

CHARACTER
LOCOMOTION IN
HALF-LIFE: ALYX

The Right Foot in the Wrong Place

Joe van den Heuvel
Valve

→ MISSING THE BAR

- Gameplay animation started out using traditional techniques
- AnimGraphs, state machines, blends, etc

- Couldn't meet our quality goals
- With ~1 year left of development, needed to find a new approach...





Goals

What we needed from a new gameplay animation system



QUALITY

- VR “Character Presence”
 - Character version of VR ‘Presence’
 - Easily broken by “gamey” movement
 - Both challenge and opportunity!
- Goal:
 - Reduce or remove foot slide



MOVEMENT

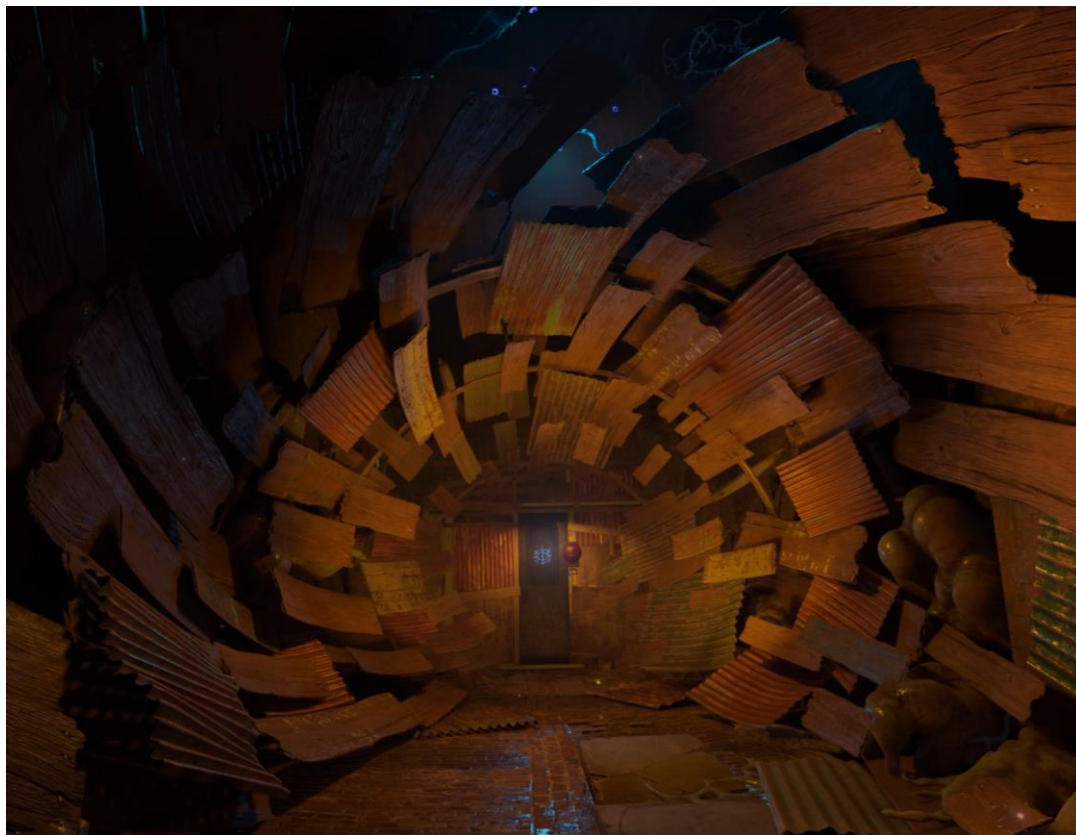
- Tight, dense virtual environments
 - Frequent changes of direction
 - Small window for attacks
- Goal:
 - Character cannot leave navigation path
 - Character must stop exactly at path goal



CONTENT

- Small gameplay animation team
- Large variety of characters
 - Could not rely on mocap

- Goal:
 - Work with limited content
 - Work for bipeds, quadrupeds... all the -ped



PERFORMANCE

- VR Motion Sickness is a “big deal”
- Can’t let game make players feel nauseous
- Must maintain 90+ frames per second
 - 0.011 seconds for entire frame

- Goal:
 - Must be fast to calculate



Options

How are others solving these problems?

MOTION MATCHING

Pros:

- Shipped in other games
- Conceptually simple
- Debuggable

Cons:

- Content Quantity => Quality
- Not gonna mocap a headcrab

MACHINE LEARNING

Pros:

- Lots of examples of good results
- Dynamic, adapts to environment

Cons:

- Requires **lots** of example content
- Hard to debug
- Slow iteration time (training large data sets)

What we went with

SEMI-PROCEDURAL LOCOMOTION

- 2009 Thesis paper by Rune Skovbo Johansen
- Change foot steps at runtime
- <http://runevision.com/thesis/>

Pros:

- Can remove foot slide
- Procedural: More variety, Less content
- Works with non-humanoids

Cons:

- Multi-step animations?
- Extracted motion?
- Transitions?
- Foot Rotations?



Creating Foot Motion Data



Position (Toe) + Direction (to Heel)

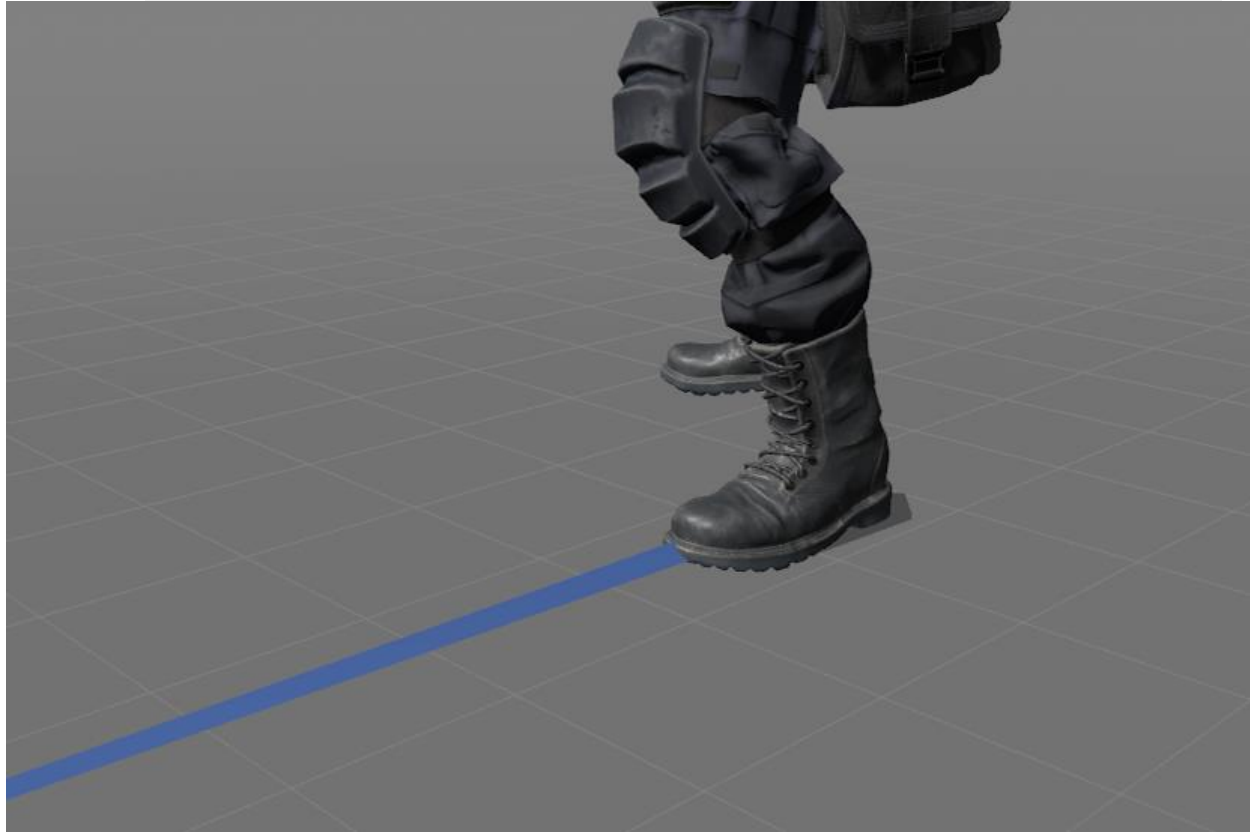
Always Touching Lowest Part of Foot



STRIDES

For each animation:

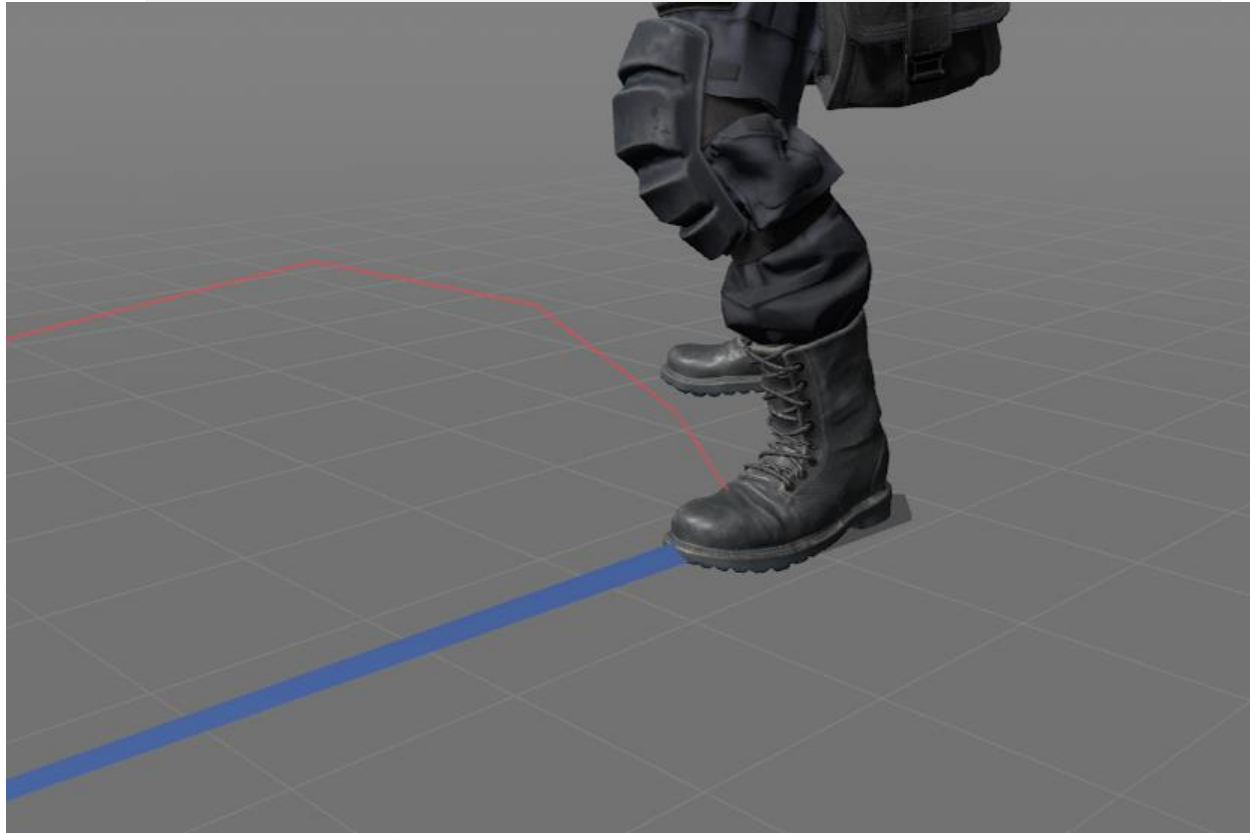
- Segment into strides
- Stride start frame: “Stance Frame”
 - Middle of time on ground
 - Foot not moving
 - Close to body



STRIDES

For each Stance Frame:

- Calculate FootBase relative to character
- “Foot Cycle”: time between steps



TRAJECTORIES

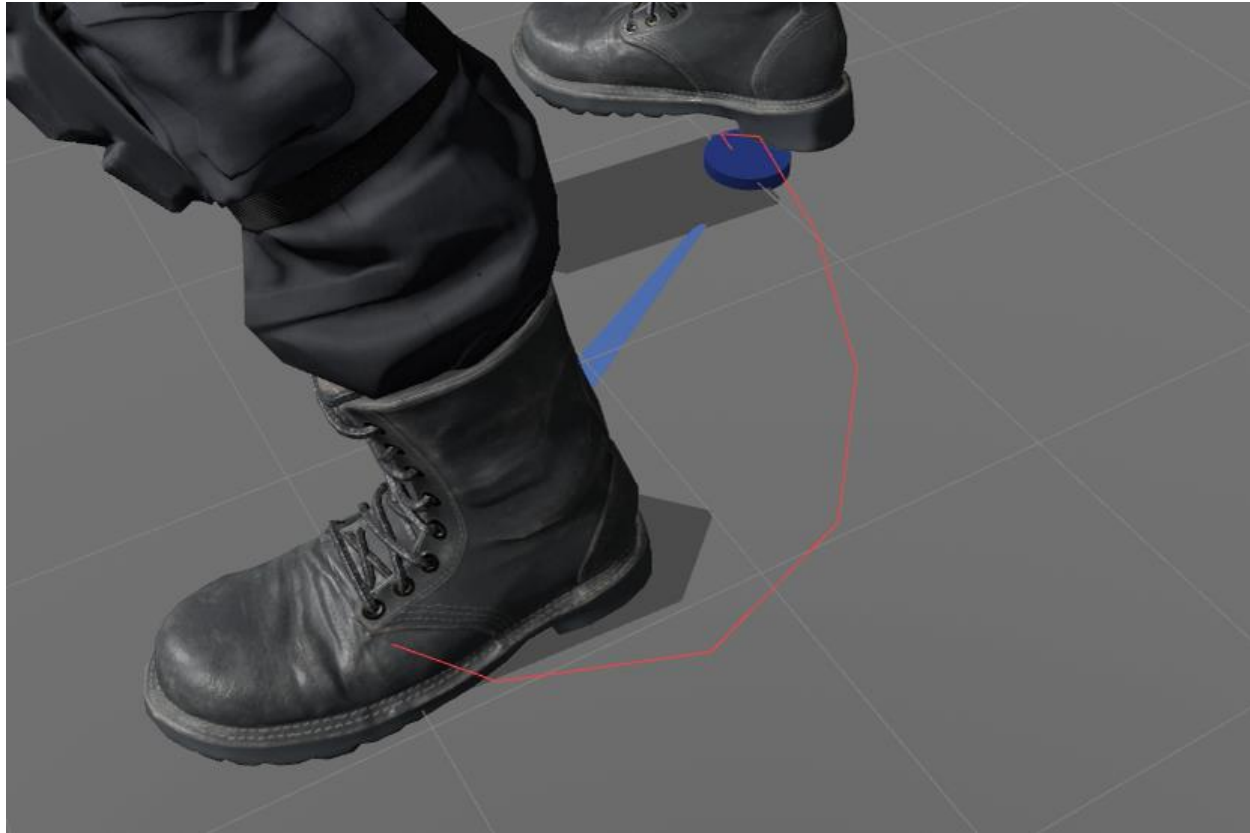
For each frame of each Foot Cycle:

- Calculate Footbase Position + Direction
- Project onto vector between steps (“Stride Vector”)
- Convert to offset from projected position
- Convert offset to be stride-relative



STATIONARY ANIMATIONS

- Previous Step Position == Next Step Position
- All motion contained in Trajectory Offset



ROTATION

Just like Translation:

- $\text{RotationReference} = \text{Lerp}(\text{Start}, \text{End}, \text{Cycle})$
- $\text{Final Rotation} = \text{RotationReference} + \text{RotationOffset}$
- Must handle > 180 degree rotations!



