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Dynamic Walking
with
Semi-Procedural Animation

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unity

Walking

unity

Importance of Walking

- Players often spend most of the time walking around
- Games have increasingly detailed environments
- We want to make it look good when walking through these environments

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Keeping Experts in Control

- **Adaptation to Terrain**
  with believable walking over any steps and slopes
- **Animators**
  in full control of style and personality
- **Game Programmers**
  in full control of game logic and character movements

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What is Wanted

Minimum Work

- Only few animations are needed (as few as 2 per character)
- Fully automatic blending of multiple walk cycles

Maximum Flexibility

- Should work for humans, quadrupeds, bugs, spiders, ...
- Walking with any direction and curvature on any terrain

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Demo of Locomotion System

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Clarification

The Locomotion System is *not*:

- A physics-based system or active animated ragdoll system
- A behavior-based system
  (like NaturalMotion's euphoria)
- A unified system that can be used for all animation of a character

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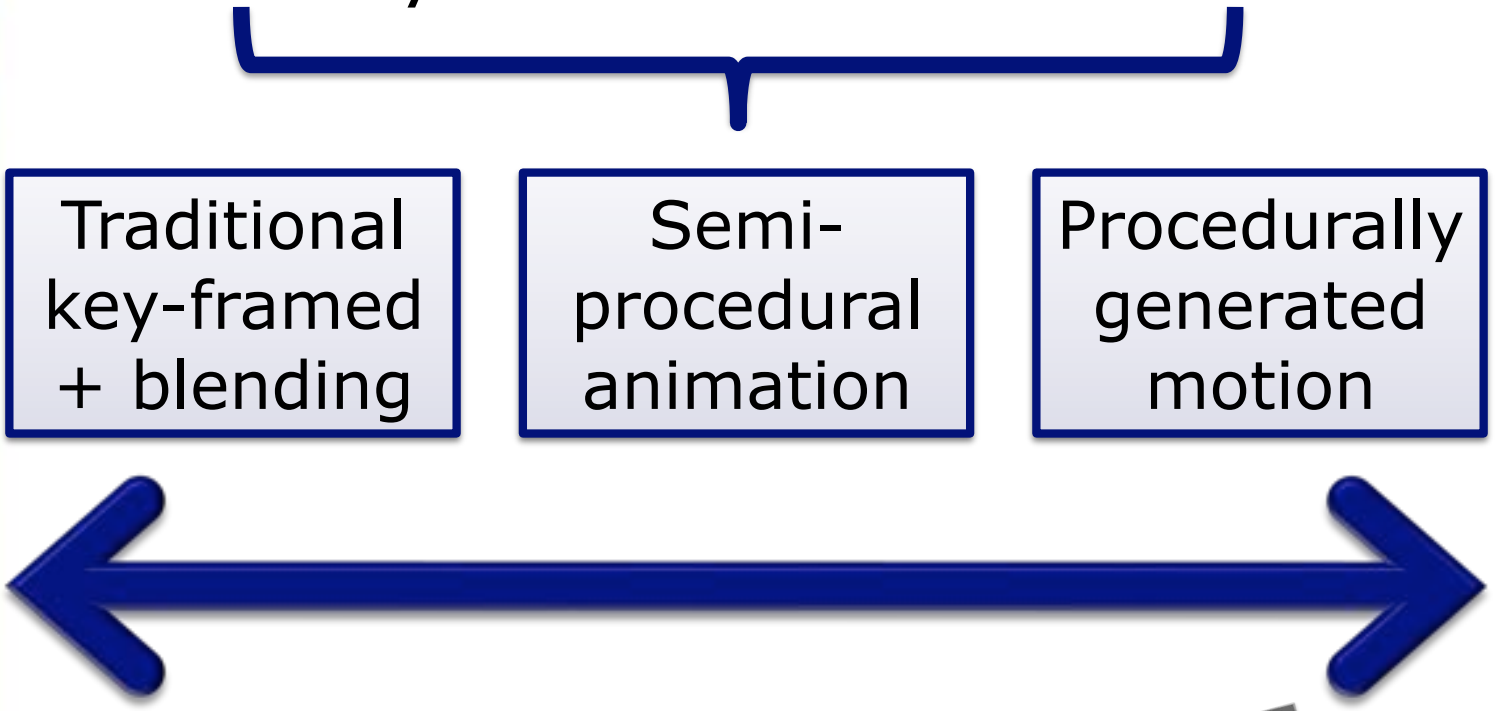
Best of Both Worlds

- Full control over style
- Dynamic movements



unity

Minimal Model

Procedural animation

=

simulation based on a **model**

- Models are based on *assumptions*
- Get a highly *flexible* system by *reducing* the assumptions

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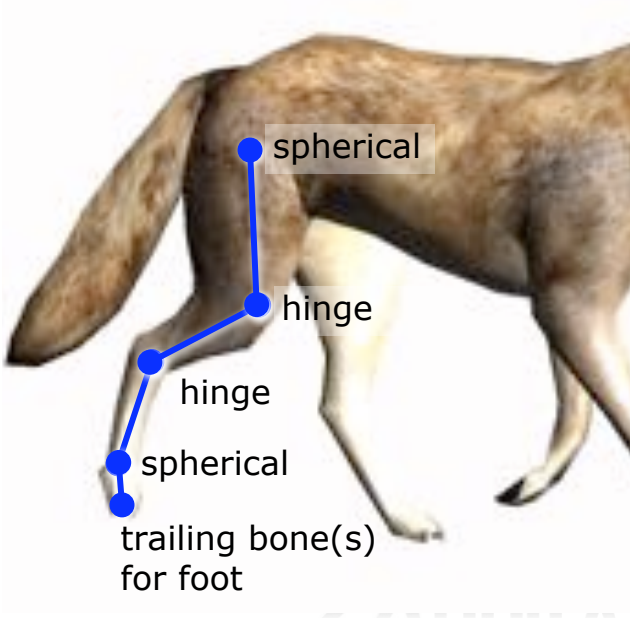
Character Requirements

- One or more legs
- Each leg has two or more bones from hip to foot
- First and last joints are spherical (ball-and-socket) joints
- Middle joints are (at least) hinge joints
- No animated scaling / stretching of leg bones
  (in current implementation…)



Animation Requirements

- Animations must be cyclic!
- Animations are in character space
  "walking on the spot"
- Legs (knees) should not over-bend
- The feet should be at their lowest when in contact with the ground
  (and not penetrate the ground too much)
- Feet should be moving backwards* when in contact with the ground, with linear speed

* for a forward walking animation

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Automating the Hard Work

Easy setup

- List of legs
- List of animations

Each animation is automatically analyzed:

- Speed and direction (velocity)
- Foot cycle lifting and landing keytimes

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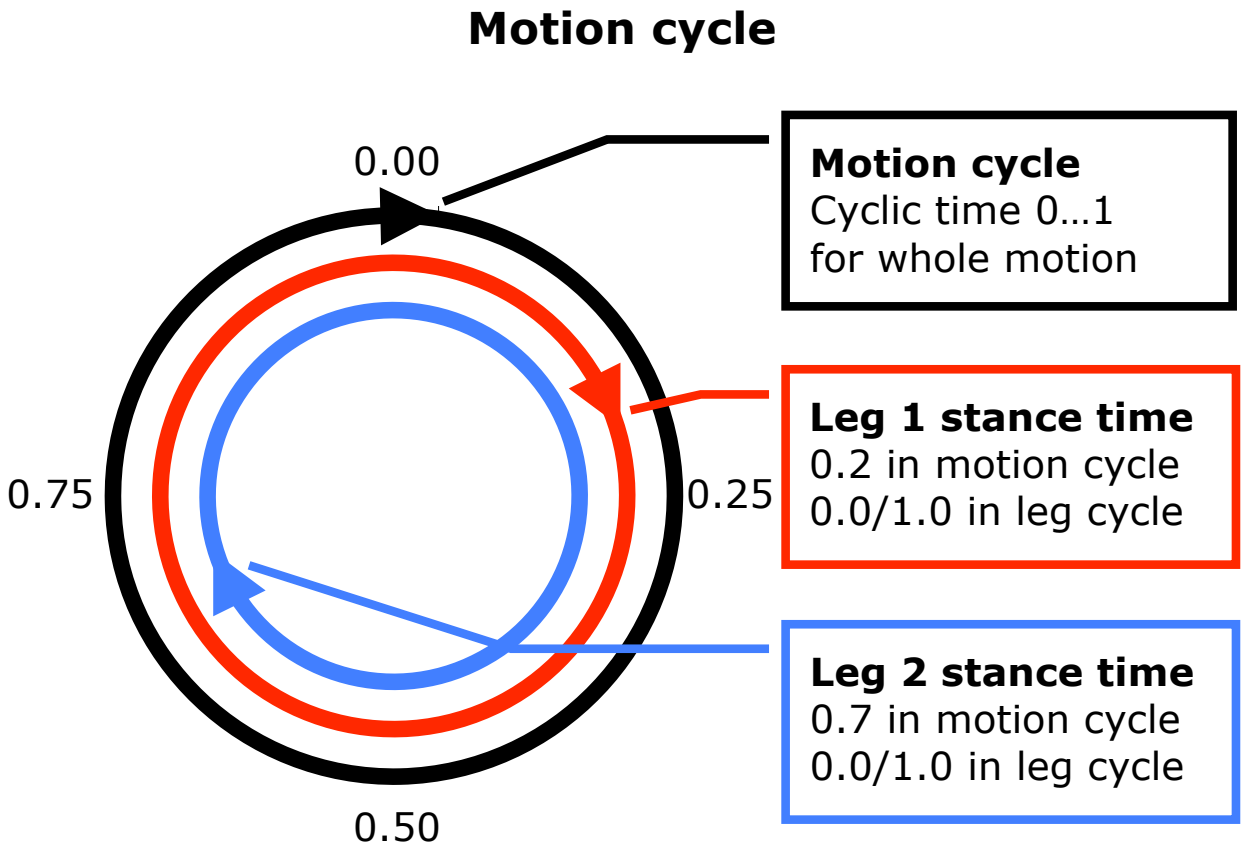
The Motion Cycle



