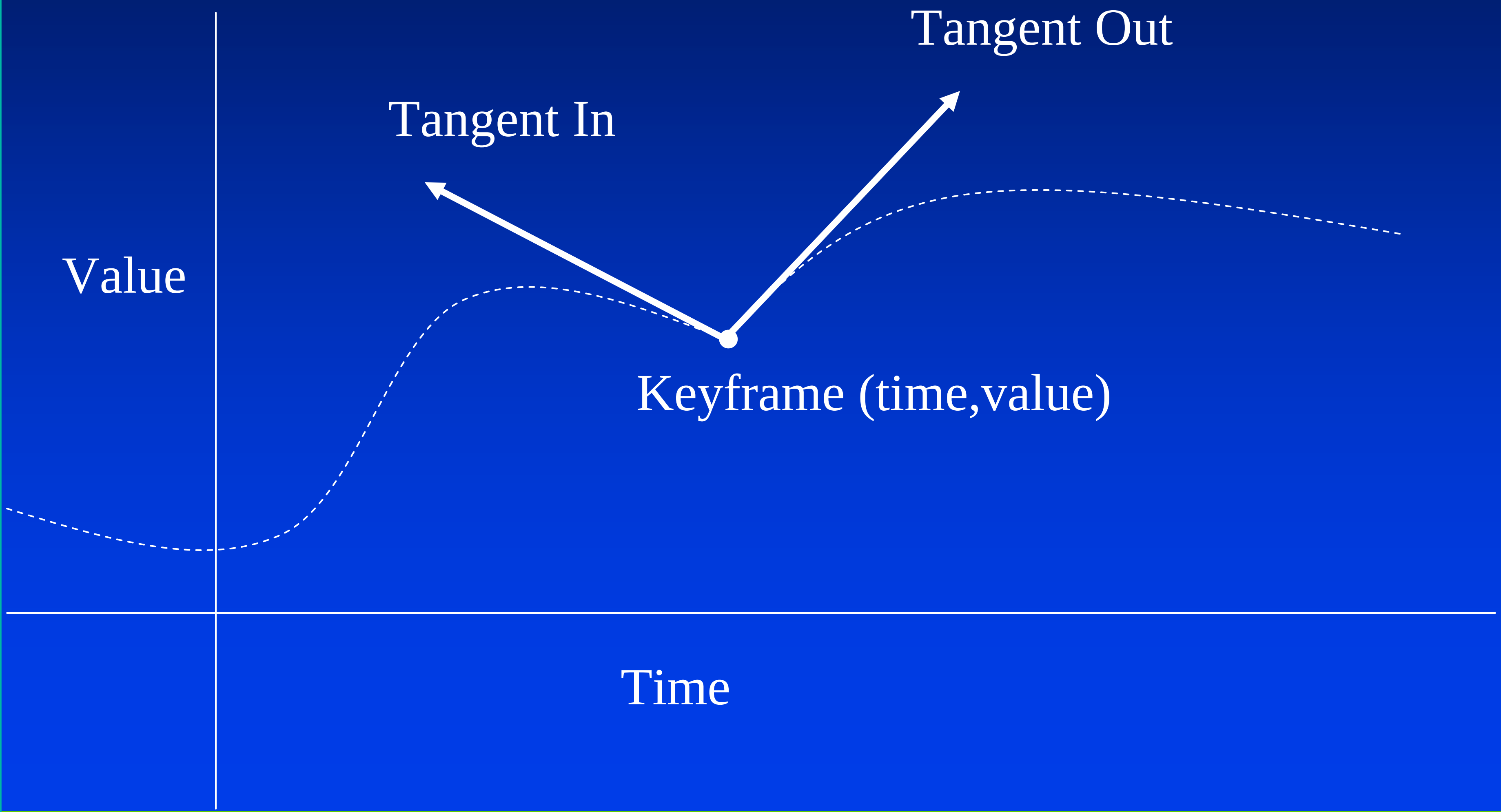
- *A channel can be stored as a sequence of keyframes*
- *Each keyframe has a time and a value and usually some information describing the tangents at that location*
- *The curves of the individual spans between the keys are defined by 1-D interpolation (usually piecewise Hermite)*

```
class Keyframe;
class Channel {
        float *m_keyframe_array;
        float Evaluate(float time);
        bool Load(FILE*);
};
```

Keyframe Channel



Keyframe



Keyframe Tangents

- *Keyframes are usually drawn so that the incoming tangent points to the left (earlier in time)*
- *The arrow drawn is just for visual representation and it should be remembered that if the two arrows are exactly opposite, that actually means the tangents are the same!*
- *Also remember that we are only dealing with 1D curves now, so the tangent really just a slope*

Why Use Keyframes?