FOOT CYCLE DEFINITION (ONE FOR EACH STEP)

```
Float3  stancePosition;           // Starting Footbase position, in model space
Float   stanceDirection;         // Starting Footbase direction, in model space
Float   stanceCycle;             // Animation cycle (0-1) when foot cycle starts

Float3  middlePosition;          // Footbase position halfway through the step
Float3  toStrideStartPos;        // Vector from the end of the stride to the start

// Foot cycles (0-1) of when the foot lifts and lands
Float  footLiftCycle, footOffCycle, footStrikeCycle, footLandCycle;
```



FOOTBASE TRAJECTORY (ONE FOR EACH FRAME)

```
Float3  translationOffset;    // Stride-relative offset from stride vector
Float   rotationOffset;     // Stride-relative offset from stride rotation
Float   progression;        // Location of projected pos as % along stride vector
```



Stride Retargeting



RUNTIME PLAYBACK

1. Predict next step position
2. Calc FootBase from Trajectories
3. Use FootBase as IK target



STRIDE RETARGETING



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Lowest point on foot must touch the FootBase

Calculate ankle position & rotation from FootBase

Use ankle as IK target for leg



STRIDE RETARGETING



SIGGRAPH 2021



INVERSE KINEMATICS

Can't use original ankle rotation



STRIDE RETARGETING

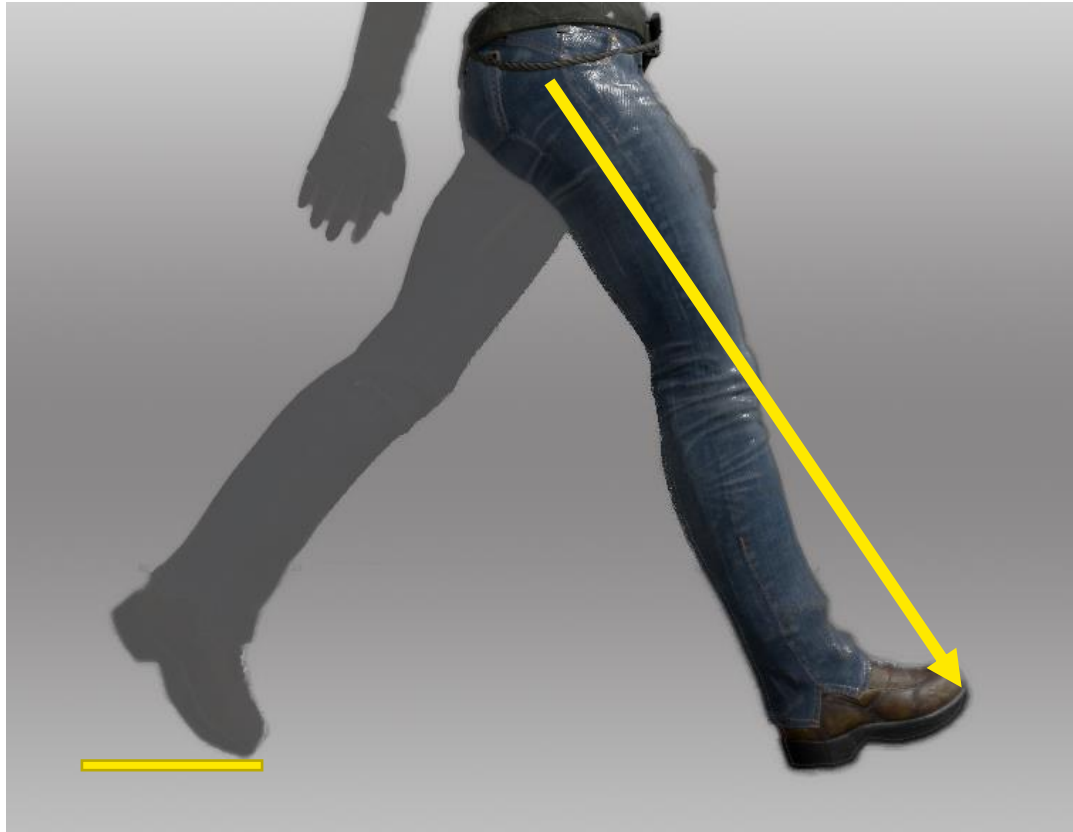


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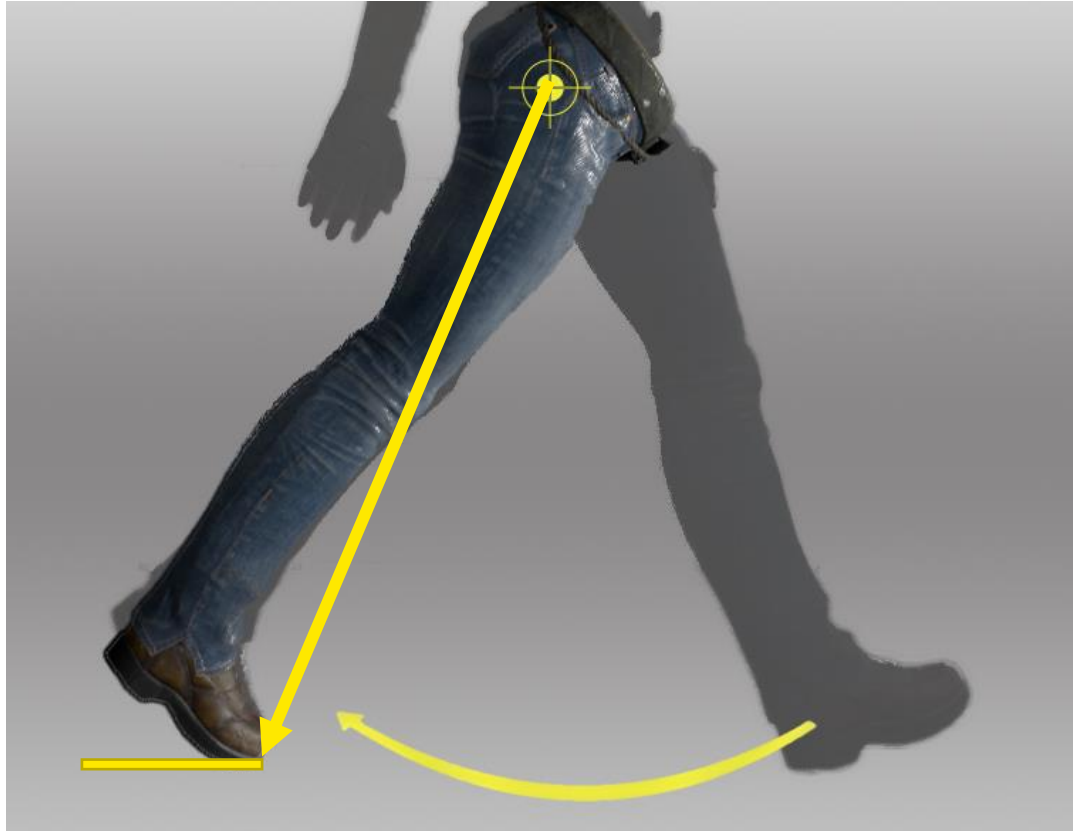
INVERSE KINEMATICS

Bad things happen



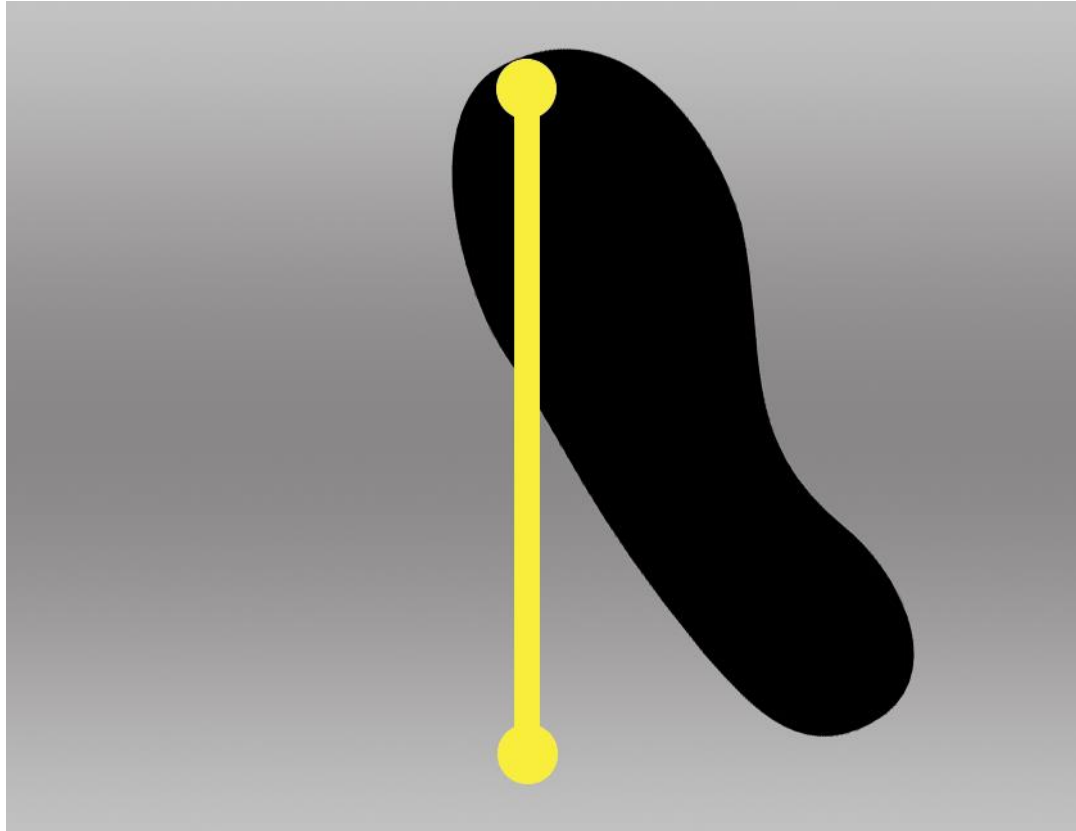
INVERSE KINEMATICS

1. Start by rotating the leg about the hip



INVERSE KINEMATICS

1. Start by rotating the leg about the hip
 - Preserves natural foot angle



INVERSE KINEMATICS

1. Start by rotating the leg about the hip
2. **Align Horizontally**
 - Align Foot to FootBase as it gets flat
 - Otherwise, pop when lowest point changes



INVERSE KINEMATICS

1. Start by rotating the leg about the hip
2. Align Horizontally
3. **Align Vertically**
 - Align with sloped FootBase based on:
 - How flat Foot is in original anim
 - At beginning or end of stride

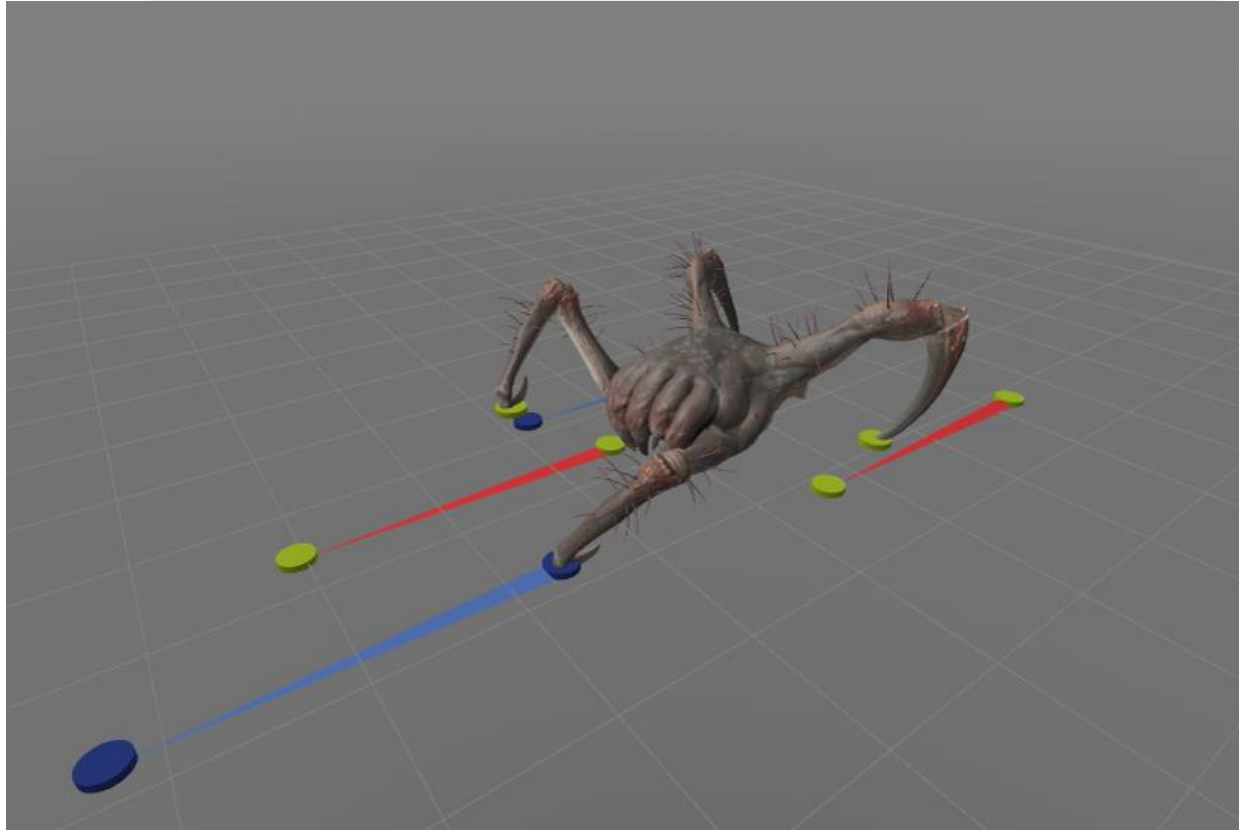


INVERSE KINEMATICS

1. Start by rotating the leg about the hip
2. Align Horizontally
3. Align Vertically
4. **Solve Leg IK for Ankle Position**
 - Second pass to enforce Ankle limits