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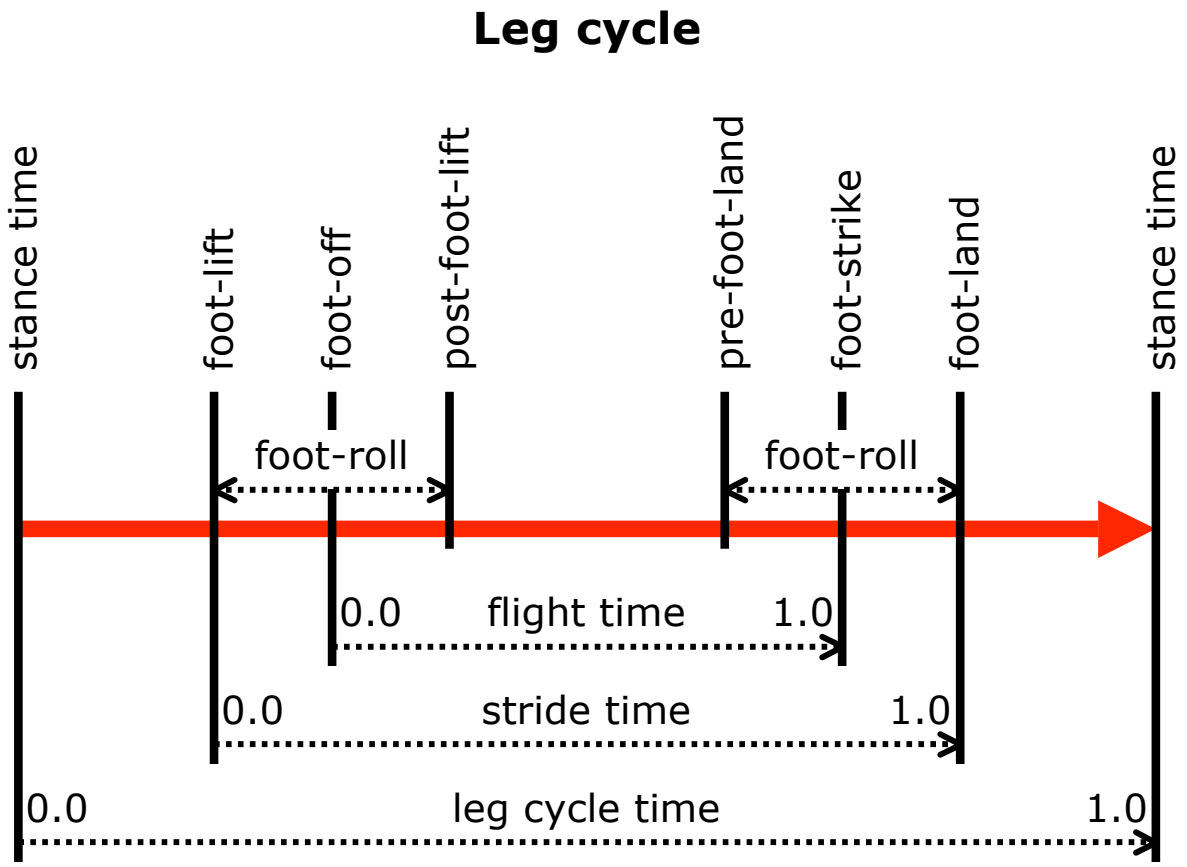
Leg Cycle and Keytimes



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Sample Heel and Toe Trajectories

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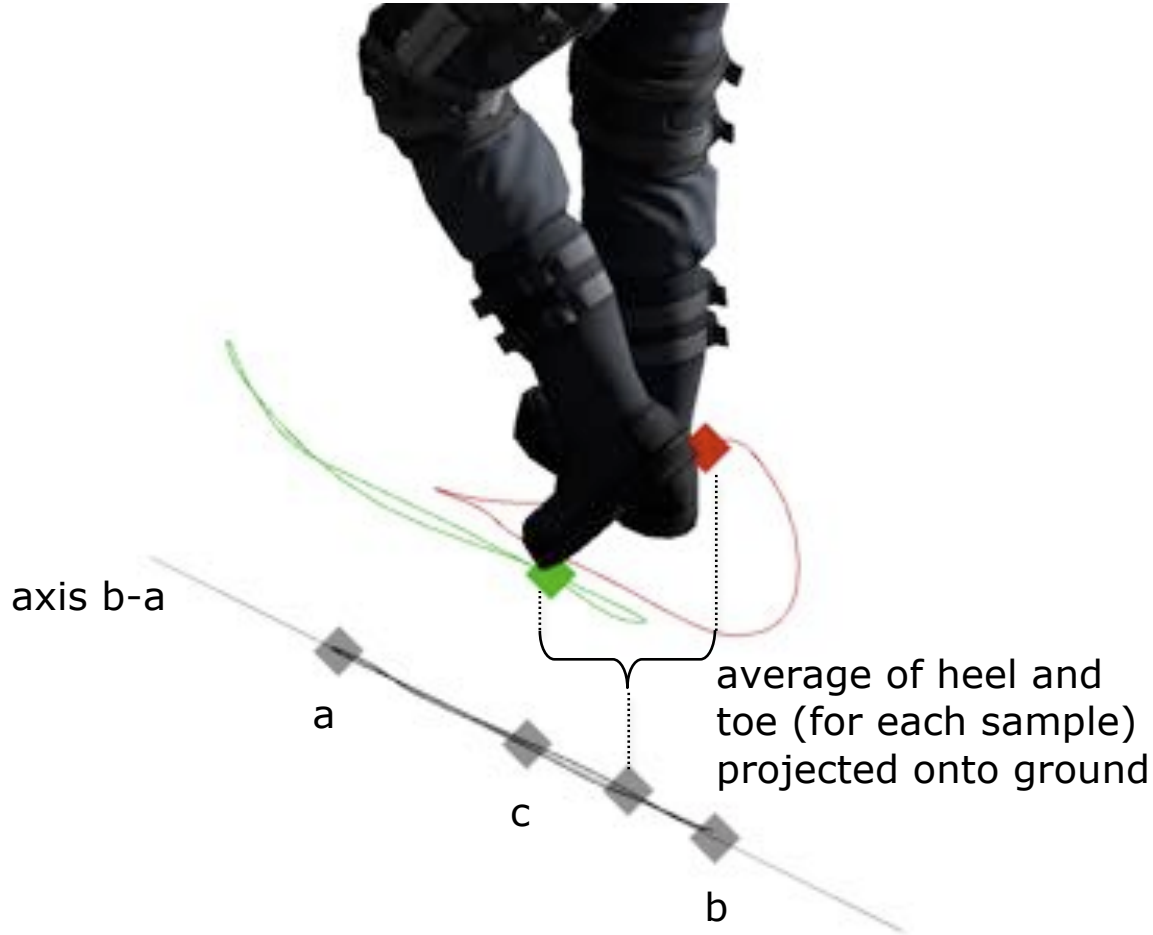
Movement Axis

Movement Axis



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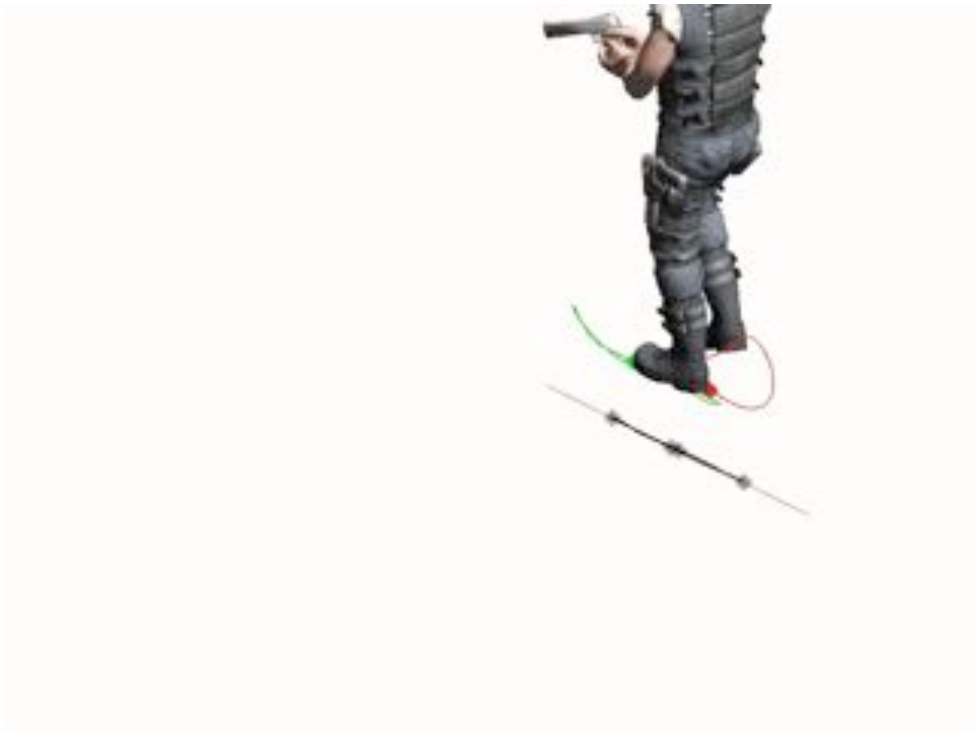
Stance Time



To determine the stance time, a cost value is calculated for each sample based on:

- Height of the heel and toe at that sample
- Position along movement axis (middle=low cost)

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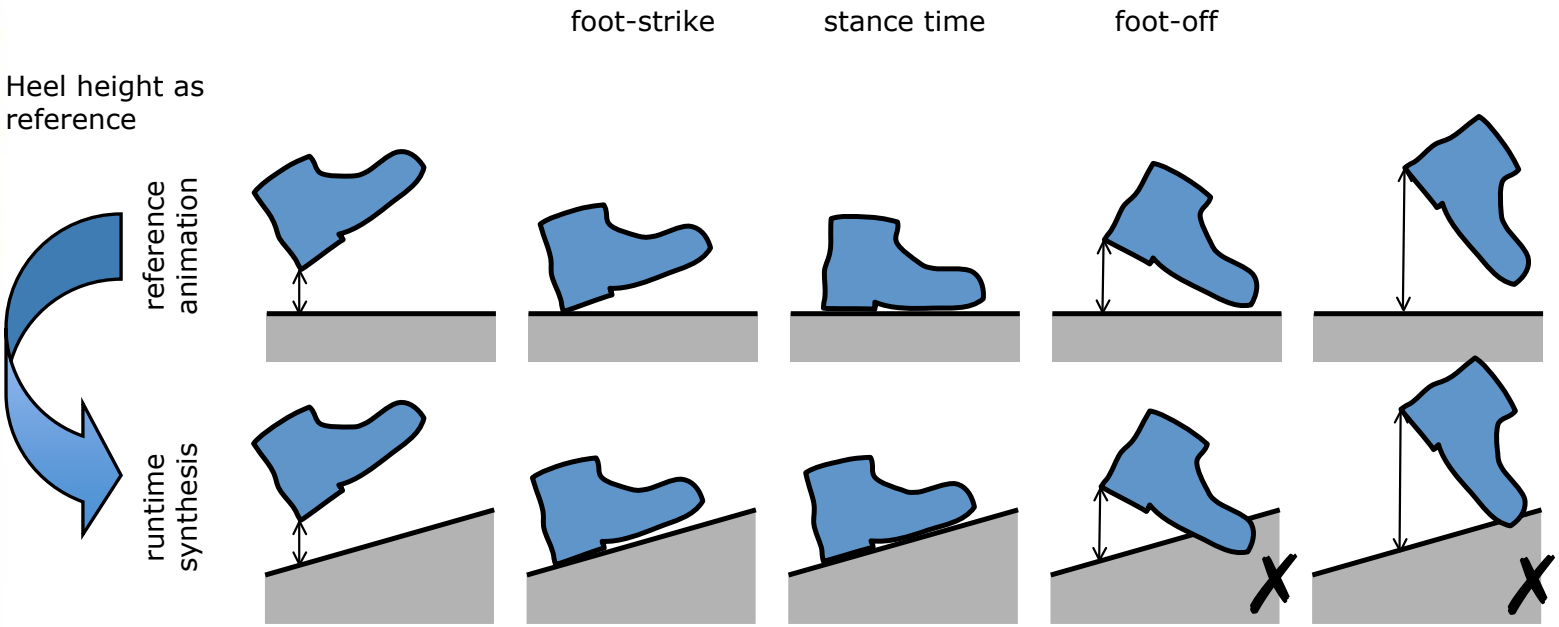
Foot Relative To Ground



How to measure height of foot over the ground?