- ***Good user interface for adjusting curves***
- ***Gives the user control over the value of the DOF and the velocity of the DOF***
- ***Define a perfectly smooth function (if desired)***
- ***Can offer good compression (not always)***

- ***Every animation system offers some variation on keyframing***
- ***Video games may consider keyframes for compression purposes, even though they have a performance cost***

Animating with Keyframes

- ***Keyframed channels form the foundation for animating properties (DOFs) in many commercial animation systems***
- ***Different systems use different variations on the exact math but most are based on some sort of cubic Hermite curves***

Curve Fitting

- *Keyframes can be generated automatically from sampled data such as motion capture*
- *This process is called ‘curve fitting’, as it involves finding curves that fit the data reasonably well*
- *Fitting algorithms allow the user to specify tolerances that define the acceptable quality of the fit*
- *This allows two way conversion between keyframe and raw formats, although the data might get slightly distorted with each translation*

Keyframe Data Structure

```
class Keyframe {
        float Time;
        float Value;
        float TangentIn,TangentOut;
        char RuleIn,RuleOut;    // Tangent rules
        float A,B,C,D;          // Cubic coefficients
}
```

Data Structures:

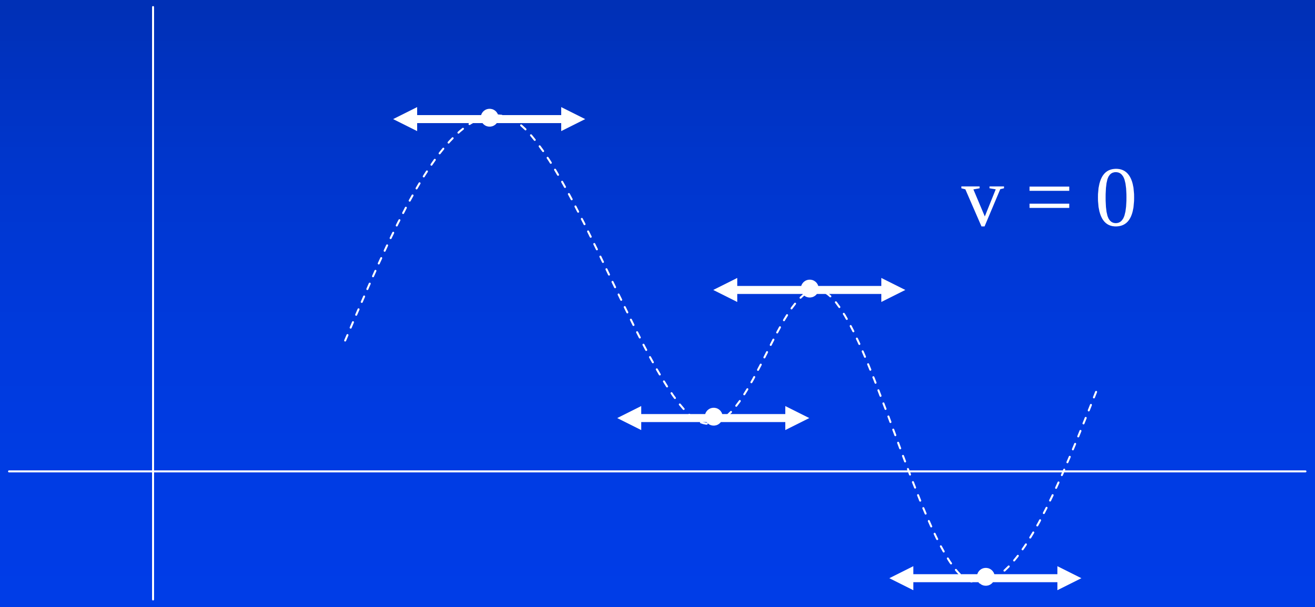
- Linked list
- Doubly linked list
- Array

Tangent Rules

- ***Rather than store explicit numbers for tangents, it is often more convenient to store a 'rule' and recompute the actual tangent as necessary***
- ***Usually, separate rules are stored for the incoming and outgoing tangents***
- ***Common rules for Hermite tangents include:***
  - Flat (tangent = 0)
  - Linear (tangent points to next/last key)
  - Smooth (automatically adjust tangent for smooth results)
  - Fixed (user can arbitrarily specify a value)
- ***Remember that the tangent equals the rate of change of the DOF (or the velocity)***
- ***Note: I use 'v' for tangents (velocity) instead of 't' which is used for time***