Manipulating the Foot Motion Data



STEP LENGTH

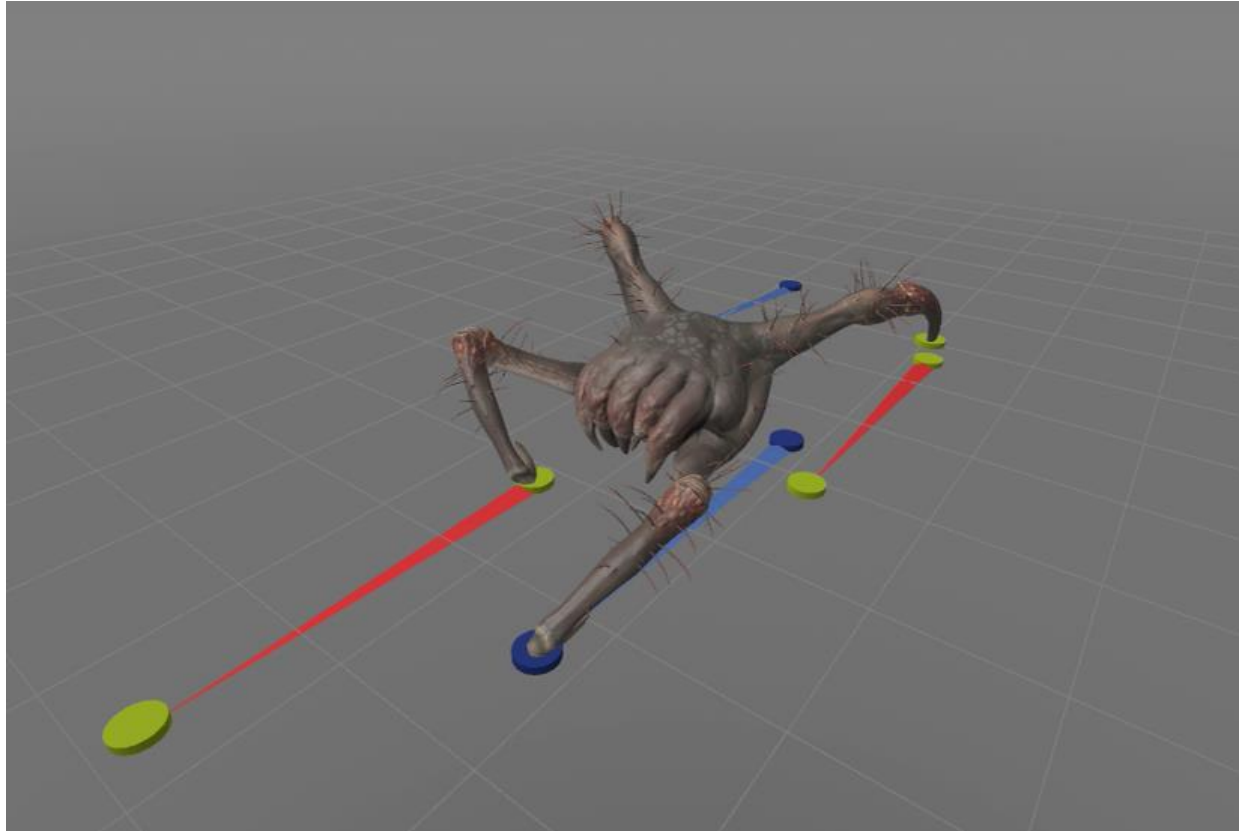
- Scale distance traveled
- Affects foot step distance

Height Scale Off



STEP HEIGHT

- Scale Trajectory Translation Offset
- Affects height/intensity of step
- Scale step height with distance for consistency

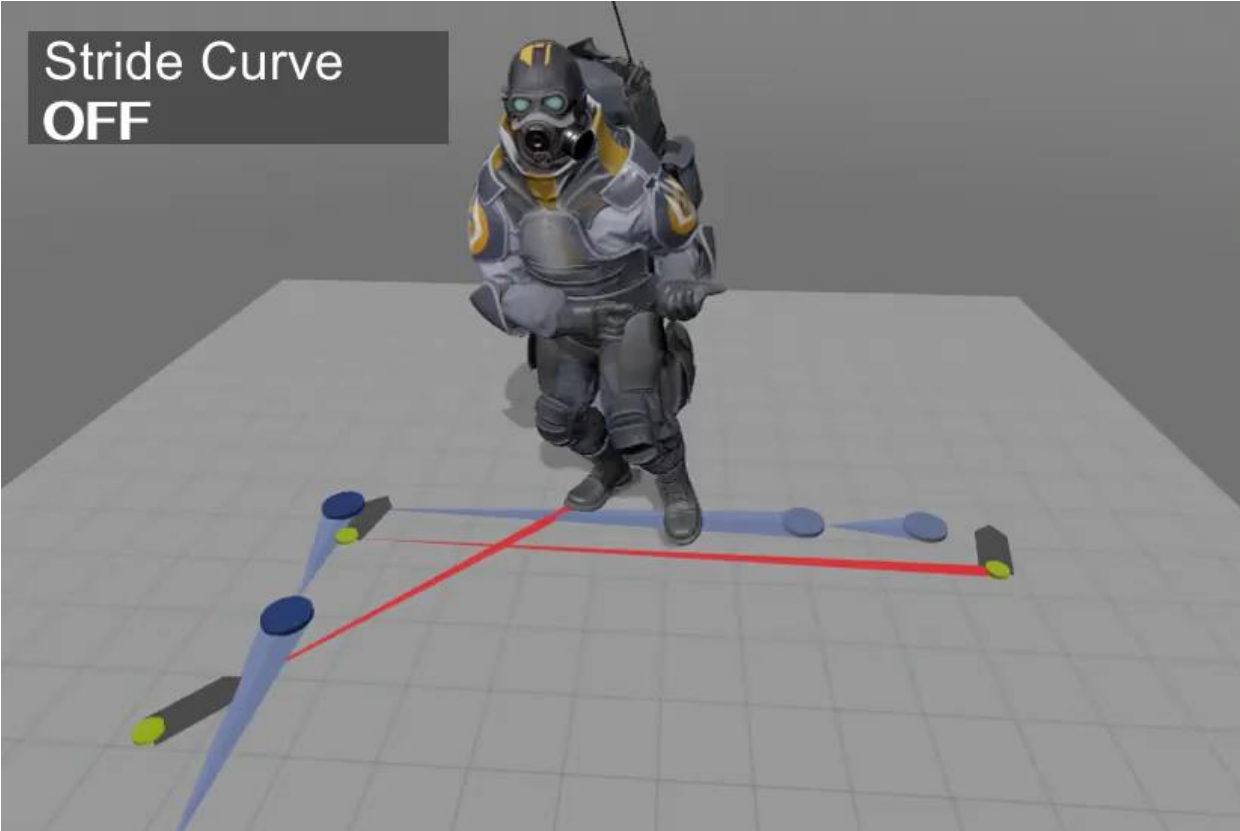


STEP LOCATION

Change steps to go to new location

- Turning
- Uneven ground / stairs

Stride Curve
OFF



CURVED STRIDE PATHS

- Curve path through original midpoint to prevent leg intersection
- Increase arch when walking up slopes



Transitions & Blending

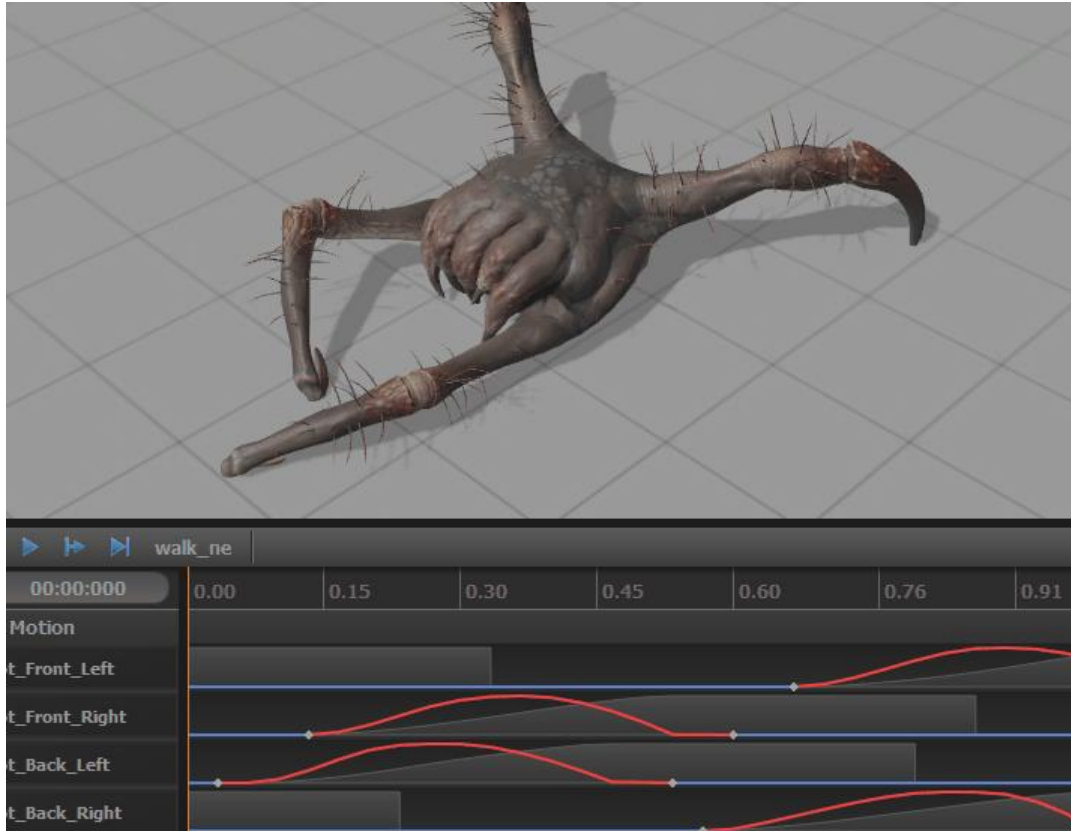
All foot motion data can blend...

Except for **Progression**

Blends

Transitions

Everything Else



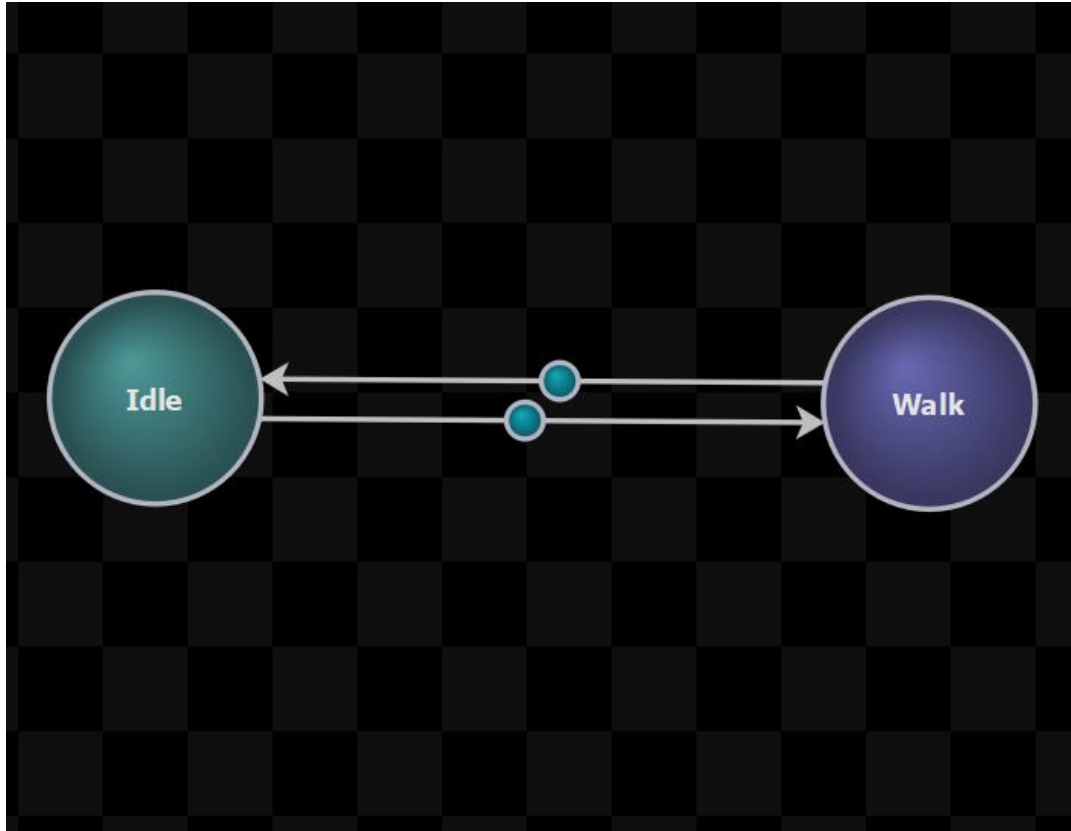
BLEND

Match timing between animations

- Sync foot cycles between animations
 - Force steps to start and end at same time
- Common practice in games