- Heel as reference point doesn't work.
- Neither does the toe, or the middle.

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The Footbase

Introducing: **The footbase**

- Like a plate under the foot
- Always perpendicular with the ground underneath
- Foot touches footbase with heel, toe, or both

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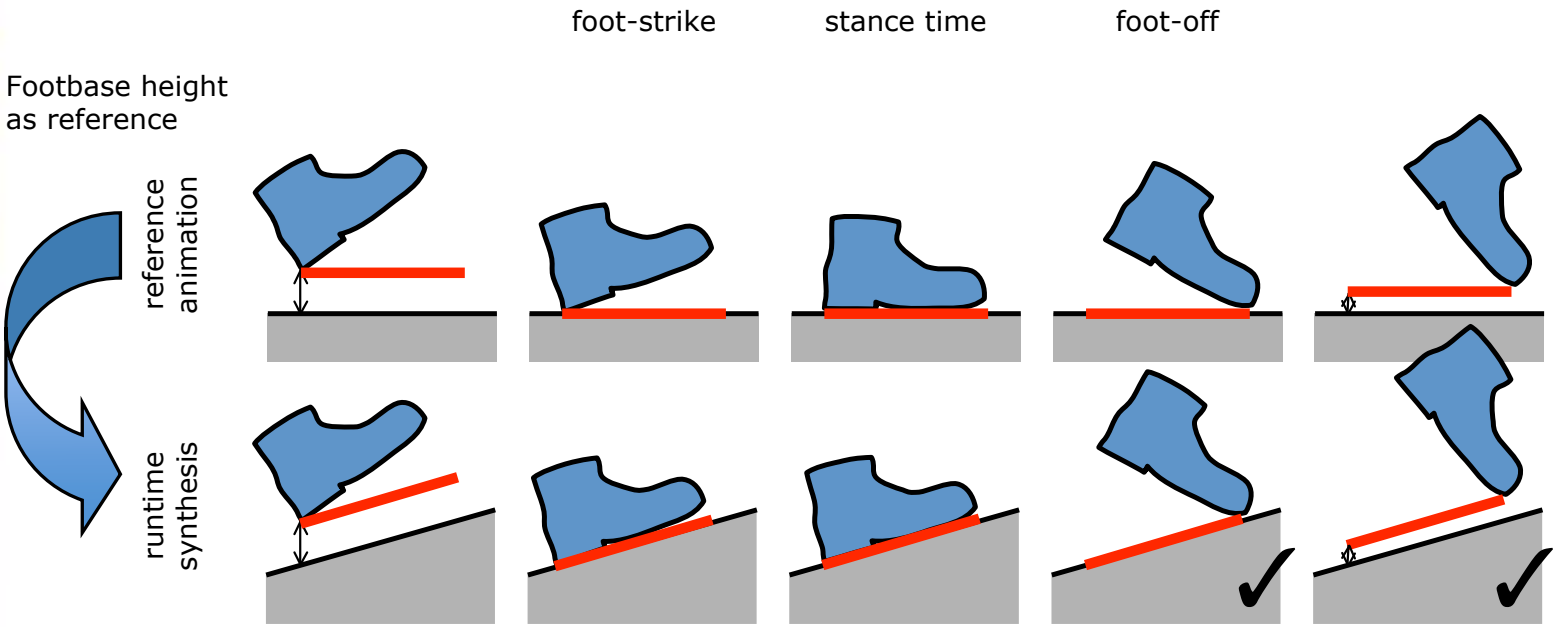
The Footbase



How to measure height of foot over the ground?

- Find the footbase, given position and alignment of foot, and the slope of the ground
- Measure the height of the footbase above the ground

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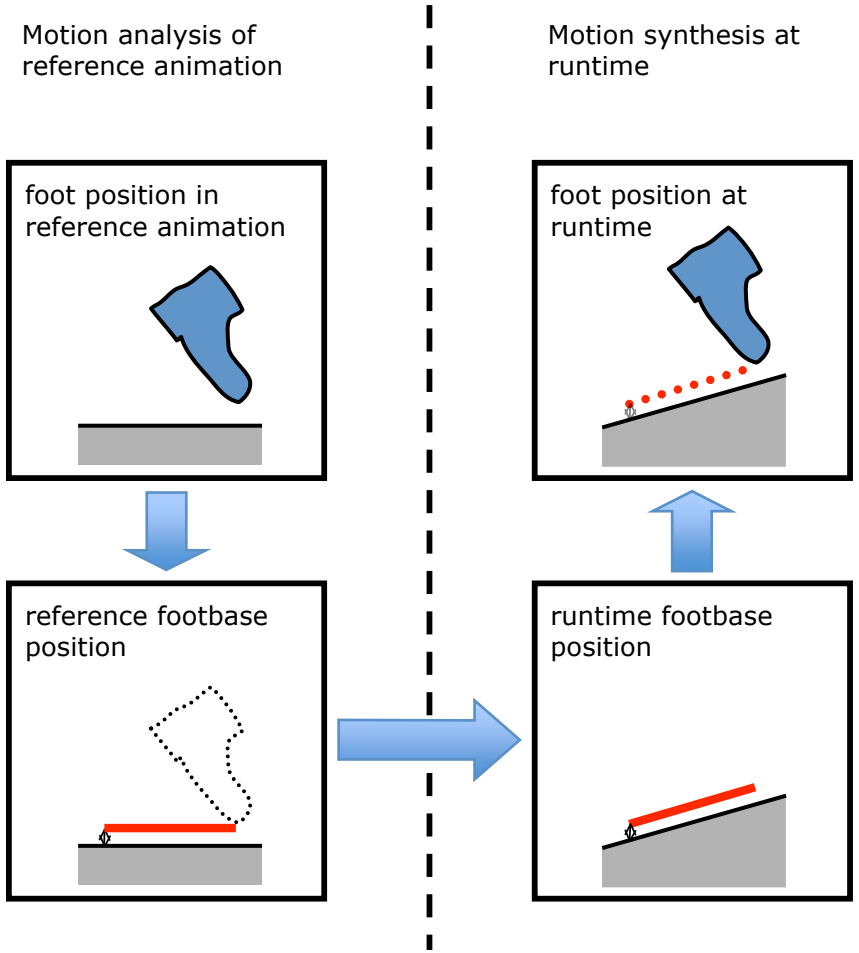
The Footbase



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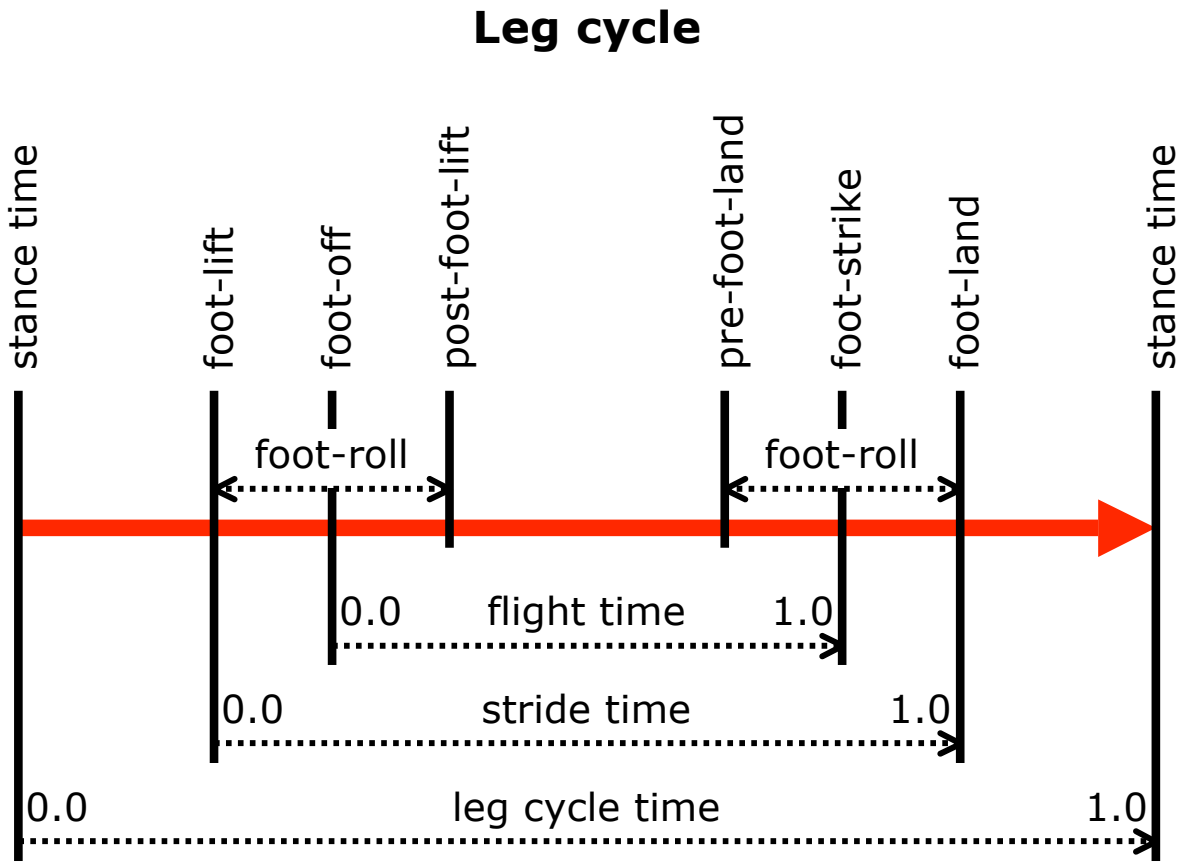
Finding the Keytimes



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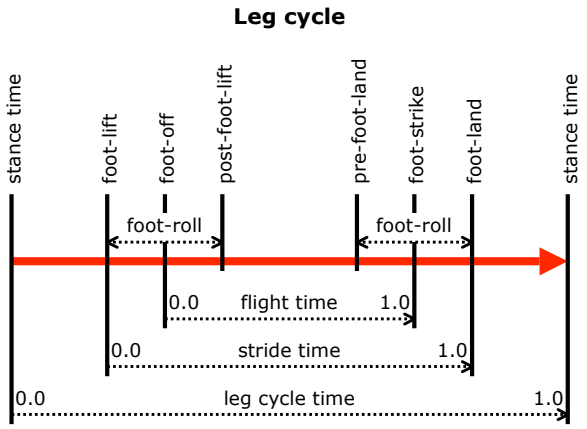
Finding the Keytimes

- Keytimes need to be set for each leg, for each animation.
- Animators can annotate these.
- In the implemented system, an automatic heuristic was used as part of the motion analysis.