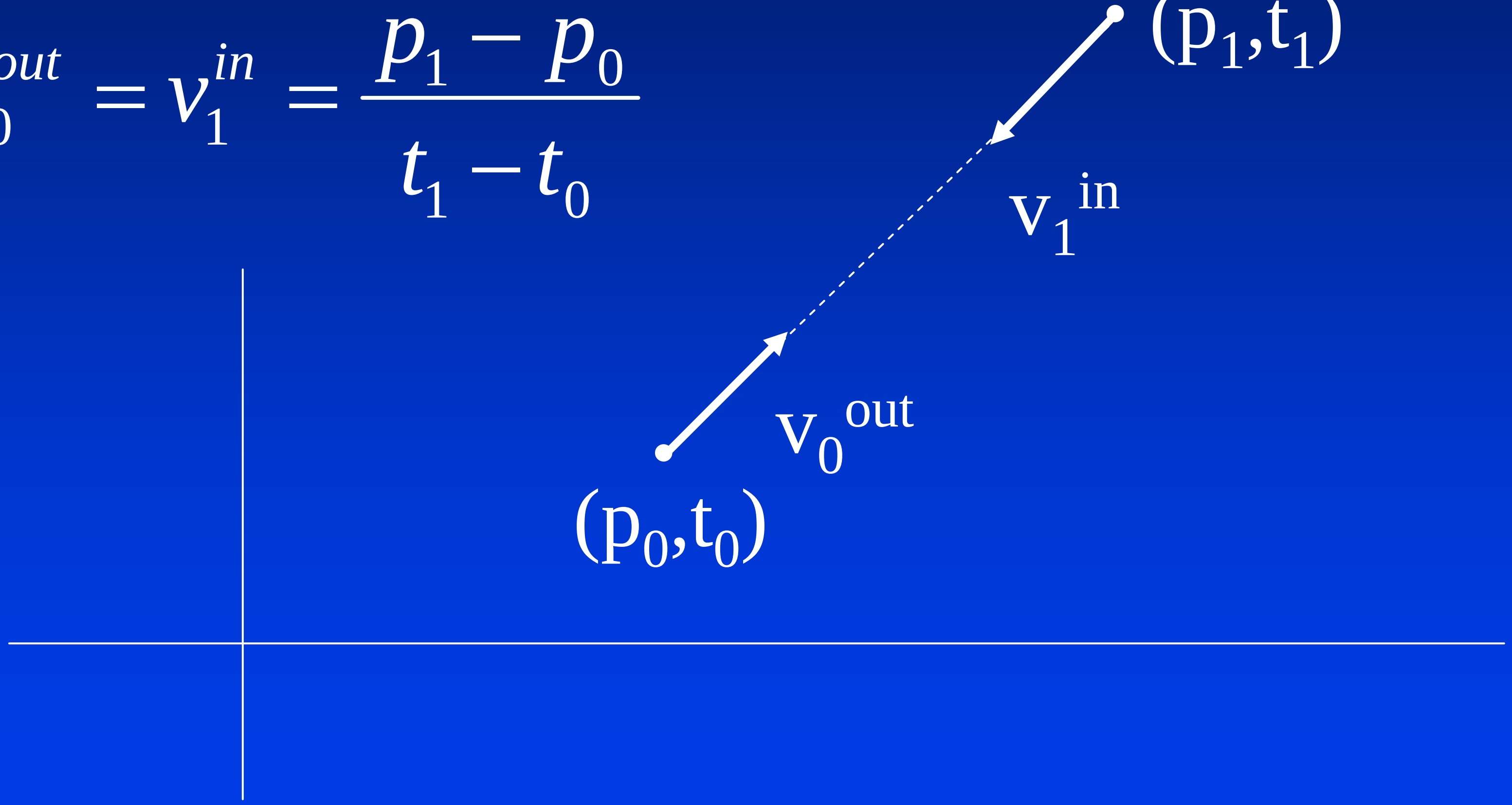
Flat Tangents

Flat tangents are particularly useful for making 'slow in' and 'slow out' motions (acceleration from a stop and deceleration to a stop)