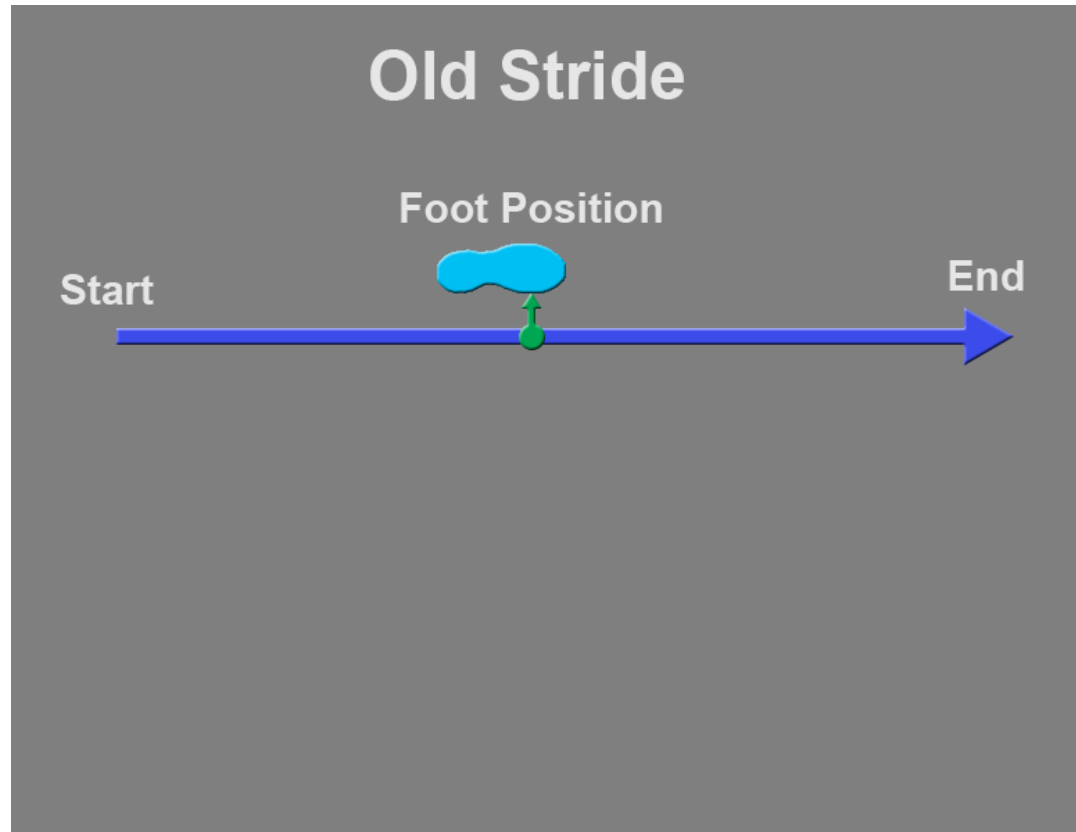
Can cheat!

- Fudge numbers on foot motion data
- System will move feet to right place

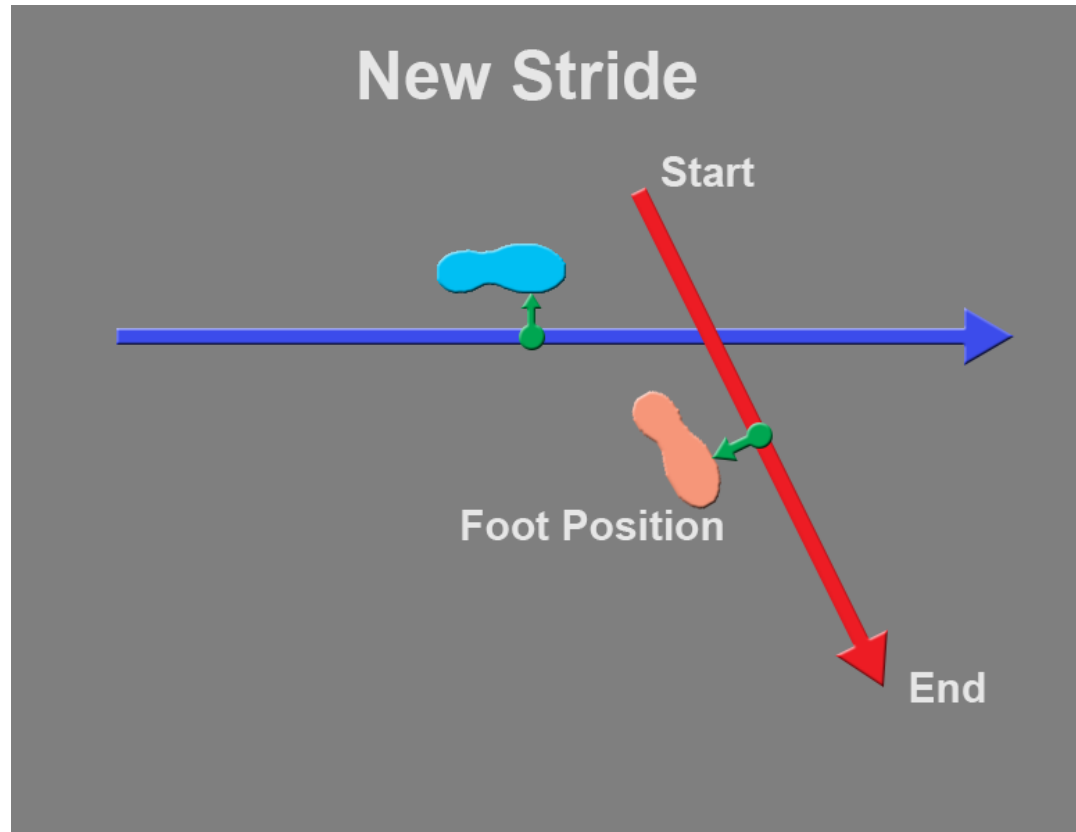


TRANSITIONS

- Foot cycles are out of sync
- Can't blend, must transition

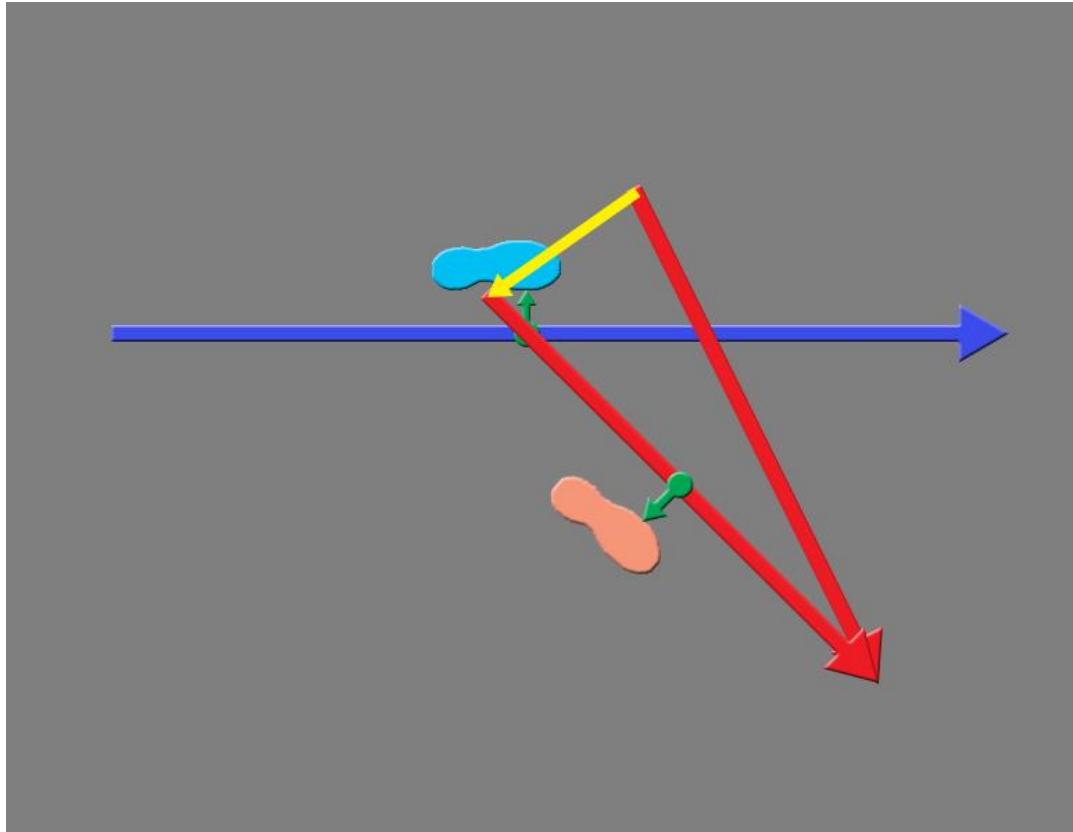


TRANSITIONS



TRANSITIONS

- Can't change End of new stride
- Can change Start



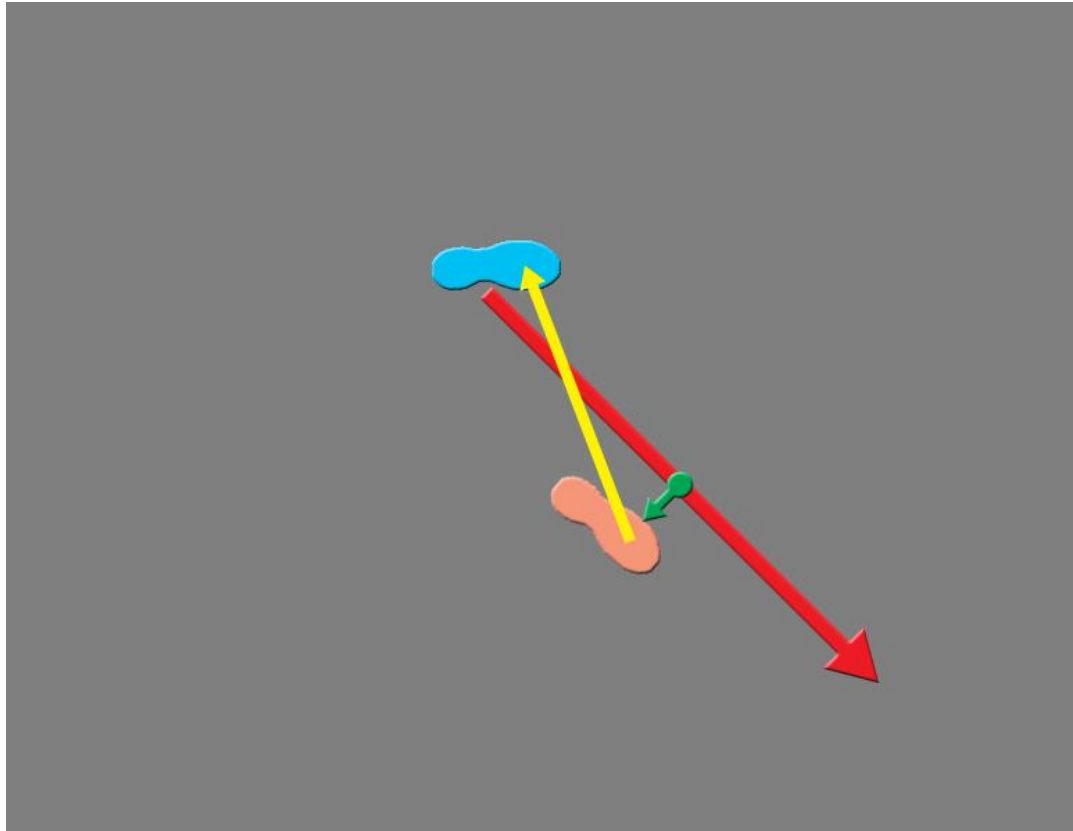
TRANSITIONS

If foot is stationary on ground

- StartPos = CurrentPos

Else

- Move StartPos so reference points match
- Clamp length of stride to original length



TRANSITIONS

- Calc remaining Offset between old and new foot positions
- Blend out Offset over time



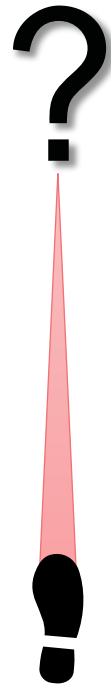
EVERYTHING ELSE

- Additive, per-bone blends, etc work
- But have to pick which source to pull foot motion from



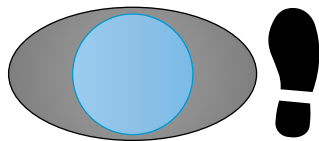
Predicting the Next Step

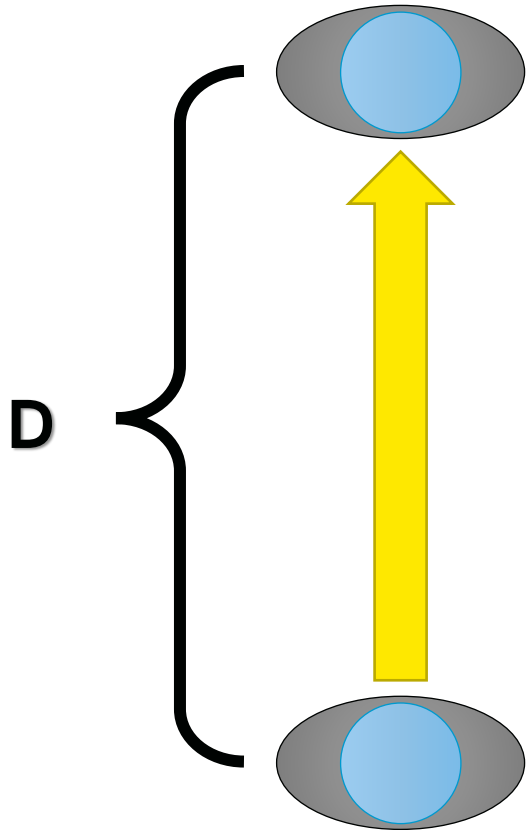
WHERE WILL THE NEXT STEP LAND?