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Finding the Velocity

- Measure the distance that footbase has moved from *foot-land* time to *foot-lift* time.
- Divide by time-span between those two times.
- Do the above for each foot, then use the average as the velocity for the motion.

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Normalized Footbase Trajectories

» With the velocity known, we know the footbase trajectory relative to the ground (i.e. in world space).

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Normalized Footbase Trajectories

Normalize the trajectory and store it:

- Trajectory starts at (0,0,0)
- Ends at (0,0,1):
  - Aligned with z-axis
  - Scaled to have step length of 1
- Keep vertical and sideways components un-scaled

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Analysis done!

(repeat for each motion)

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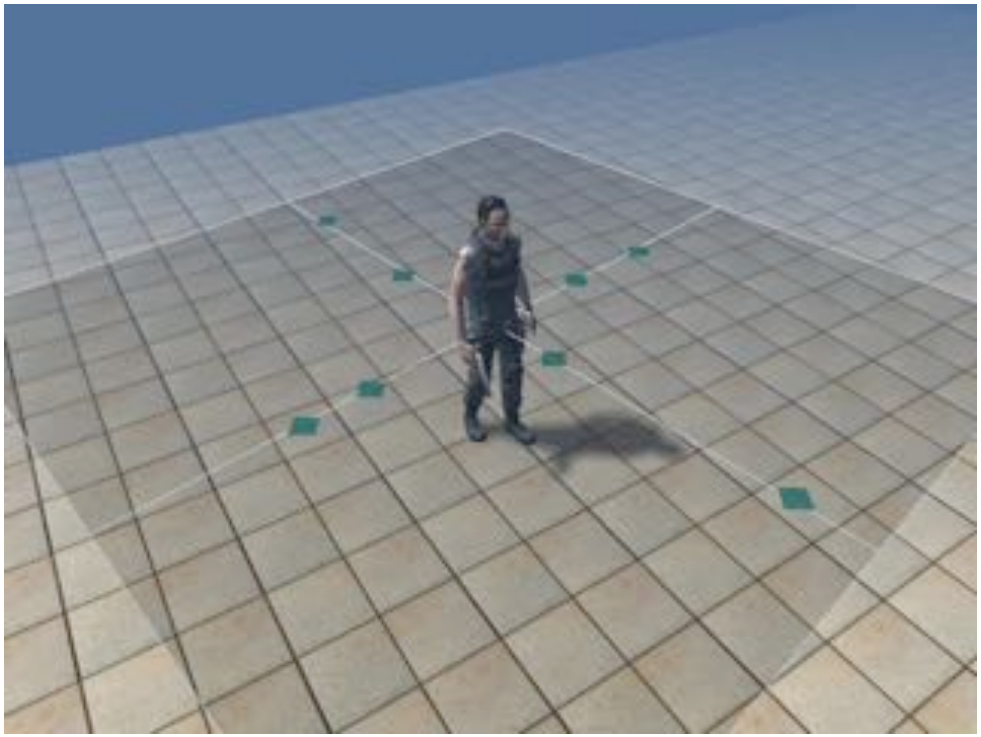
Automatic Blending



- The velocity of each sample animation is known.
- Based on current velocity, assign weights to neighboring samples.
- A problem of scattered data interpolation.
  (Plenty of research on the subject.)

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Automatic Blending

- Only few animations are needed. (As few as 2)
- Forward animations can double as backwards.
- Walking sideways may not always be needed but always make turning look better.

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Blending the Data Too

Blending weights are used to blend animations *and:*

- Normalized footbase trajectories
- Keytimes
- Stance position
  (Position of foot relative to body at stance time)
- Basically all data analyzed for each animation!

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Leg Movements

Inverse kinematics (IK) can be used at runtime to move a leg around by specifying the hip and ankle positions

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Leg Movements

...but *how* should the feet be moved around?

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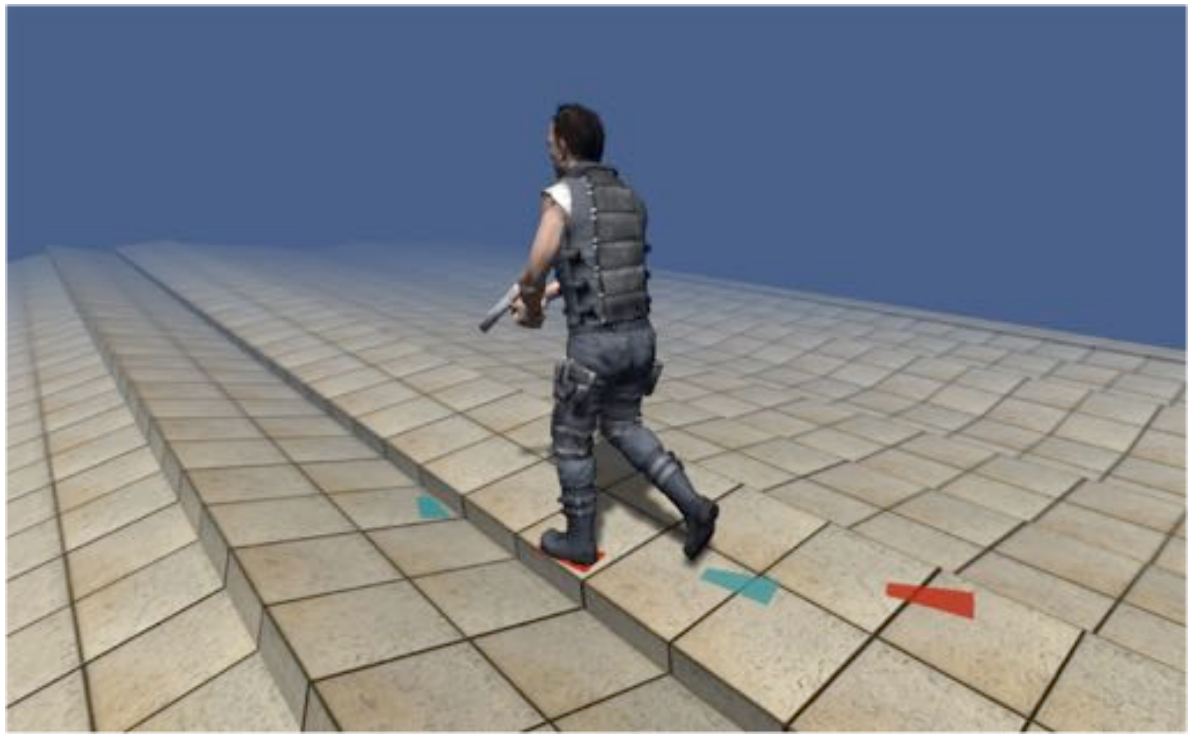
Leg Movements



- We determine spots on the ground where the feet land – the “footprints”
- The foot takes a step from one footprint to the next

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Footprint Prediction

At the ***stance time*** (the start/end of the leg cycle) the foot is at its ***stance position*** (the "resting" position of the foot in character space).

- Predict where the character is (the transform) at the next *stance time*.
- Multiply the *stance position* with the predicted character transform.
- Result: The next ***footprint***
  (The next place where the foot lands on the ground)
- Keep updating the footprint prediction until the foot is planted

unity

Footprint Prediction

- For each foot, the next footprint is predicted according to current velocity and rotational velocity.
- The prediction is updated until the foot is planted.
- Raycasts are used to place the footprints on the ground.

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Footprint Prediction

- Prediction is individual for each leg.
- Works for any number of legs.
- Everything derived from sample animations.

unity

Foot Flight Between Footprints

The foot must move from the *prev* to *next* footprint with a proper trajectory.

- Proper horizontal curve that follows character…
- Vertical lift that fits the (uneven) terrain…
- If supporting leg is higher than lifted, lift to that height…
- Preserve trajectory movements from original motion…

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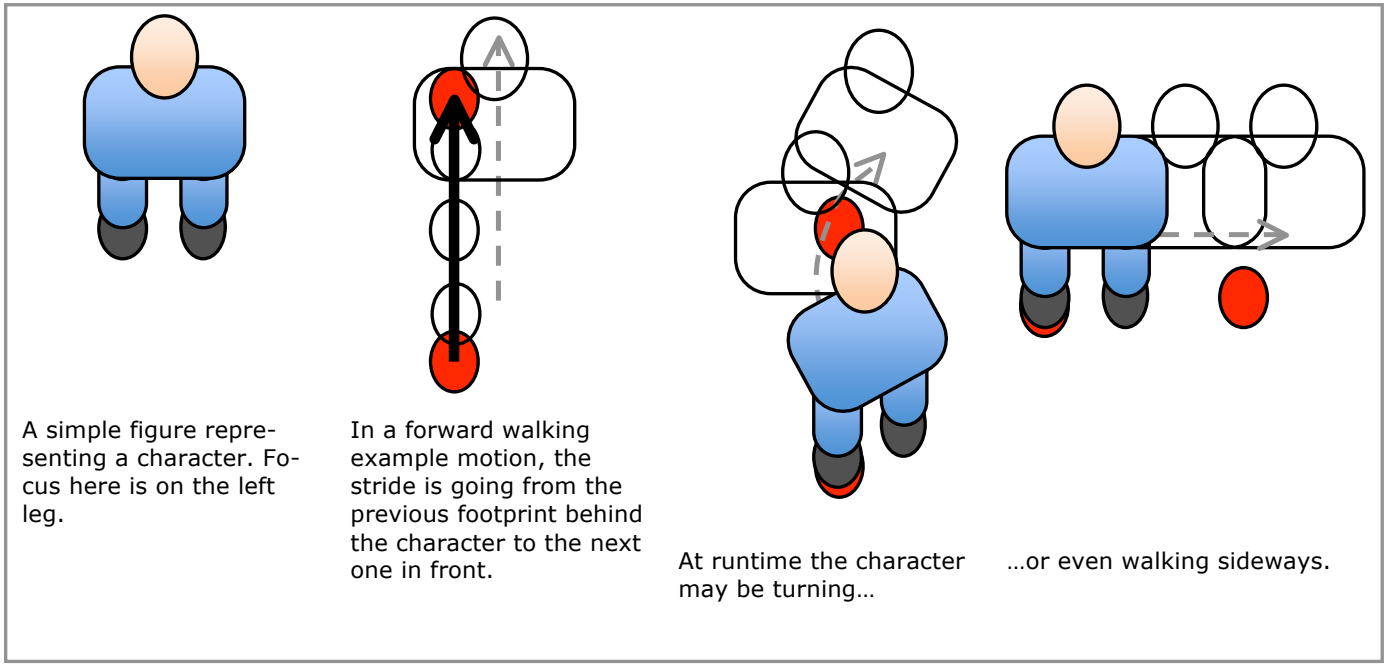
Proper Horizontal Curve?



Need trajectories from *prev* to *next* footprint that work great no matter if adjusted velocity and curvature is completely different than in blended sample animations.

unity

Proper Horizontal Curve?

- Use normalized footbase trajectory to move foot from *prev* to *next* footprint.
- Doesn't work in a straight line though!

unity

Proper Horizontal Curve?