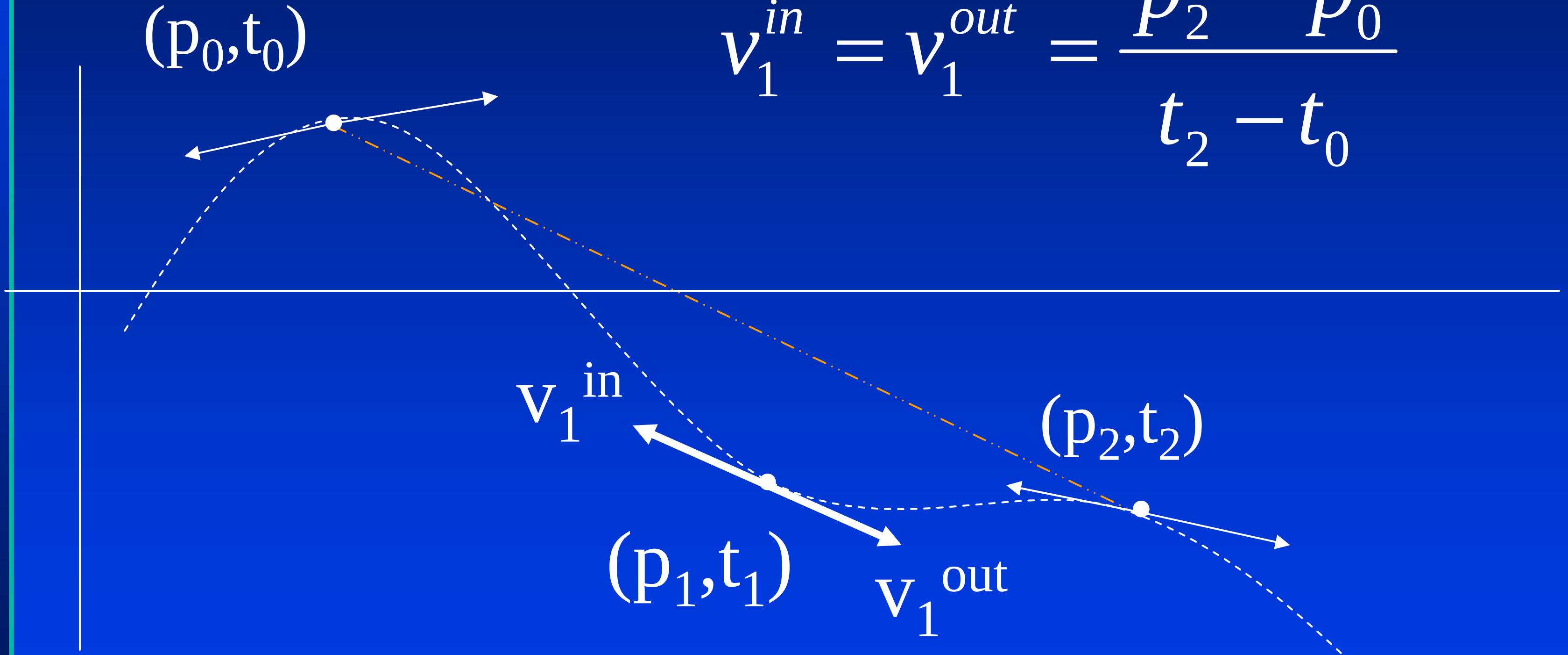


Linear Tangents

$$v_0^{out} = v_1^{in} = \frac{p_1 - p_0}{t_1 - t_0}$$



Smooth Tangents



$$v_1^{in} = v_1^{out} = \frac{p_2 - p_0}{t_2 - t_0}$$

Keep in mind that this won't work on the first or last tangent (just use the linear rule)

Cubic Coefficients

- *Keyframes are stored in order of their time*
- *Between every two successive keyframes is a span of a cubic curve*
- *The span is defined by the value of the two keyframes and the outgoing tangent of the first and incoming tangent of the second*
- *Those 4 values are multiplied by the Hermite basis matrix and converted to cubic coefficients for the span*
- *For simplicity, the coefficients can be stored in the first keyframe for each span*

Cubic Equation (1 dimensional)