WHERE WILL THE NEXT STEP LAND?

- Foot Motion Data
 - Offset from character at each step
 - Animation frame of each step
- => Figure out where character will be at that time



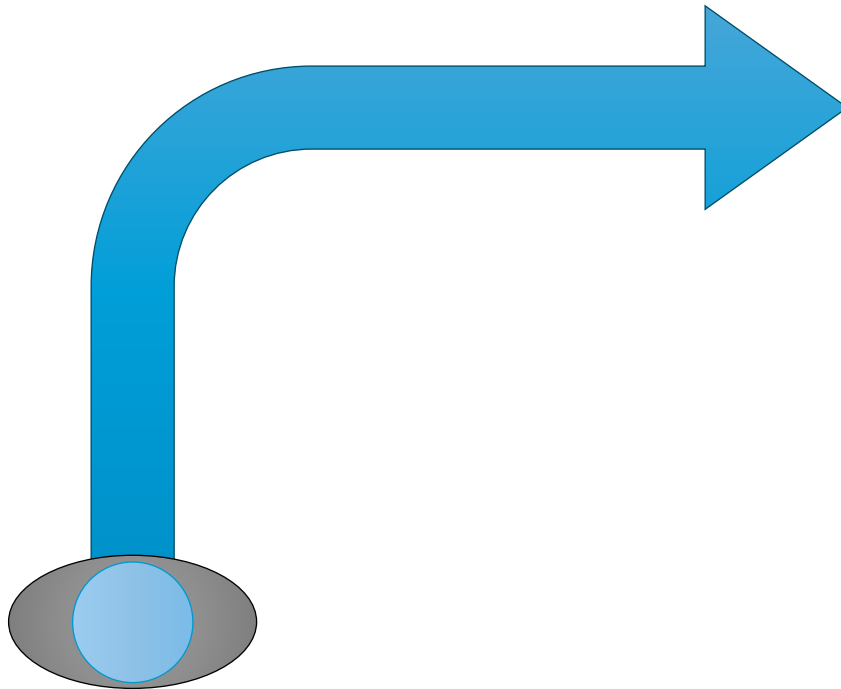


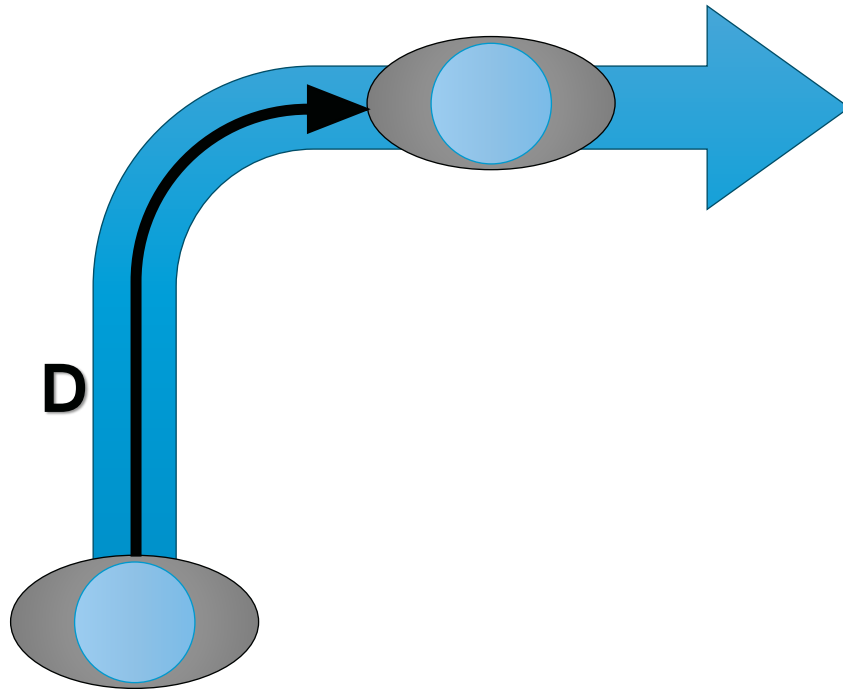
ROOT MOTION

- Add up root motion from now till next step

PATHS

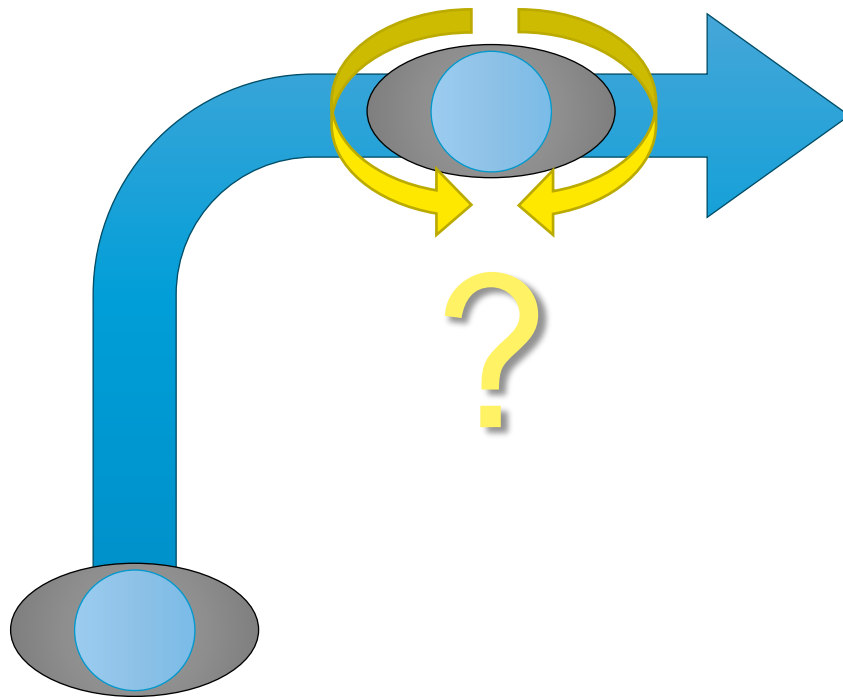
Given a navigation path...





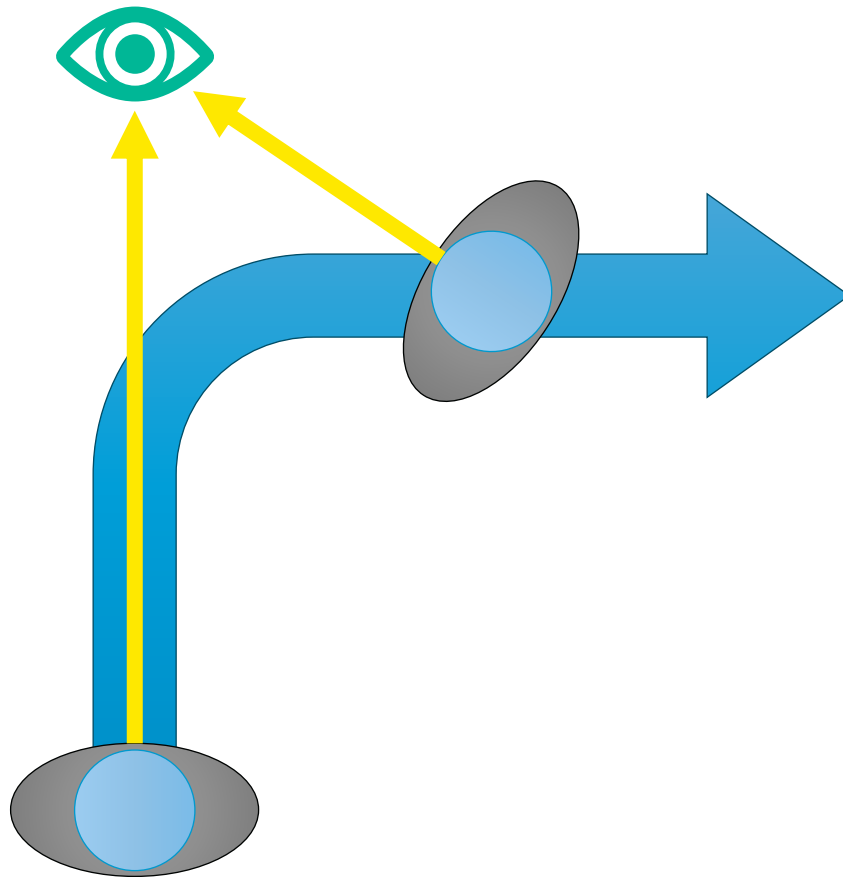
PATHS

... Move along the path by same distance as animation



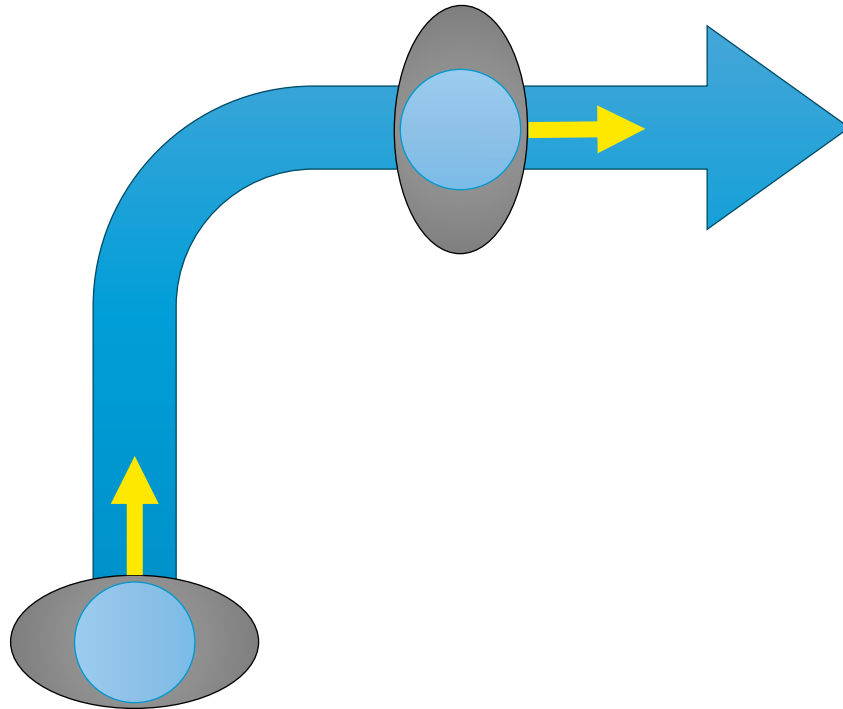
ROTATION

- Need to know facing direction at future location
- 2 Modes:
 - Target Look Mode
 - Path Look Mode



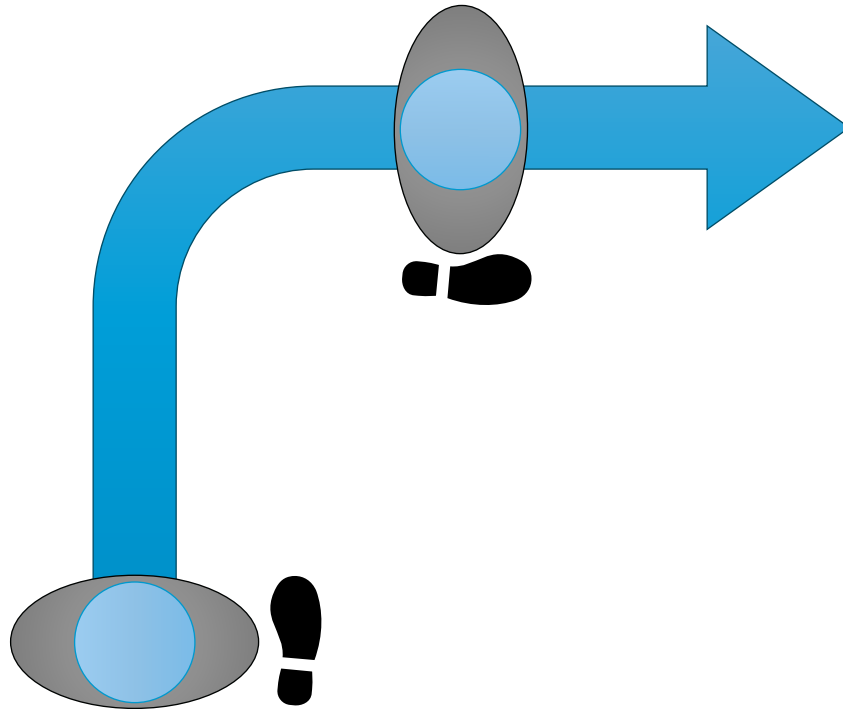
ROTATION

- Target look mode
 - Always facing a target point in the world
 - Assume stationary target