- We also can't simply lerp into the original foot motion midway through the flight.
- Gives wrong deltas if velocity at runtime is very different than velocity of blended sample animations.
- (Footbase path from a forward walking animation applied to a sideways walking character will result in strange foot curves, even when only applied in mid-flight.)

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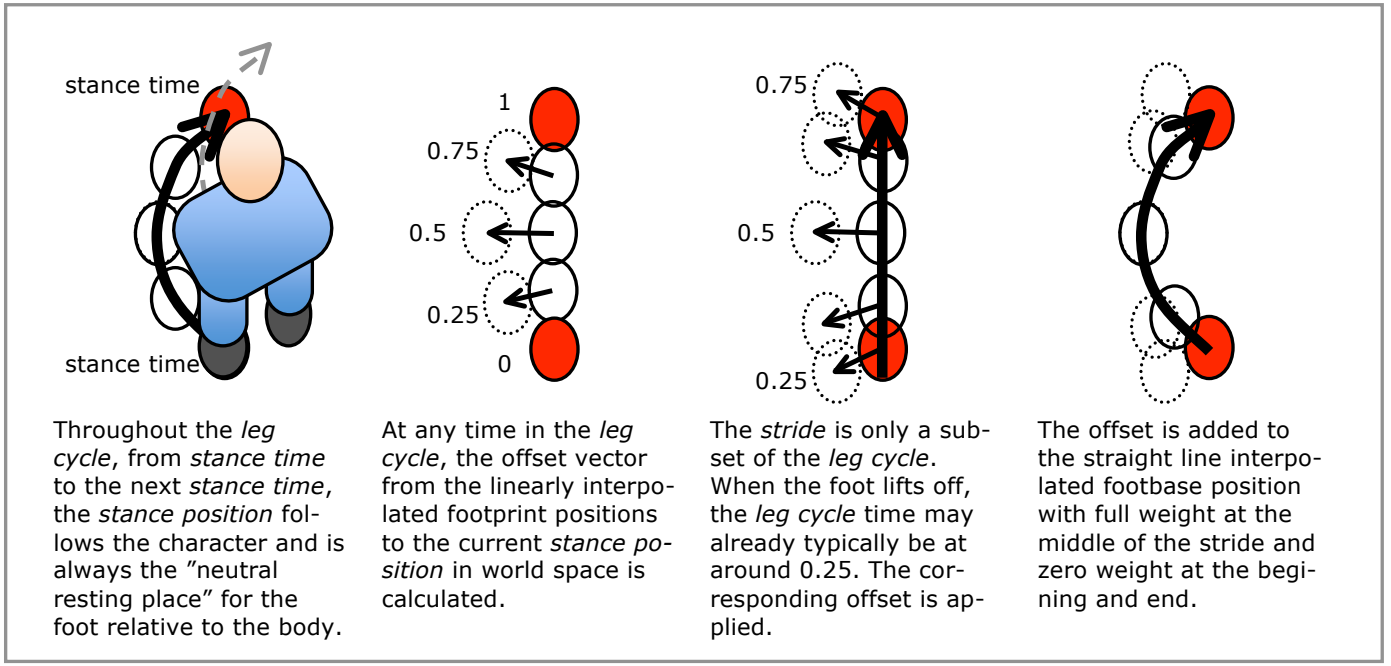
Proper Horizontal Curve!



Throughout the *leg cycle*, from *stance time* to the next *stance time*, the *stance position* follows the character and is always the "neutral resting place" for the foot relative to the body.

At any time in the *leg cycle*, the offset vector from the linearly interpolated footprint positions to the current *stance position* in world space is calculated.

The *stride* is only a subset of the *leg cycle*. When the foot lifts off, the *leg cycle* time may already typically be at around 0.25. The corresponding offset is applied.

The offset is added to the straight line interpolated footbase position with full weight at the middle of the stride and zero weight at the beginning and end.

- Use straight line trajectory as a basis.
- Add offset based on current stance position relative to lerped position between prev and next footprint.

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Proper Horizontal Curve!

- Nice smooth curve for any adjusted movement.
- Acceleration ("ease in / ease out") is still based on normalized footbase trajectory.

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Adjusted to New Velocities

- Flexibility of foot trajectories make it possible to adjust animations to work for completely new directions.
- (May not always look natural)
- But highly useful for turning.

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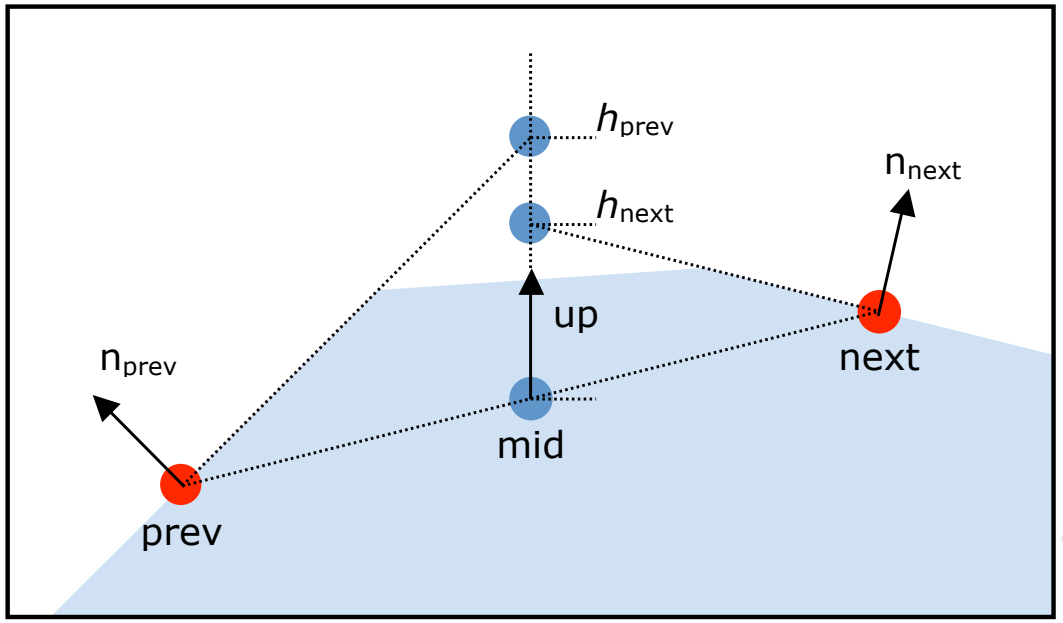
Vertical Lift Fitting the Terrain

- The foot should follow the terrain roughly, but in a smooth way.
- Look at tangents of ground at prev and next footprint.
  - Can be derived from ground normals at the footprint positions.



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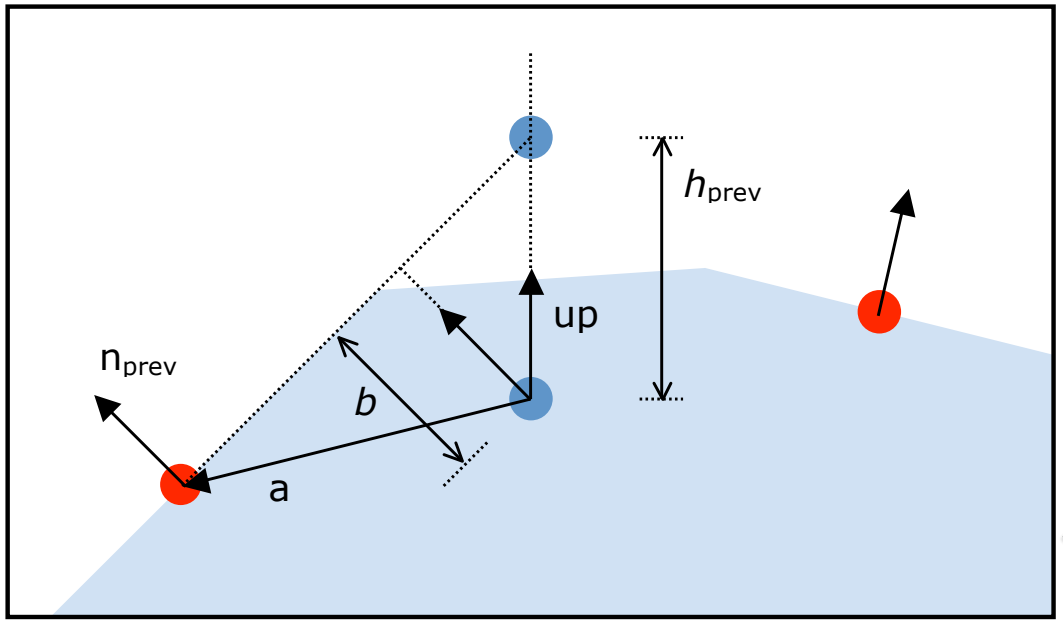
Vertical Lift Fitting the Terrain

- Find the intersection of tangent and vertical axis above mid-point between prev and next.
- Use the intersection point with the highest altitude of the two.