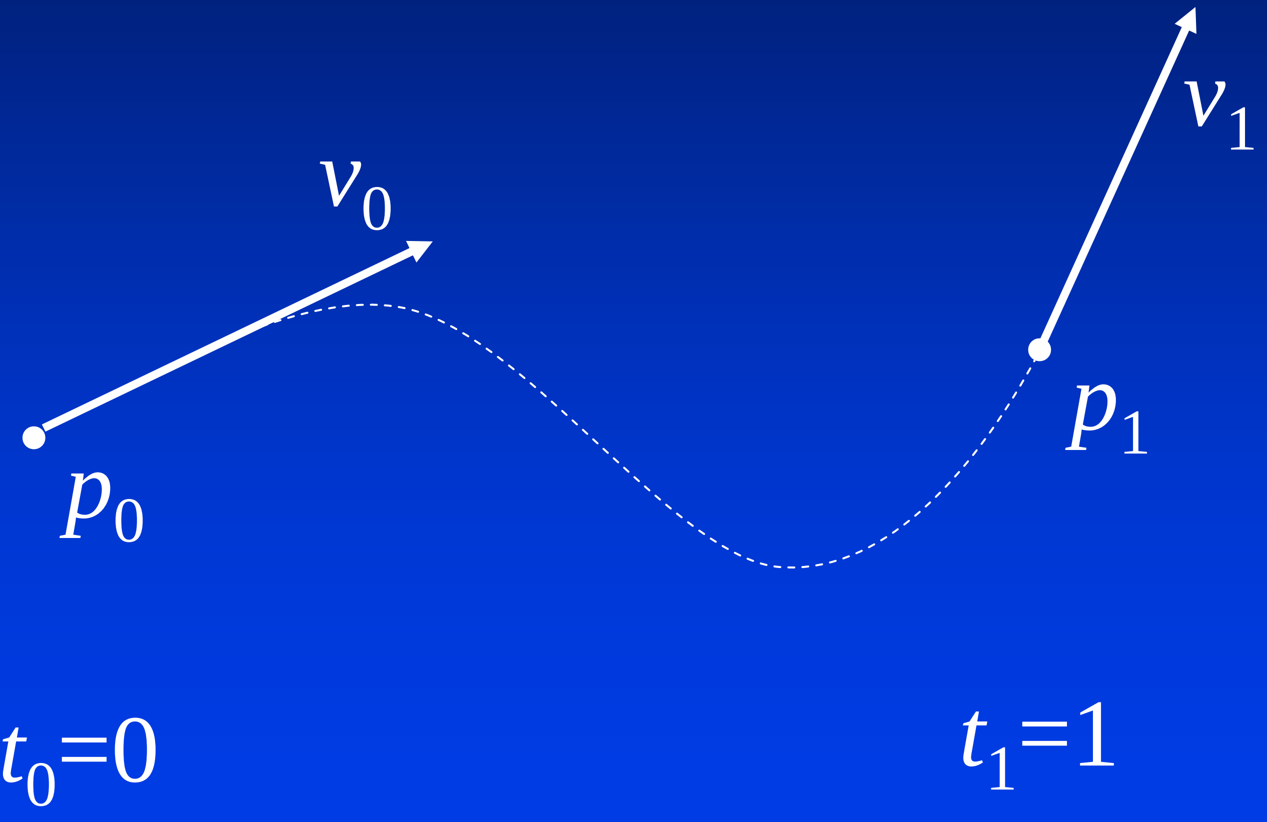
$$f(t) = at^3 + bt^2 + ct + d$$

$$\frac{df}{dt} = 3at^2 + 2bt + c$$

$$f(t) = \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$

$$\frac{df}{dt} = \begin{bmatrix} 3t^2 & 2t & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$

Hermite Curve (1D)



Hermite Curves

We want the value of the curve at t=0 to be f(0)=p_0, and at t=1, we want f(1)=p_1

We want the derivative of the curve at t=0 to be v_0, and v_1 at t=1

$$f(0) = p_0 = a0^3 + b0^2 + c0 + d = d$$

$$f(1) = p_1 = a1^3 + b1^2 + c1 + d = a + b + c + d$$

$$f'(0) = v_0 = 3a0^2 + 2b0 + c = c$$

$$f'(1) = v_1 = 3a1^2 + 2b1 + c = 3a + 2b + c$$

Hermite Curves

$$p_0 = d$$

$$p_1 = a + b + c + d$$

$$v_0 = c$$

$$v_1 = 3a + 2b + c$$

$$\begin{bmatrix} p_0 \\ p_1 \\ v_0 \\ v_1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 3 & 2 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$

Matrix Form of Hermite Curve

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 3 & 2 & 1 & 0 \end{bmatrix}^{-1} \cdot \begin{bmatrix} p_0 \\ p_1 \\ v_0 \\ v_1 \end{bmatrix}$$

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} p_0 \\ p_1 \\ v_0 \\ v_1 \end{bmatrix}$$

Matrix Form of Hermite Curve

$$f(t)=\begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix} \cdot \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} p_0 \\ p_1 \\ v_0 \\ v_1 \end{bmatrix}$$

$$f(t)=\mathbf{t}\cdot\mathbf{B}_{Hrm}\cdot\mathbf{g}_{Hrm}$$

$$f(t)=\mathbf{t}\cdot\mathbf{c}$$

Remember, this assumes that t varies from 0 to 1

Inverse Linear Interpolation

- ***If t_0 is the time at the first key and t_1 is the time of the second key, a linear interpolation of those times by parameter u would be:***
- $$t = Lerp(u, t_0, t_1) = (1-u)t_0 + ut_1$$
- ***The inverse of this operation gives us:***
- $$u = InvLerp(t, t_0, t_1) = \frac{t-t_0}{t_1-t_0}$$
- ***This gives us a 0…1 value on the span where we now will evaluate the cubic equation***
- ***Note: $1/(t_1-t_0)$ can be precomputed for each span***