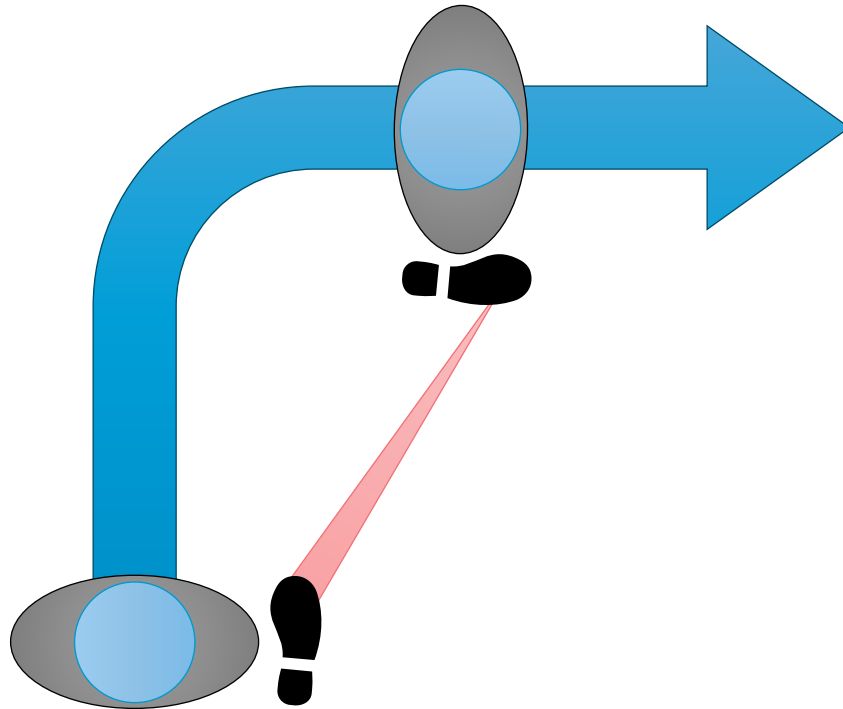
ROTATION

- Path Look Mode:
 - Always facing forward along the path



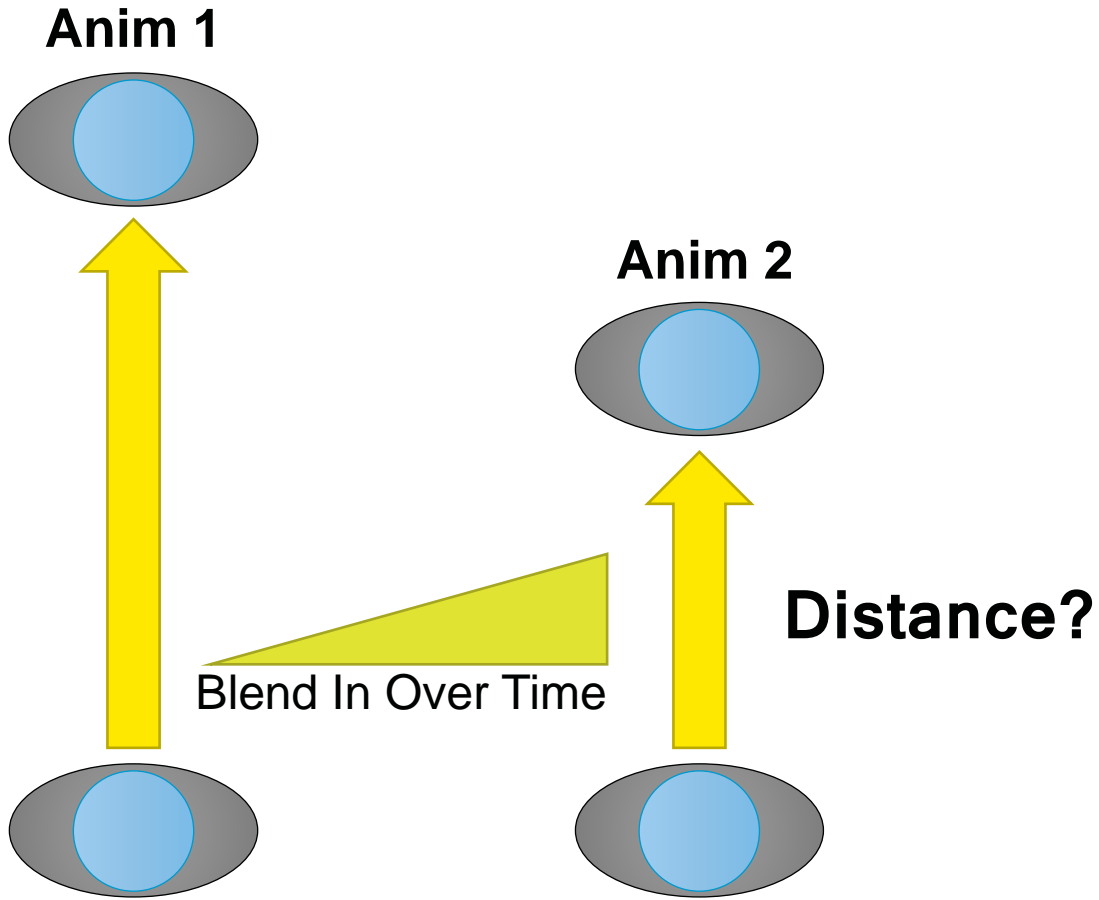
PLACE FOOT

- Use FootBase offset to find foot position/rotation



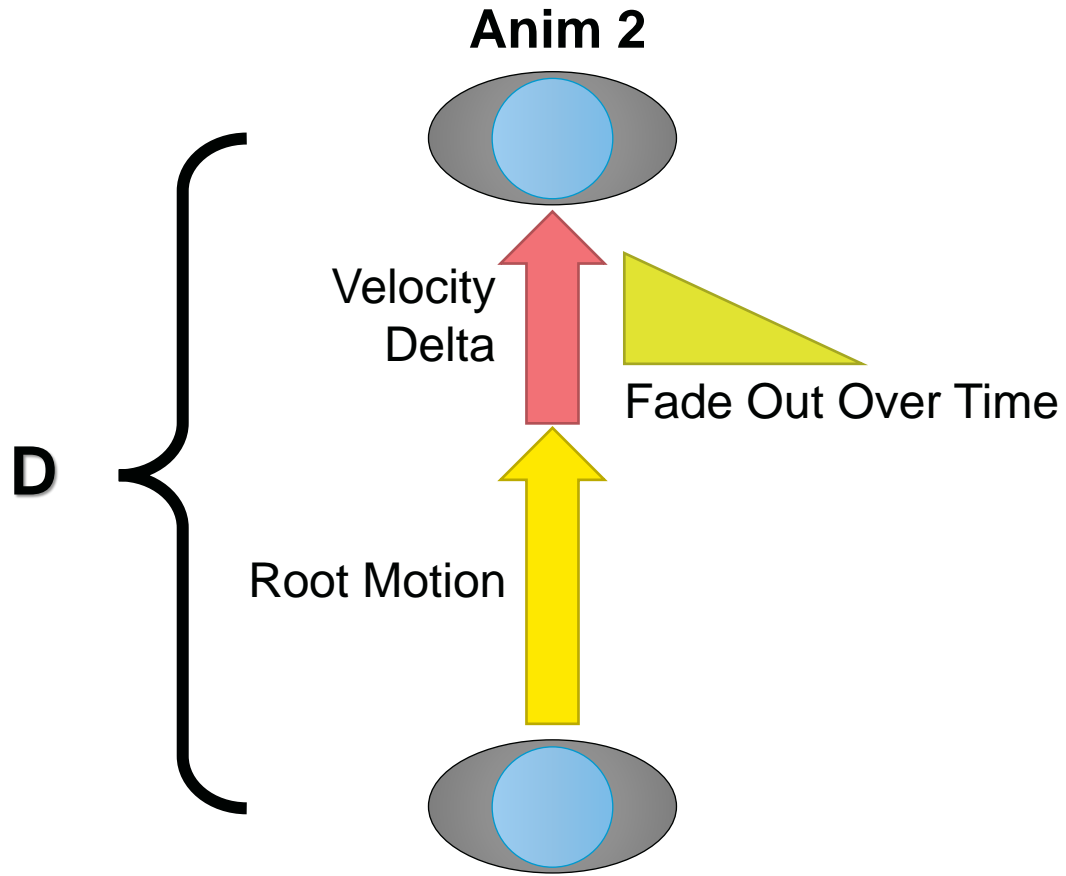
PLACE FOOT

- Update predicted foot position each frame
 - Ideally, shouldn't move
 - Don't change once foot lands
 - Becomes the "Previous" position for next step



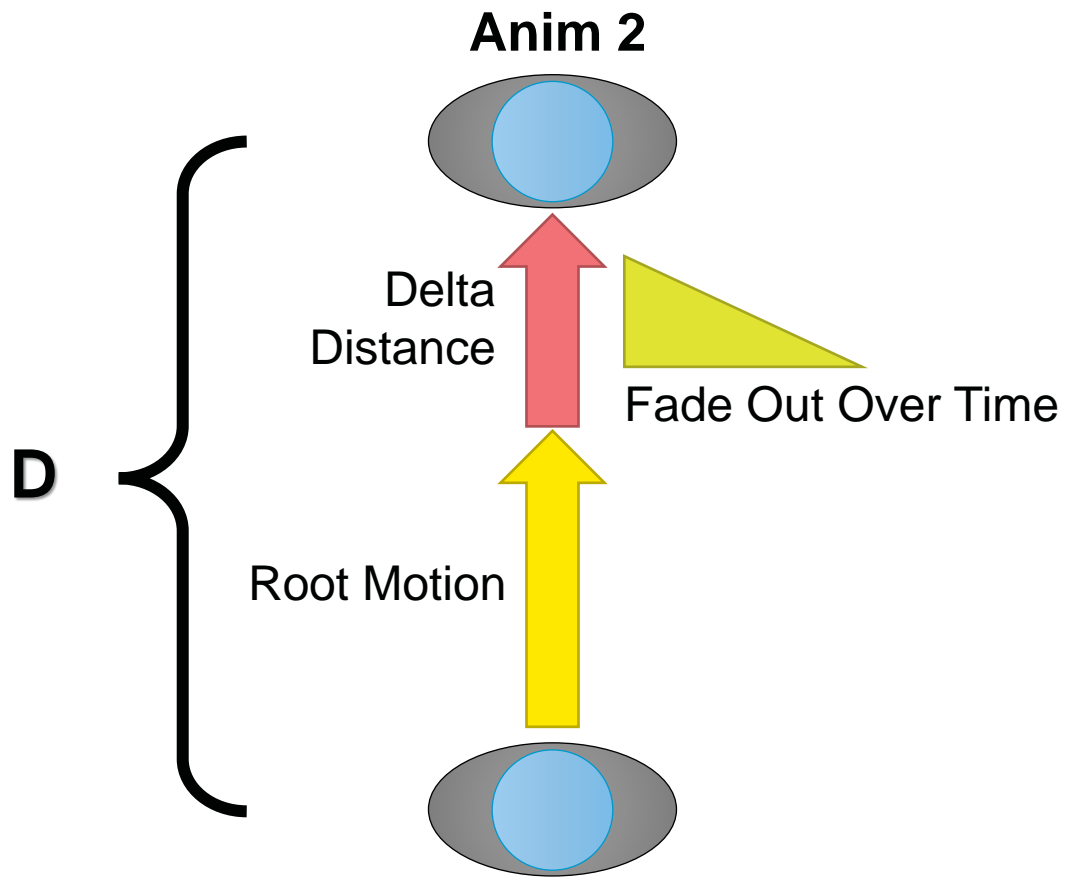
TRANSITION BLENDING

- How to predict character position when cross-fading animations?



TRANSITION BLENDING

- Find Velocity Delta at start of transition
- Add Velocity Delta to root motion each frame
- Reduce Velocity Delta to 0 over time



FIND TOTAL MOVEMENT FROM VELOCITY DELTA

- Velocity added to Root Motion at time t:

$$V(t) = \text{VelocityDelta} * (1 - t / \text{BlendTime})$$

- Integrate to get distance at time t:

$$D(t) = (K/2)*t^2 + \text{VelocityDelta} * t + C$$

Where $K = -\text{VelocityDelta} / \text{BlendTime}$

$$\text{Total Delta Distance} = \int_{t_0}^{t_1} D(t)$$



Animation Selection

- Stride Retargeting can change animations
- Extreme changes look bad
- Need to pick closest animation...

- Stride Retargeting can change animations
 - Extreme changes look bad
 - Need to pick closest animation...
-
- **Motion Matching**

Why Now?

- Don't need anim for every possibility
 - Stride Retargeting fills the gaps
- Already calculating future “goal” state
- Leverage foot motion data

Metric 1

Metric 2

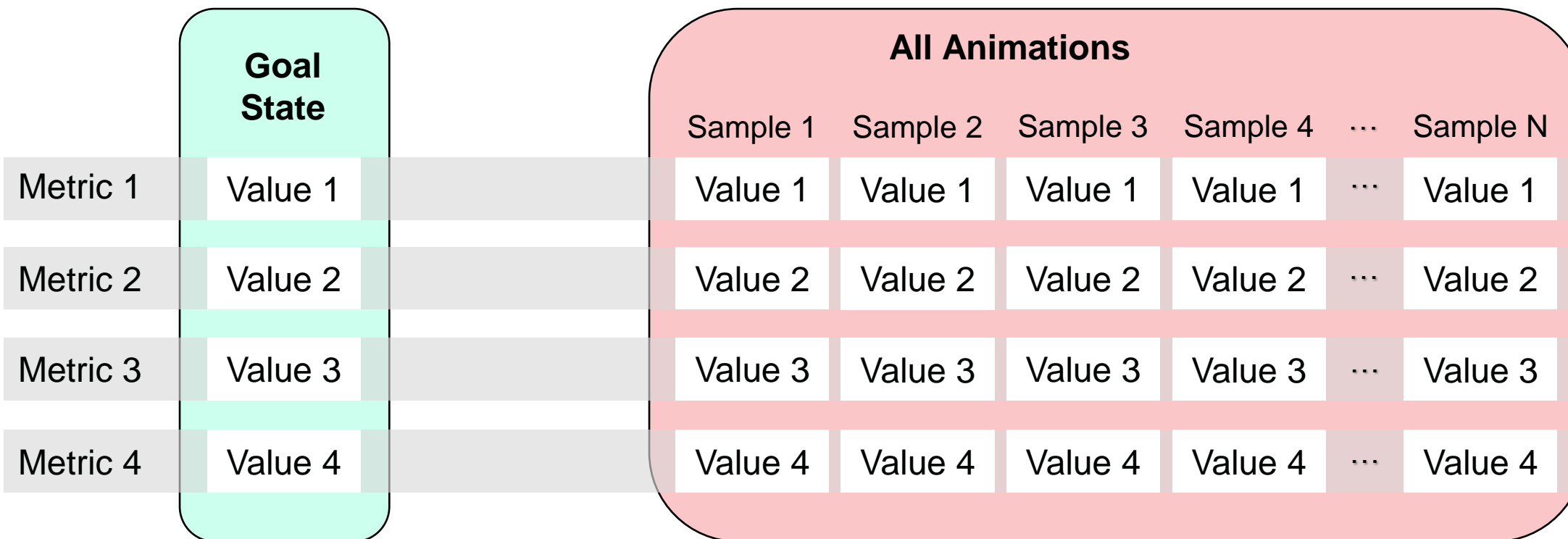
Metric 3

Metric 4

- Metrics = measurements about the state of an animation. Can be about current state or desired future state
 - Eg: Current Velocity, Future Velocity