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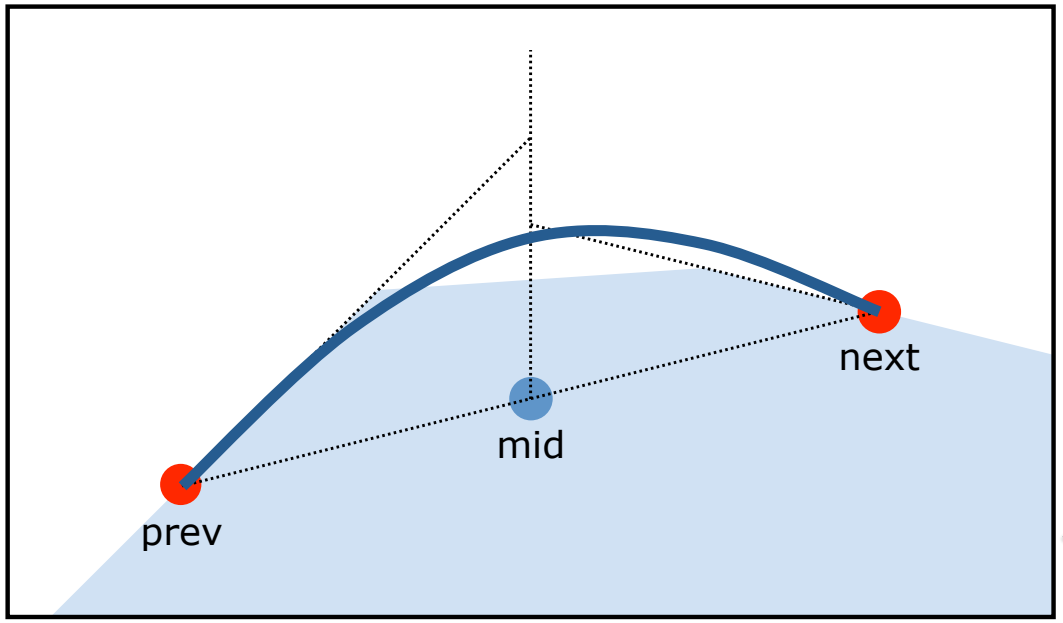
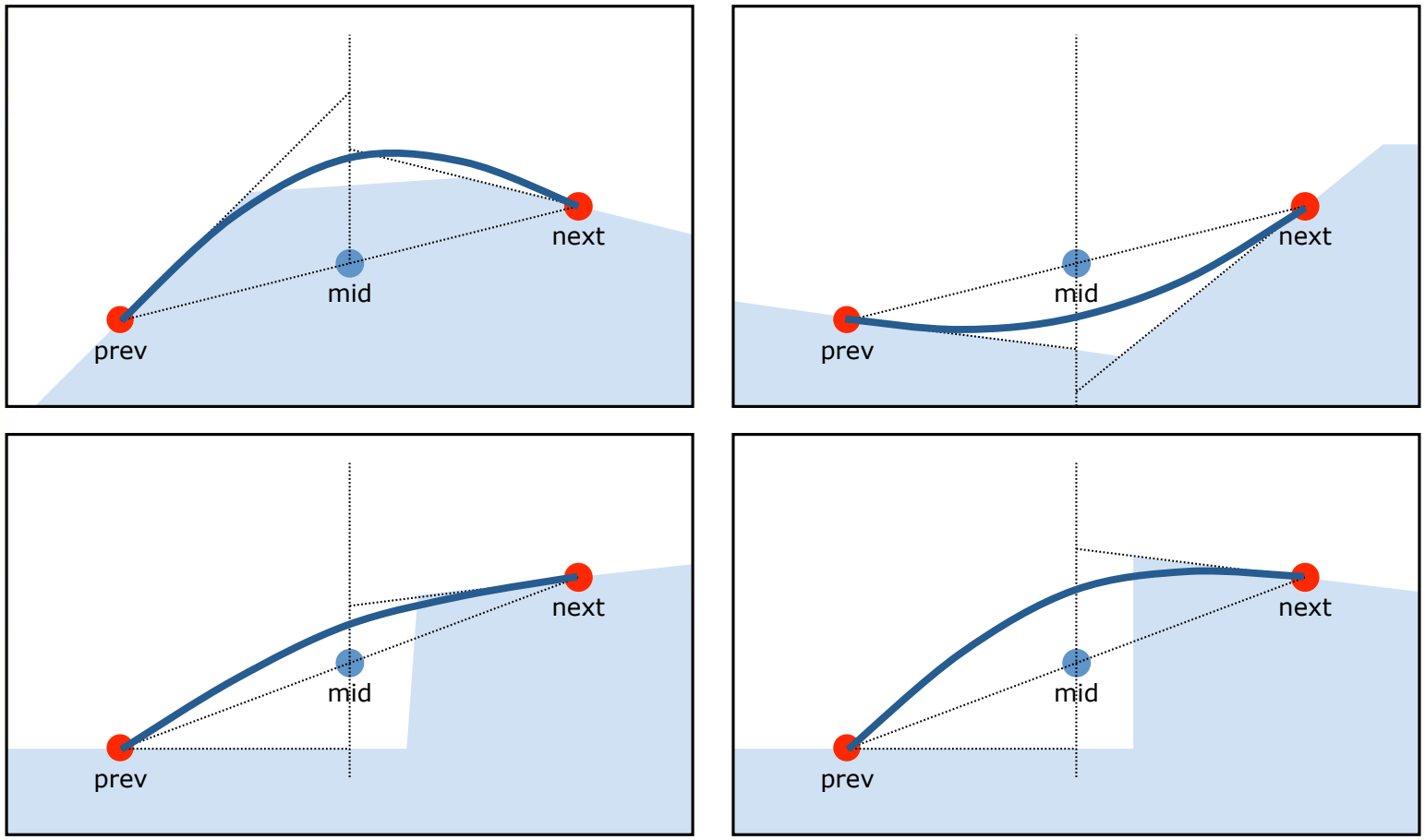
Vertical Lift Fitting the Terrain

- Use the height of the intersection point relative to the mid-point to determine the magnitude of an arc that is added to the footbase trajectory.
- The arc follow the “highest” tangent.



unity

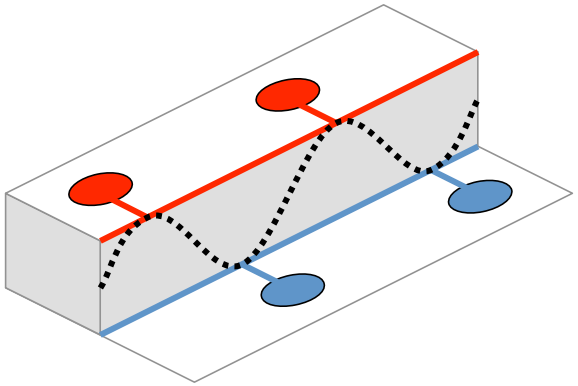
Vertical Lift Fitting the Terrain



(This is the base trajectory. The original lifting is later added on top.)

unity

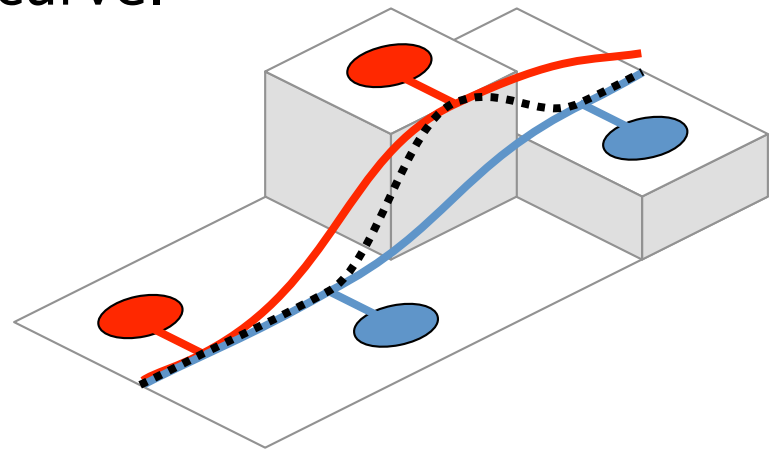
Lift to Height of Supporting Leg(s)



unity

Lift to Height of Supported Leg(s)

- Calculate "basis height" of character:
- For each foot, create a smooth curve going through the footprints.
  - Minus offset of stance position.
- Make weighted average of those curves:
  - Grounded feet have full weight.
  - Feet in mid-flight have almost zero weight.
- Measure the height at the current position on the curve.

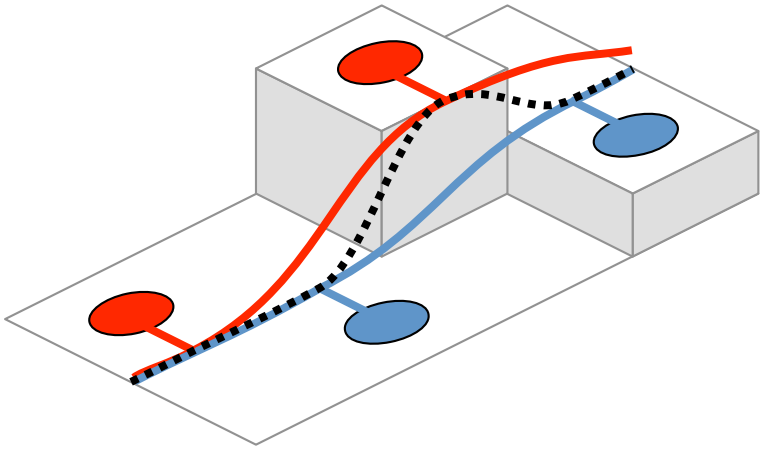


unity

Lift to Height of Supported Leg(s)

For each foot:

- If the basis height is higher than this foot while in flight, lift the foot up:
- From foot-off, lerp the lifting in until it has full influence at mid-flight, then back to zero influence at foot-strike.



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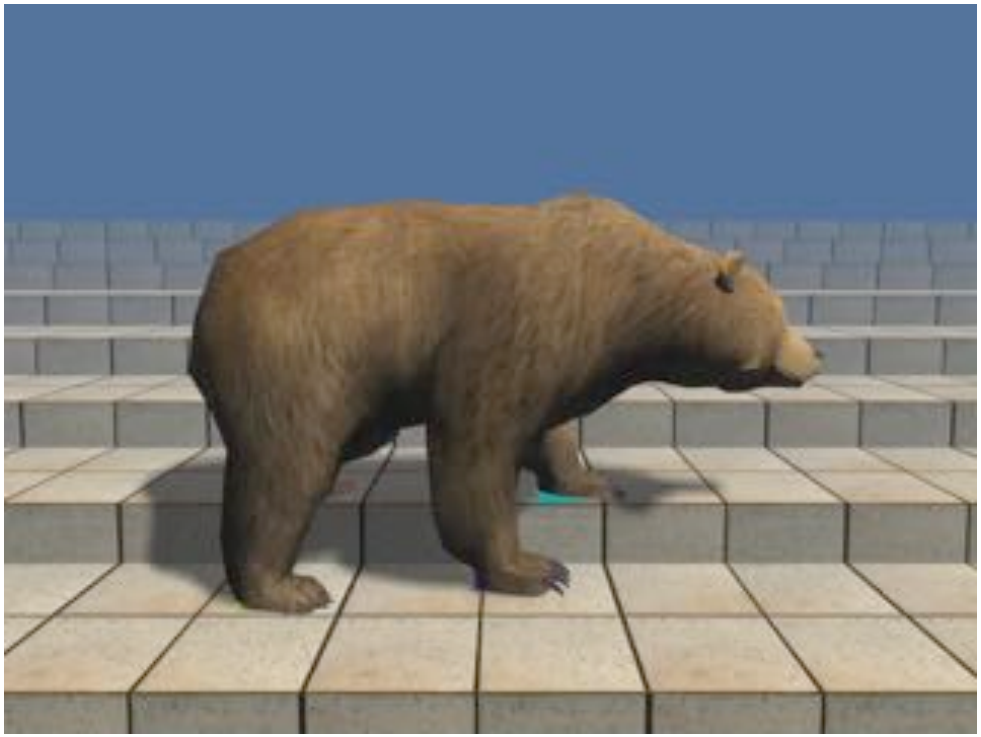
Lift to Height of Supporting Leg**(s)**



- Advantage:
  Does not assume specific number of legs

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Preserve Original Trajectories

- All the trajectory calculations so far were just to take uneven terrain and non-constant velocity / turning into account.
- (When walking on plain horizontal surface, they result in just a ***straight line*** trajectory for the footbase.)
- Now, add the ***normalized footbase trajectories*** (from the motion analysis) as additional offset.
- The style is preserved!

unity

Foot Alignment

- Now the footbase trajectories are calculated, but we still need to find good foot *alignments*
- Feet move differently on a flat surface than they do on e.g. stairs
- So alignment of feet cannot be used directly from animation data

unity

Foot Alignment

When the foot is flat on the ground:

- Keep original ***alignment relative to ground***.

When the foot is lifted in the air:

- Keep original ***ankle joint rotation***.

Transition smoothly between these two states.