Evaluating Cubic Spans

- *Tangents are generally expressed as a slope of value/time*
- *To normalize the spans to the 0…1 range, we need to correct the tangents*
- *So we must scale them by (t_1-t_0)*

Precomputing Constants

For each span we pre-compute the cubic coefficients:

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} p_0 \\ p_1 \\ (t_1 - t_0)v_0 \\ (t_1 - t_0)v_1 \end{bmatrix}$$

Computing Cubic Coefficients

Do it yourself! Actually, all of the 1's and 0's in the matrix make it pretty easy to multiply it out by hand

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} p_0 \\ p_1 \\ (t_1 - t_0)v_0 \\ (t_1 - t_0)v_1 \end{bmatrix}$$

Evaluating the Cubic

To evaluate the cubic equation for a span, we must first turn our time t into a 0..1 value for the span (we'll call this parameter u)

$$u = InvLerp(t, t_0, t_1) = \frac{t - t_0}{t_1 - t_0}$$

$$x = au^3 + bu^2 + cu + d = d + u(c + u(b + u(a)))$$

Channel::Precompute()

The two main setup computations a keyframe channel needs to perform are:

- Compute tangents from rules
- Compute cubic coefficients from tangents & other data

This can be done in two separate passes through the keys or combined into one pass (but keep in mind there is some slightly tricky dependencies on the order that data must be processed if done in one pass)