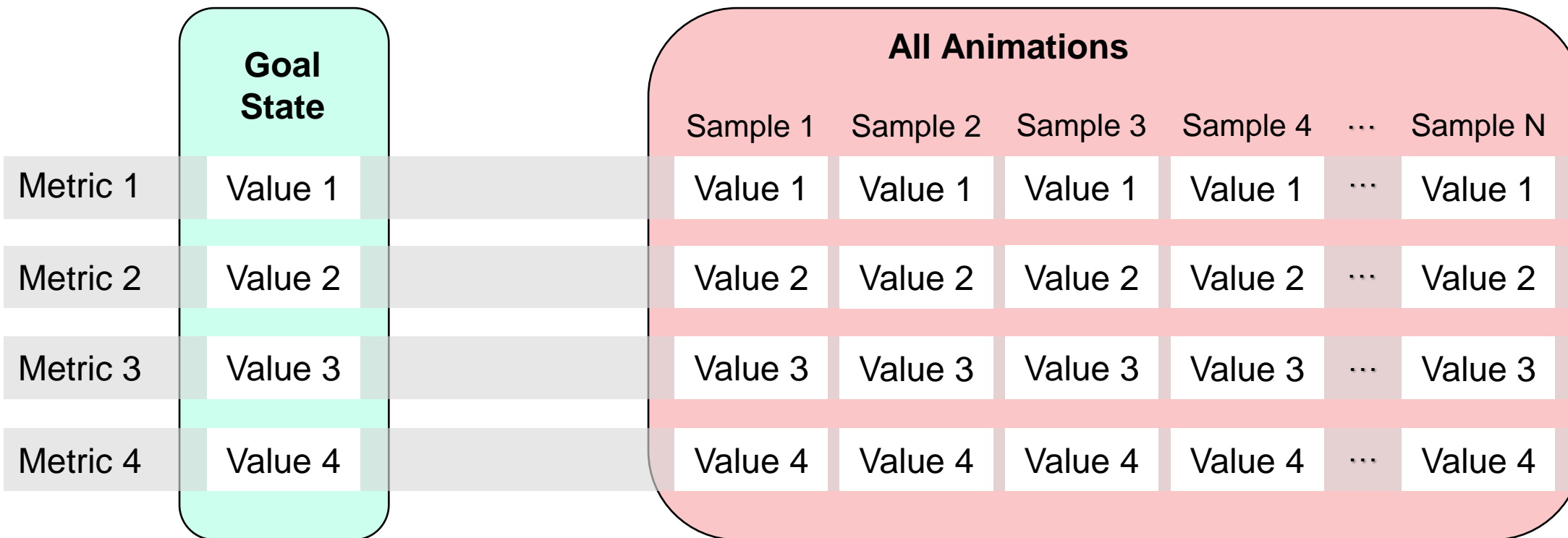
	All Animations					
	Sample 1	Sample 2	Sample 3	Sample 4	...	Sample N
Metric 1	Value 1	Value 1	Value 1	Value 1	...	Value 1
Metric 2	Value 2	Value 2	Value 2	Value 2	...	Value 2
Metric 3	Value 3	Value 3	Value 3	Value 3	...	Value 3
Metric 4	Value 4	Value 4	Value 4	Value 4	...	Value 4

Sample all the animations at a fixed interval and calculate the value for each Metric



Define a Goal State, that represents the desired state of the character.

Calculate a 'score' for each sample based on how close it is to the Goal State



$$\text{Score} = \sqrt{\sum((\text{GoalValue}_n - \text{TestValue}_n)^2 * \text{MetricWeight}_n)}$$



MOTION MATCHING OVERVIEW



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	Goal State	Current State	All Animations					
			Sample 1	Sample 2	Sample 3	Sample 4	...	Sample N
Metric 1	Value 1	Value 1	Value 1	Value 1	Value 1	Value 1	...	Value 1
Metric 2	Value 2	Value 2	Value 2	Value 2	Value 2	Value 2	...	Value 2
Metric 3	Value 3	Value 3	Value 3	Value 3	Value 3	Value 3	...	Value 3
Metric 4	Value 4	Value 4	Value 4	Value 4	Value 4	Value 4	...	Value 4

Sample with lowest score becomes the current state.

Repeat process, but now the sample has to score better than the current state.

Using motion matching is like raising a child...



“Make
Good
Choices”

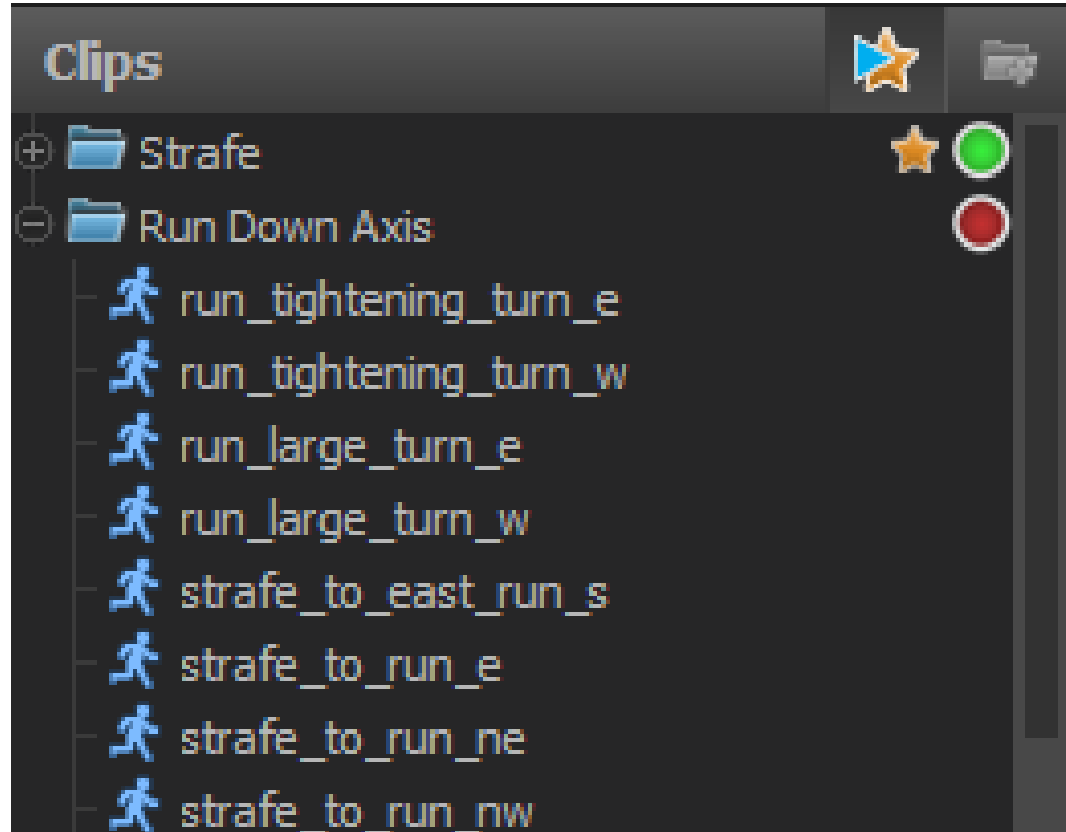




“Don’t
Make
Bad
Choices”



Avoiding Bad Choices



CLIP GROUPS

- Put anims in groups
- Only allowed to search in active groups
- Game logic determines active groups

Sample 1	Sample 2	Sample 3	...	Sample N
Value 1	Value 1	Value 1	...	Value 1
Value 2	Value 2	Value 2	...	Value 2
Value 3	Value 3	Value 3	...	Value 3
Value 4	Value 4	Value 4	...	Value 4

FILTERS

- Method to exclude certain samples
- Define valid metric range (Min/Max)
- Skip samples that fail check

Weighted Score =

$$\sqrt{\sum ((GoalValue_n - TestValue_n)^2 * MetricWeight_n)}$$

WEIGHTS

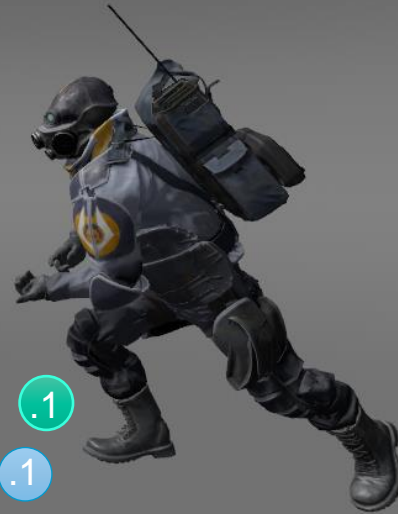
- Eventually need to pick between imperfect options
- Add weight scales score for metric
- Larger weights => More important
- Zero weight => Metric ignored
- Best results when all weights close to 1



Making Good Choices

Time-Based Sampling

- Goal Position
- Animation Position



PICKING PATH SAMPLES

- Time-based path sampling
 - Use physics to estimate future position
 - Guess at Acceleration/Jerk
 - Doesn't match all anims

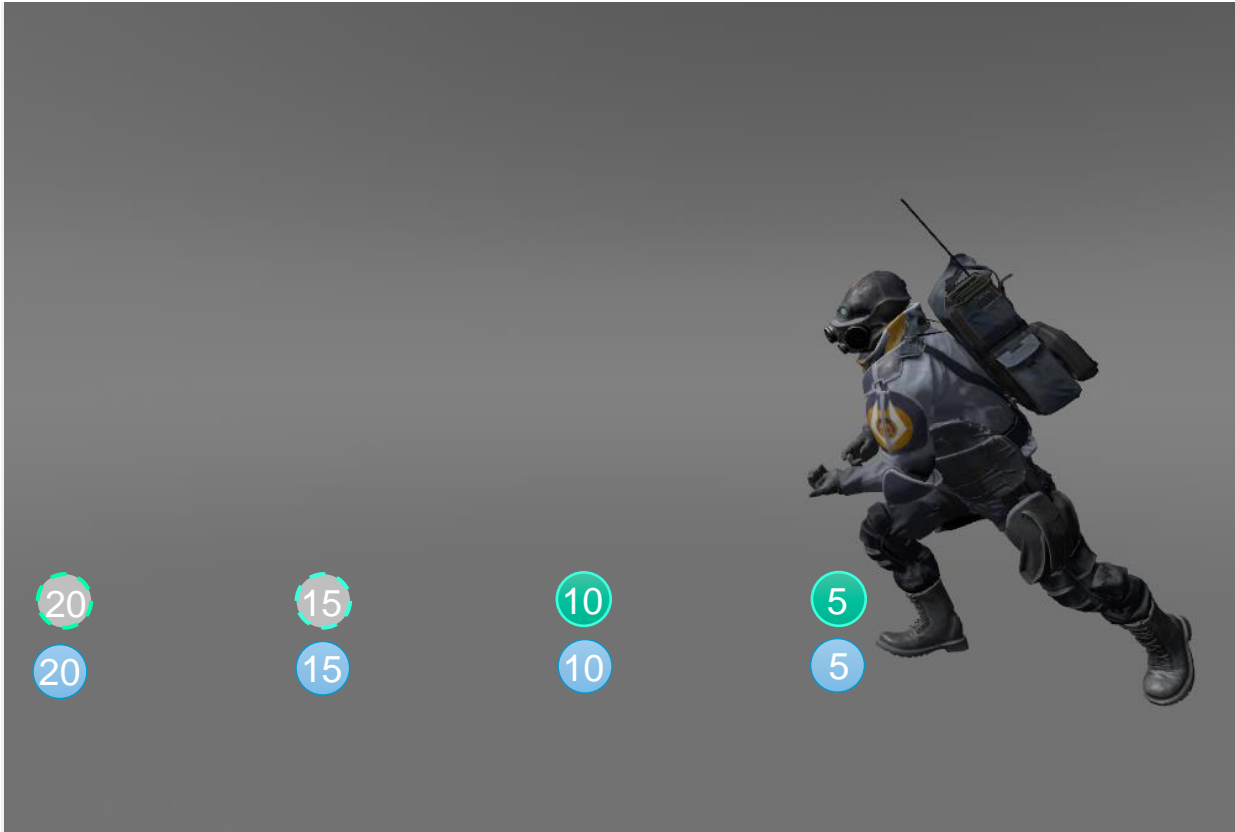
Distance-Based Sampling

- Goal Position
- Animation Position



PICKING PATH SAMPLES

- Distance-based path sampling
 - Find Position after moving X distance
 - Consistent for all animations
 - Easy to find along path