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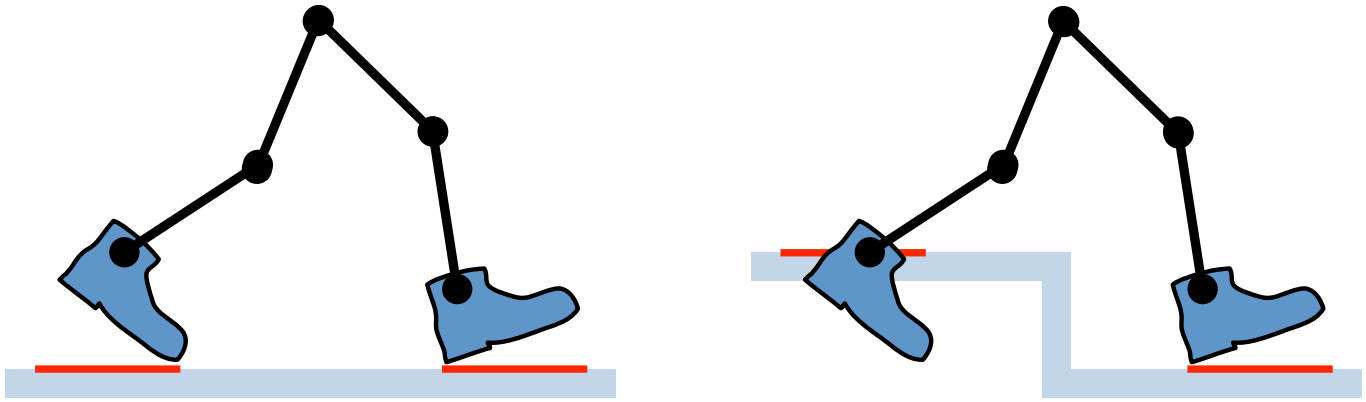
Foot Alignment

Pose in original motion

Adjusted pose at runtime



Need to have proper foot-roll on uneven terrain.

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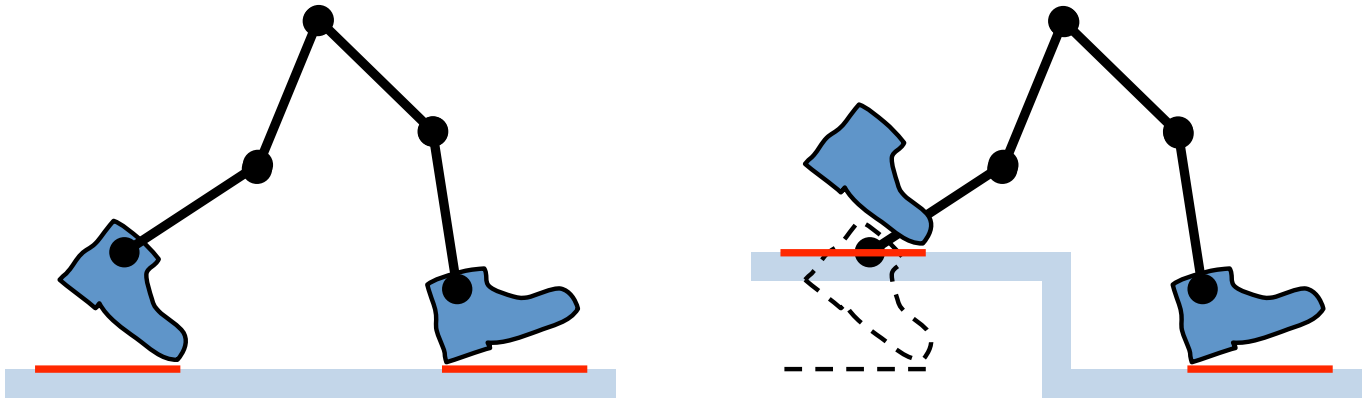
Foot Alignment

Pose in original motion

Adjusted pose at runtime



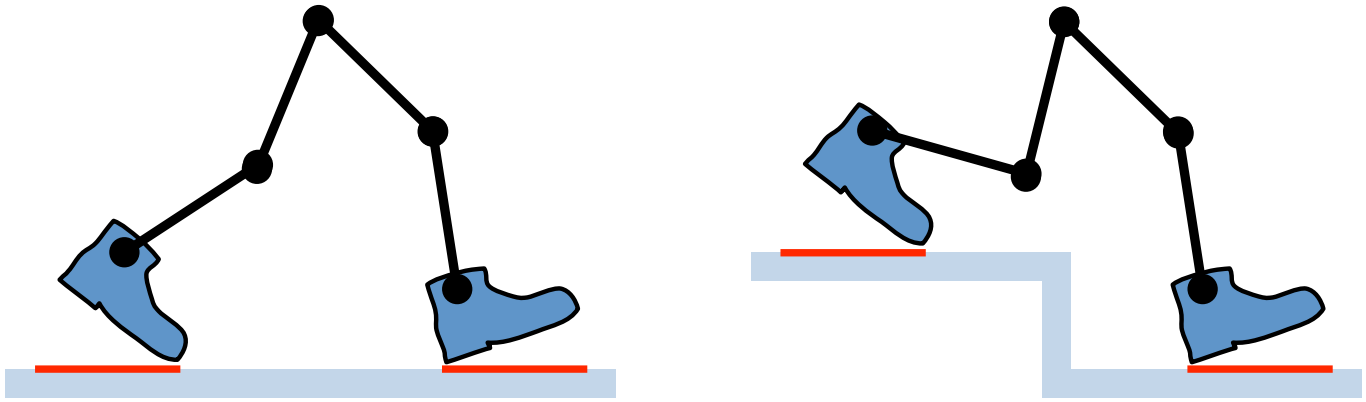
At runtime, move the foot to its footbase.

unity

Foot Alignment

Pose in original motion

Adjusted pose at runtime



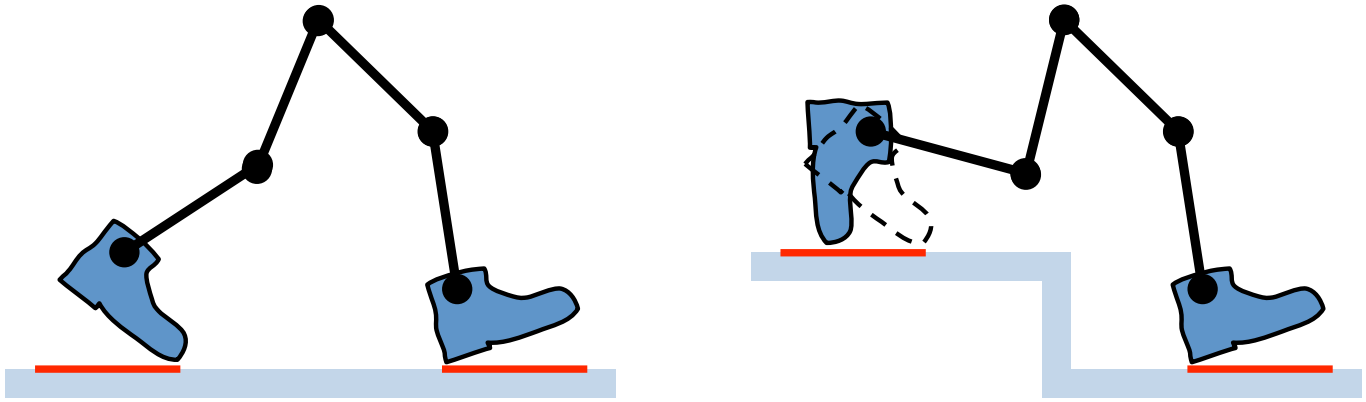
Use IK to get bone alignments between hip and ankle.

unity

Foot Alignment

Pose in original motion

Adjusted pose at runtime



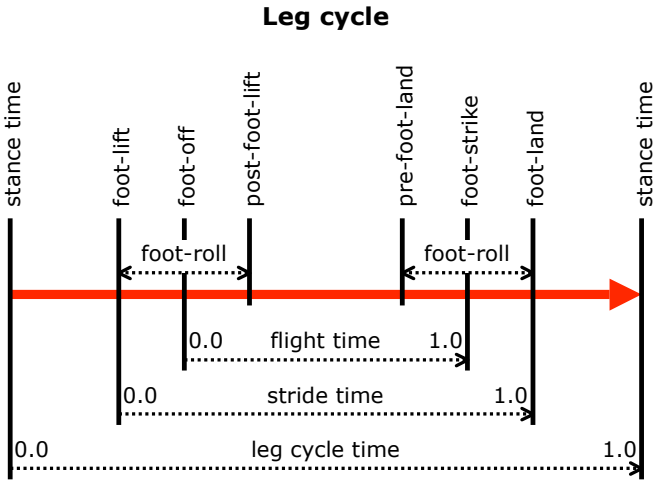
Apply the local rotation from the original motion at the ankle joint.

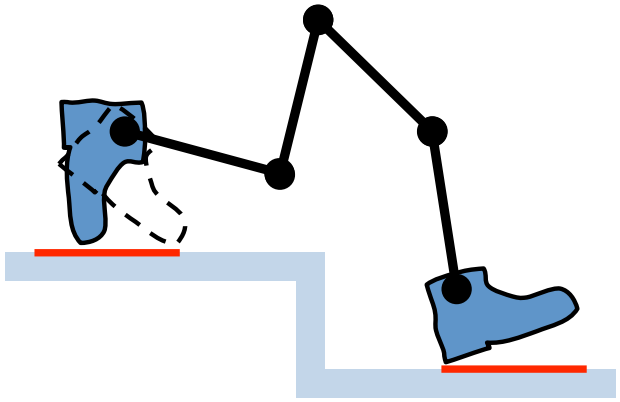
unity

Foot Alignment

Pose in original motion

Adjusted pose at runtime





Apply the local rotation from the original motion at the ankle joint.
(0% when grounded, 100% when in flight.)