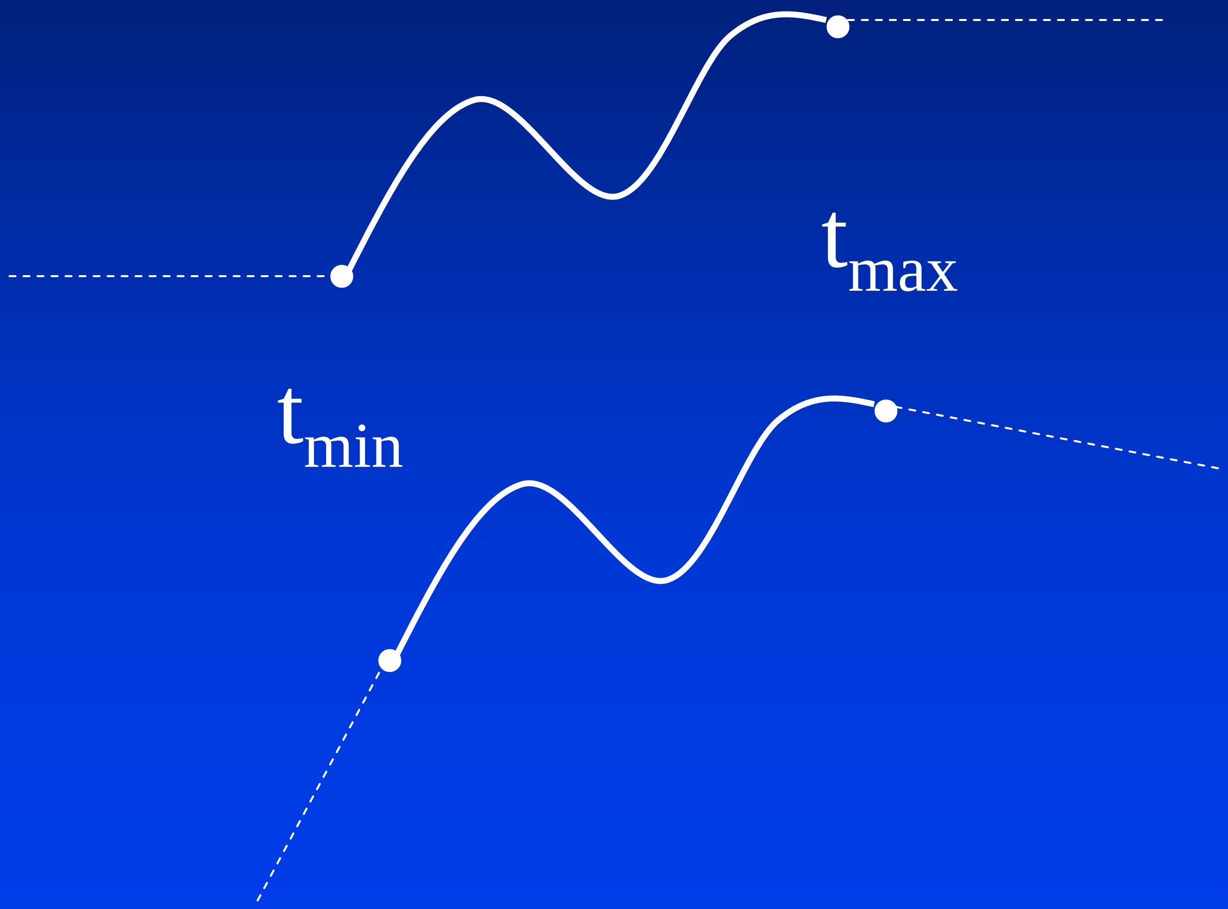
Extrapolation Modes

- ***Channels can specify 'extrapolation modes' to define how the curve is extrapolated before t_{min} and after t_{max}***
- ***Usually, separate extrapolation modes can be set for before and after the actual data***
- ***Common choices:***
  - Constant value (hold first/last key value)
  - Linear (use tangent at first/last key)
  - Cyclic (repeat the entire channel)
  - Cyclic Offset (repeat with value offset)
  - Bounce (repeat alternating backwards & forwards)

Extrapolation

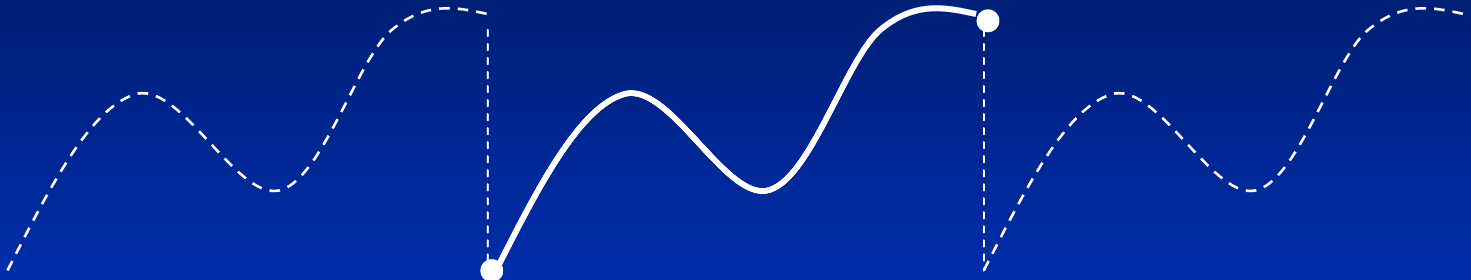
Flat:

Linear:

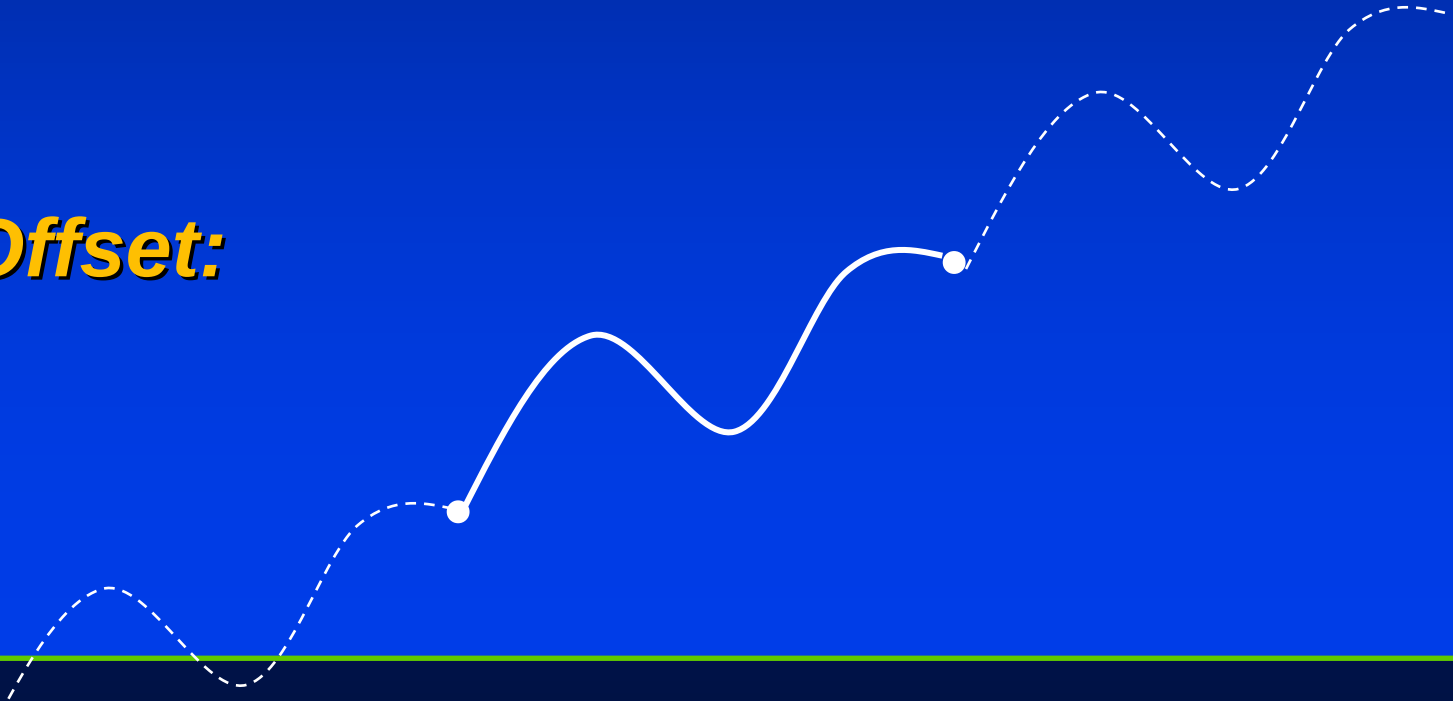


Extrapolation

Cyclic:

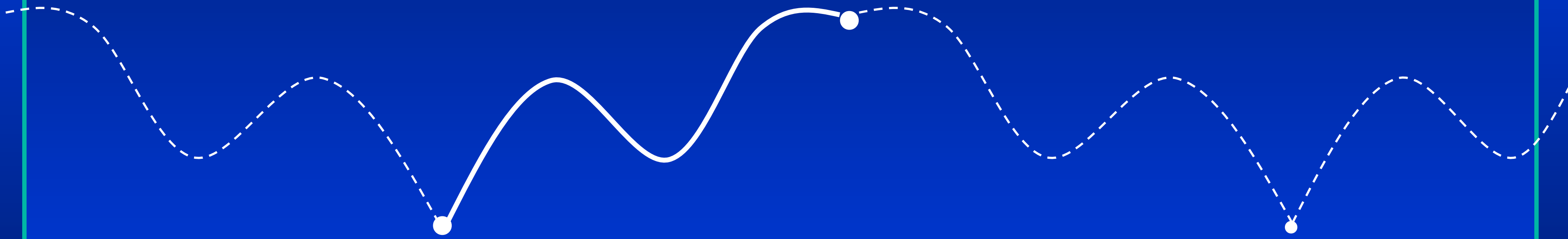


Cyclic Offset:



Extrapolation

Bounce:



Keyframe Evaluation

The main runtime function for a channel is something like:

float Channel::Evaluate(float time);

This function will be called many times…

For an input time t, there are 4 cases to consider:

- t is before the first key (use extrapolation)
- t is after the last key (use extrapolation)
- t falls exactly on some key (return key value)
- t falls between two keys (evaluate cubic equation)

Channel::Evaluate()

- ***The Channel::Evaluate function needs to be very efficient, as it is called many times while playing back animations***
- ***There are two main components to the evaluation:***
  - Find the proper span
  - Evaluate the cubic equation for the span

Random Access

- *To evaluate a channel at some arbitrary time t, we need to first find the proper span of the channel and then evaluate its equation*
- *As the keyframes are irregularly spaced, this means we have to search for the right one*
- *If the keyframes are stored as a linked list, there is little we can do except walk through the list looking for the right span*
- *If they are stored in an array, we can use a binary search, which should do reasonably well*

Finding the Span: Binary Search

- ***A very reasonable way to find the key is by a binary search. This allows pretty fast (log N) access time with no additional storage cost (assuming keys are stored in an array (rather than a list))***
- ***Binary search is sometimes called ‘divide and conquer’ or ‘bisection’***
- ***For even faster access, one could use hashing algorithms, but that is probably not necessary, as they require additional storage and most real channel accesses can take advantage of coherence (sequential access)***

Finding the Span: Linear Search

- *One can always just loop through the keys from the beginning and look for the proper span*
- *This is an acceptable place to start, as it is important to get things working properly before focusing on optimization*
- *It may also be a reasonable option for interactive editing tools that would require key frames to be stored in a linked list*
- *Of course, a bisection algorithm can probably be written in less than a dozen lines of code…*