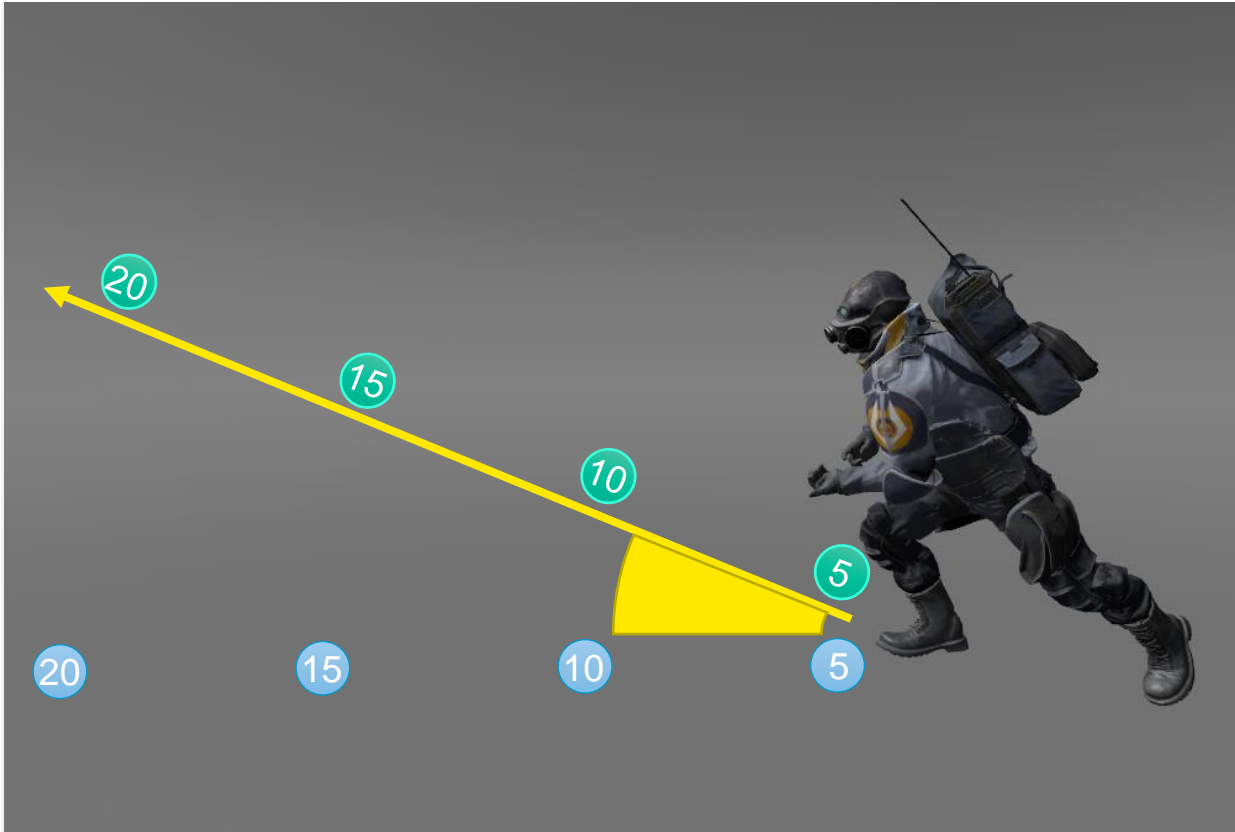
EXTRAPOLATING SAMPLES

- What if Animation doesn't move far enough?
- Estimate position based on final speed



SLOPES / UNEVEN TERRAIN

- Goal samples at different heights/distances
- Anim samples flat
- => Flatten Goal samples

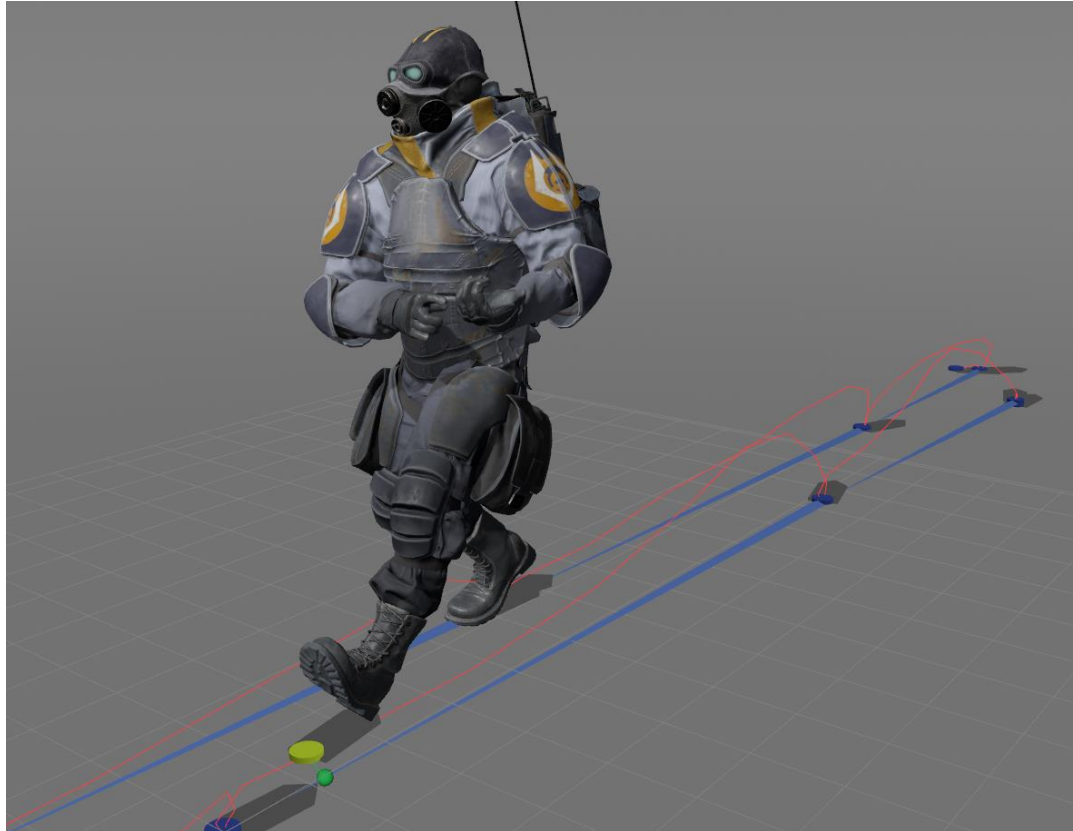


CORRECTIONS

- Match is never perfect
- Apply Correction for Position and Rotation
- Must include corrections in Score for Current Choice

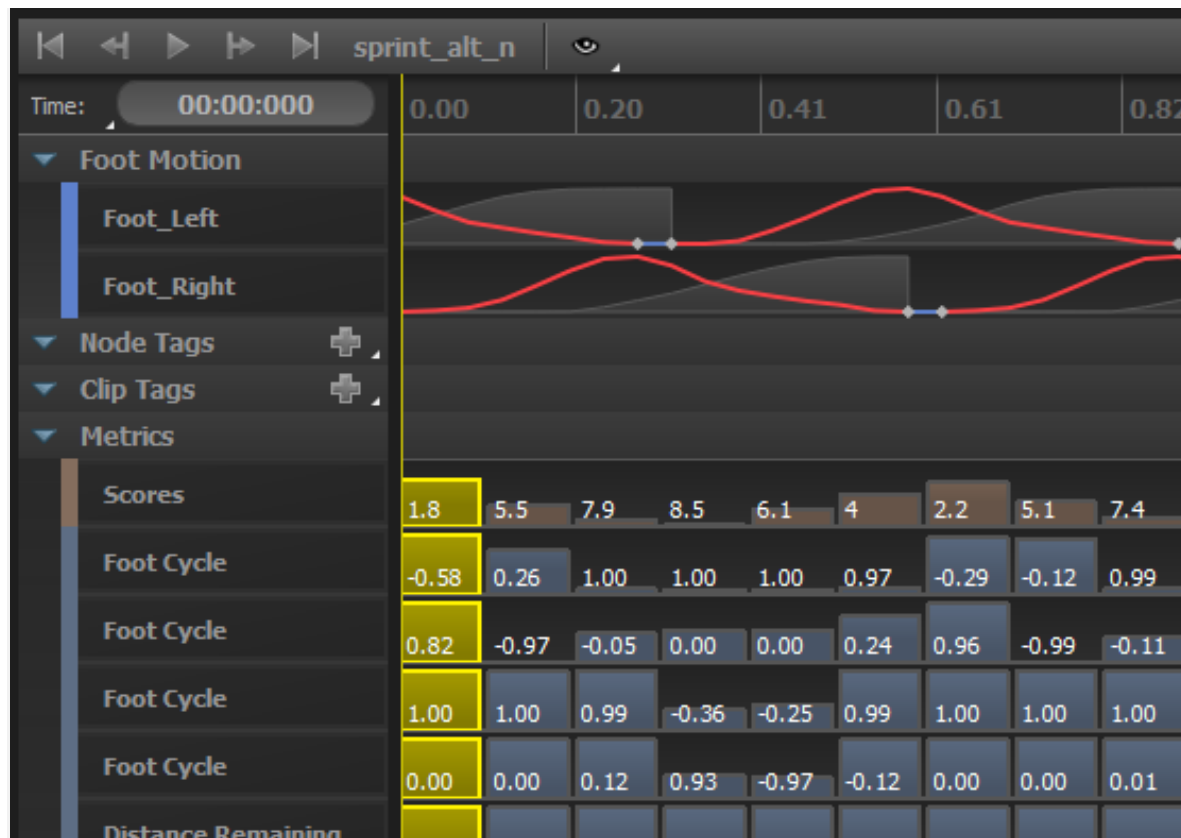


Leveraging Foot Motion



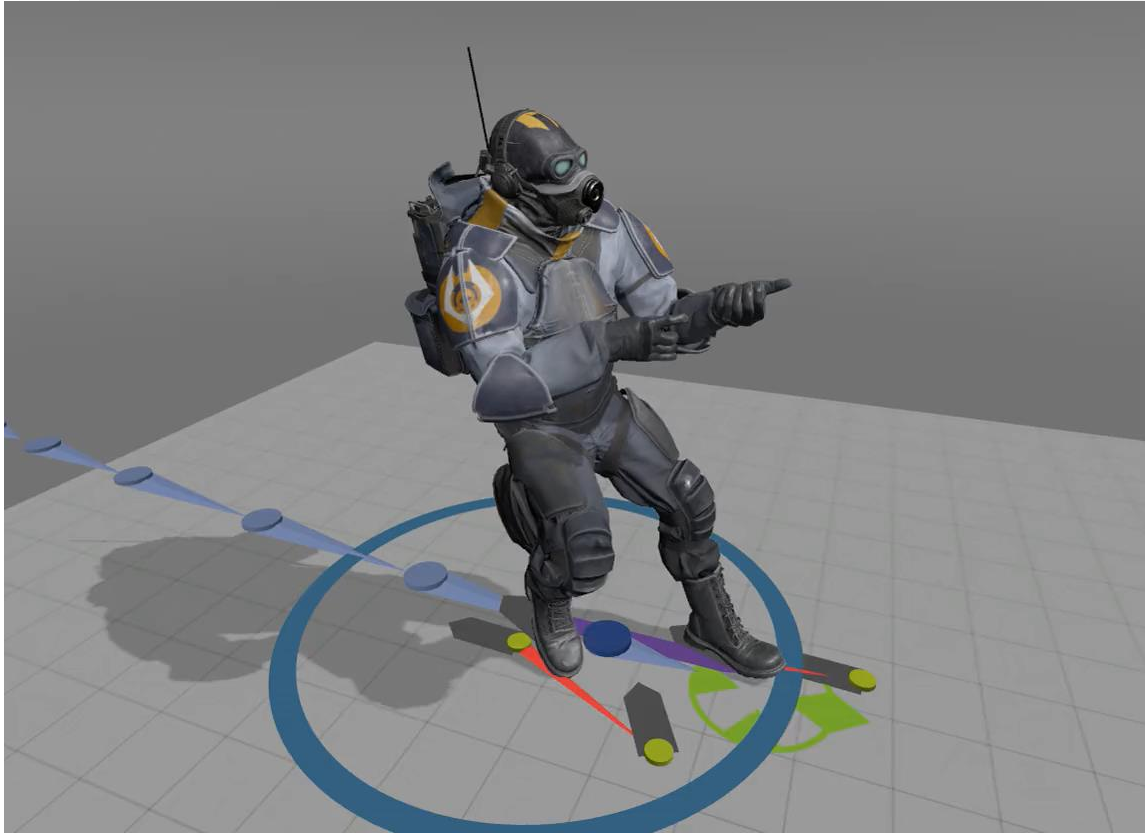
FOOT POSITION METRIC

- X,Y,Z position of FootBase
- Character-relative
- More accurate than foot bone position metric



FOOT STEP PROGRESSION METRIC

- Metric for foot step progression
- Matches how far through a step samples are
- Convert Progression (0->1) to a 2D direction vector
 - So start and end match



STEPS REMAINING FILTER

- On stopping anims, Root still moves after feet stop
- Don't want to pick these for short steps
- Add "Steps Remaining" metric, use as filter





DISTANCE REMAINING FILTER

- Need to stop exactly at end of path
- MM was picking clips that stopped just short
- Add “Distance Remaining” metric
 - Filter out samples that don’t reach goal
- Scale root motion to stop at goal



SEARCH FREQUENCY

- Can perform new search at fixed intervals
- Looked slightly better if only searching when a foot is planted

Metrics  		
Weight	Category	Type
1.00	<i>Pose Metric</i>	Current Velocity
1.00	<i>Pose Metric</i>	Bone Velocity (ankle_L)
1.00	<i>Pose Metric</i>	Bone Velocity (ankle_R)
0.00	<i>Filter Metric</i>	Steps Remaining
0.00	<i>Goal Metric</i>	Time Remaining
1.00	<i>Pose Metric</i>	Foot Cycle
1.00	<i>Goal Metric</i>	Distance Remaining
1.75	<i>Goal Metric</i>	Path
1.00	<i>Goal Metric</i>	Future Facing
1.75	<i>Goal Metric</i>	Future Velocity
1.00	<i>Pose Metric</i>	Foot Position

COMBINE SOLDIER

- Metrics used by the combine soldier



117 Animations used for motion matching

- **Strafe Mode (77)**
 - Idle*
 - Run Loop* x 8 directions
 - Short Hops*, 8 distances x 8 directions
 - Run Fwd then Bwd, Bwd then Fwd
 - Run Left then Right, Right then Left
 - Square Strafe Clockwise, Counter-Clockwise
- **Face Path Mode (70)**
 - Running turns: Left/Right x Large/Small Radius
 - Strafe then Face Path x 8 directions
 - Face Path then Strafe x 8 directions
 - Stand to Run x 8 directions
 - Run to Stand x 8 directions
 - Plant turns: 90/180 Left/Right
 - All Strafe Mode Animations

* Created before MM implementation and re-used



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QUESTIONS?

LIVE Q & A ON DATE TBD