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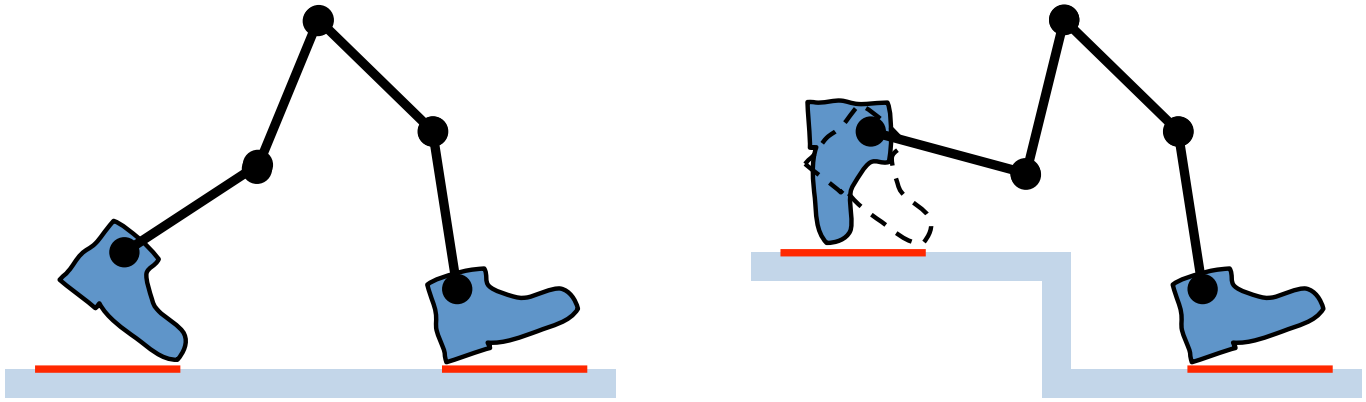
Foot Alignment

Pose in original motion

Adjusted pose at runtime



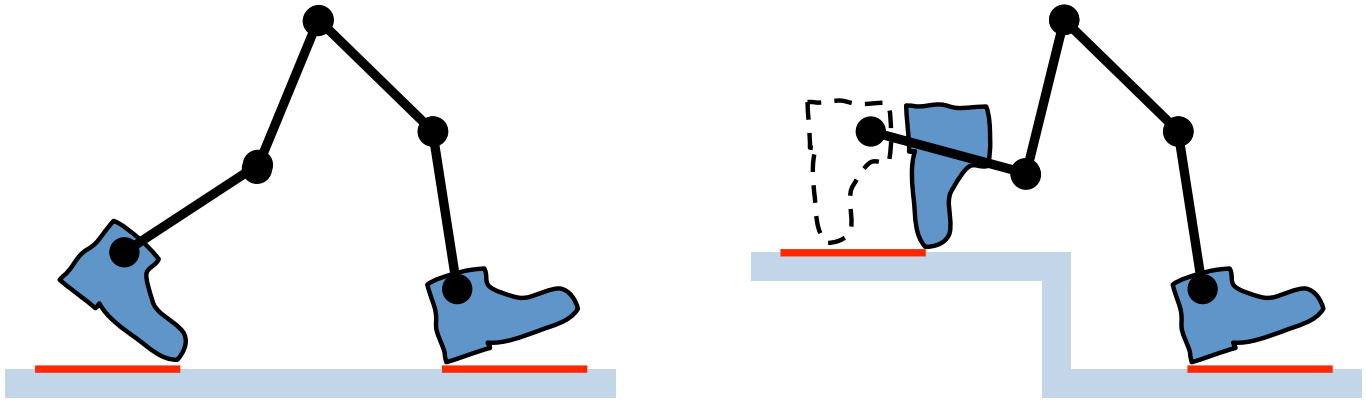
Apply the local rotation from the original motion at the ankle joint.
(0% when grounded, 100% when in flight.)

unity

Foot Alignment

Pose in original motion

Adjusted pose at runtime



Move the foot to its footbase again.

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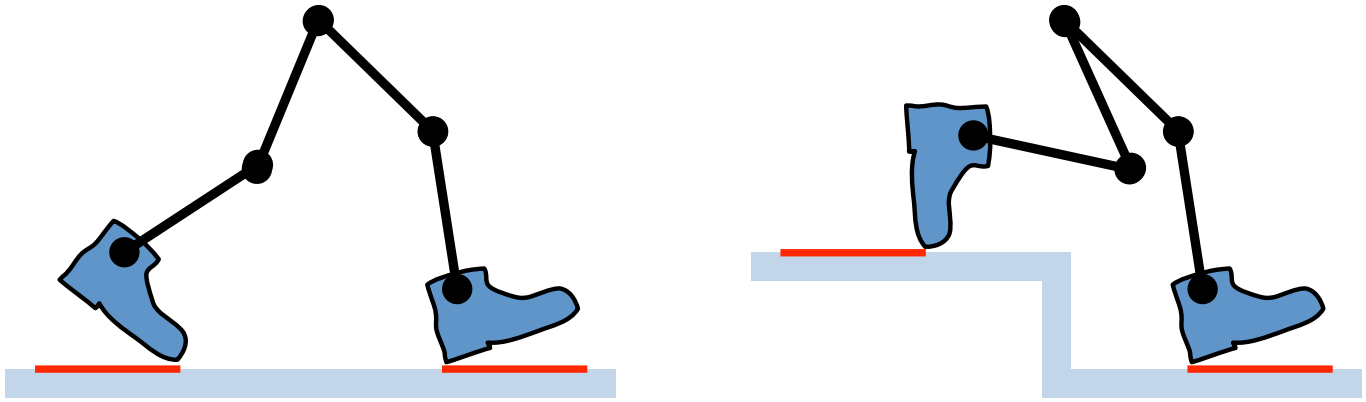
Foot Alignment

Pose in original motion

Adjusted pose at runtime



Use IK to get bone alignments between hip and ankle again.

Done. (Perform all steps in each frame.)

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Demo:
Adapted Foot-Rolls

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Starting and Stopping Walking

- Character may start or stop walking at any time
- Fixed key-framed transitions are not flexible
- Automatic transitions are desired

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Starting and Stopping Walking

- Walking and running is a continuous cycle where the feet touch the ground one at a time
- In idle animations both feet are grounded at the same time
- How to transition?

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Starting and Stopping Walking

- Each leg has its own *leg cycle*.
- Normally the leg cycles all turn around together with the overall motion cycle.
- But they ***can*** independently "stop turning" one at a time (or start).

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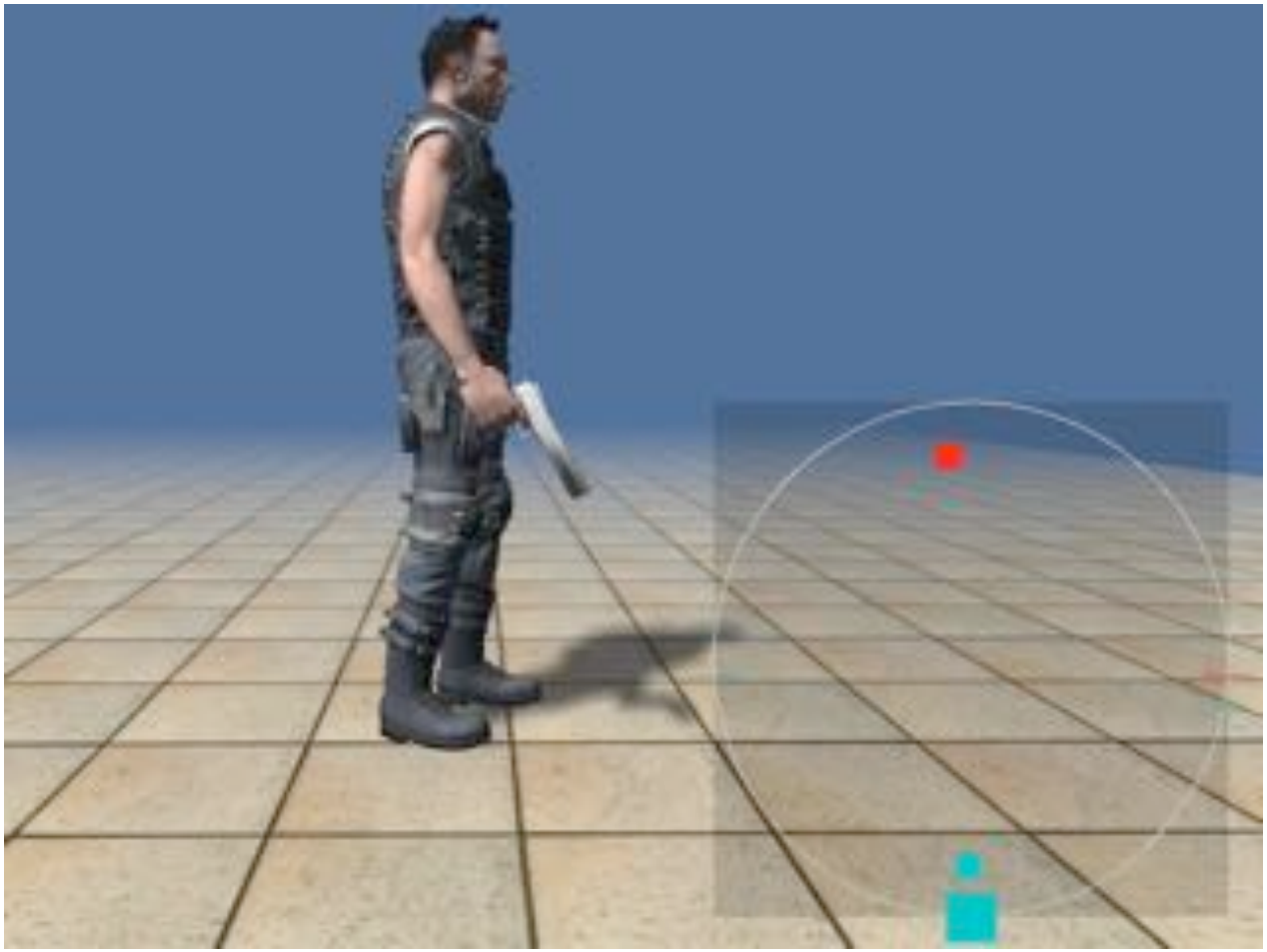
Starting and Stopping Walking

For each leg:

- If length of next step is below given threshold:
  - "Park" the leg cycle next time it reaches its stance time.
- If the leg is parked, and the next step is above given threshold:
  - "Unpark" the leg cycle the next time the "would be" leg cycle value passes the stance time.
- Maybe allow "catching up" to make mechanism less rigid.

unity

Demo: Automated Transitions



unity

Interface and Integration

How to *integrate* the system with other animation systems used in the game?

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Controlling Styles

- Blending of idle, walking, running animations is automatic
- But how to control *style*?

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Styles Through Animation Groups

- Animation Groups are collections of animations for locomotion.
- Each group contains up to several animations with the same style but with different velocities.
- Example:
  - Group “normal” - normal idle + walk + run
  - Group “sneaky” - sneaky idle + walk

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Animation Groups

- Each animation group can be controlled as if it was a single animation

```
animation["normal"].weight = 0.8f;
animation["sneaky"].weight = 0.2f;
```

```
animation.CrossFade("sneaky",0.5f);
```

unity

Current Limitation in Motion Types

3 types of motions

- **Walk / run cycles**
  - Walking / running with feet adjusted to uneven terrain
- **Grounded animations** (feet are not moving)
  - Feet still adjusted to uneven terrain below
- **Everything else**
  - Not directly supported at this point / feet not adjusted
  - But adjustments are gracefully (gradually) turned off
  - E.g. jumping: Adjustments turned off while in air

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Performance

Reference machine: 2.4 GHz Intel Core 2 Duo

Biped: 0.25 ms per frame

1 biped:	100 -> 98 fps	50 -> 49 fps
10 bipeds:	100 -> 80 fps	50 -> 44 fps

Quadruped: 0.55 ms per frame

1 quadruped:	100 -> 95 fps	50 -> 49 fps
10 quadrupeds:	100 -> 65 fps	50 -> 39 fps

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Many Characters

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Many Characters

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Quadrupled animal models

(coyote, grizzly bear, wolf)

courtesy of WolfQuest.org

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Thank you!

Questions…?

- …

- Email: rune@unity3d.com

Resources

- Locomotion System for Unity
  unity3d.com/support/resources/
- Unity Game Engine
  unity3d.com
- The Master Thesis behind the system is coming soon…
  runevision.com/multimedia/

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