Artist-Directed Dynamics for 2D Animation

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Abstract

Animation artists enjoy the benefits of simulation but do not want to be held back by its constraints. Artist-directed dynamics seeks to resolve this need with a unified method that combines simulation with classical keyframing techniques. The combination of these approaches improves upon both extremes: simulation becomes more customizable and keyframing becomes more automatic. Examining our system in the context of the twelve fundamental animation principles reveals that it stands out for its treatment of exaggeration and appeal. Our system accommodates abrupt jumps, large plastic deformations, and makes it easy to reuse carefully crafted animations.

Keywords: simulation, animation, deformation

Concepts: Computing methodologies $\rightarrow$ Physical simulation;

1 Introduction

Animation is the art of timing and spacing. Timing determines the beat, rhythm, and tempo of motion: a large, heavy, hard ball falls with a thud, its timing between each bounce decreasing rapidly; a small, light, soft ball springs across the screen, its timing almost constant in comparison. Given the timing of key events and extremes, the spacing determines the movement and deformation in frames between the keys. At the top of its arc, the ball slows down so its spacing in nearby frames reduces (overlaps) until it falls down again, gaining speed and traversing more space on every frame. Both elements have profound effect on the final appearance. Slower timing transforms a nervous finger tap into a sluggish pensive motion. Different spacing can remake a simple up-down elevator motion into either a bouncing ball–slowing down at both the top and the bottom. Great animation requires both great timing and great spacing.

Timing is a global property and spacing is a local feature. This dichotomy complicates all systems that must control the two. Consider two classical workflows in hand-drawn animation: straight-ahead and pose-to-pose animation. Straight-ahead animation proceeds locally from one frame to another. Pose-to-pose animation maps out the most important key poses first, before breaking them down into extremes and other salient poses (e.g., passing positions). Each system has advantages and disadvantages. Straight-ahead induces creativity with fluid and natural action but timing can begin to drift and wander. Pose-to-pose crystallizes the timing but the action can become choppy and unnatural. This same tension reappears in modern workflows with simulation and keyframing. Simulation, like straight-ahead animation, sequentially propagates initial values to subsequent frames. Keyframing, like pose-to-pose, breaks down extremes into corresponding inbetweens. Simulation will deliver frame-to-frame realism but the end result may not be at the right place at the right time. Keyframing will keep key events and extremes at the right place and time but the inbetweens may not flow together.

Naturally, a combined approach can be more effective than either extreme. In hand-drawn animation, the recommended hybrid workflow begins with pose-to-pose planning. But then, instead of breaking down these extremes with passing poses, it uses straight-ahead animation to fill in and improvise between global, pose-to-pose placeholders. After one pass, the process repeats, each refinement adding more detail to the previous structure. In modern animation systems, the combined simulation and keyframing workflow is less settled. Some solutions, like pose-to-pose workflow, focus on timing by seeking simulations that place objects with the right timing [Witkin and Kass 1988]. Others, like straight-ahead workflows focus on spacing by driving simulations towards planned keys and poses [Popović et al. 2000].

Our animation system formulates a fluid workflow allowing artists to use both keyframes and simulation. When simulation needs guidance, the artist adds keyframes to nudge it to the desired path. When keyframes stifle lively action, artist lets the simulation act instead. At the core, each frame is simulated, but each simulation step incorporates the artist’s examples and trajectories. Examples guide the spacing by exaggerating or suppressing deformation, or both, on different parts of the object. Trajectories command the timing by prescribing it for the entire object, some of its parts, or none at all. Simulation fills in each unspecified part with naturalistic animation.
2 Related Work

Physically-based animation methods employ simulation to automatically displace and deform objects in a lifelike way. Rigid bodies move according to their masses, velocities and imposed forces; elastic objects further deform according to internal energy and can be modeled with reduced coordinates, e.g., frame-based degrees of freedom (DOF) [Gilles et al. 2011; Faure et al. 2011]. In contrast to keyframing, physical modeling frees the animator from manually constructing naturalistic motions, e.g., easing in and out of each pose, but since these are fundamentally initial value problems whose outcome is determined at start of time, creative control of resulting animation is challenging at best: one must somehow optimize or infer simulation parameters that yield the desired outcome [Popović et al. 2000; Chenney and Forsyth 2000; Twigg and James 2007; Ha et al. 2013].

Example-based simulation addresses this critical limitation by allowing simulated elastic objects to be augmented with examples of desirable deformations [Martin et al. 2011; Schumacher et al. 2012; Koyama et al. 2012; Coros et al. 2012; Jones et al. 2013]. These methods then attract the motion towards examples with dynamic but less controllable minimization of deformation energy. Animators think and act with visual examples and thus example-based dynamics is a better animation tool than a physically accurate simulation. However, animators often create keyframes not achievable by elastic deformations of a single shape [Lodigiani 2013]. These frames cannot be used in existing example-based techniques.

Animators enjoy the benefits of simulation but do not wish to be blocked by its constraints. Consider, for example, Chuck Jones’s classic Road Runner characters that pause in midair before pouncing, or stretch into a dramatically different shapes as they move [Lodigiani 2013]. For the seamless creation of the full range from plausible [Barzel et al. 1988] to cartoon physics scenarios, we need to enable beyond-physical exaggeration and allow for the artist’s natural desire to impose additional control simultaneously on both timing and spacing.

The variational approach of spacetime constraints provides an optimization framework for controlling physically based simulations [Witkin and Kass 1988]. At their best, this family of methods delivers a high-powered pose-to-pose solution that animates automatically, given the timing of key events and the spacing of physically based simulation. The long-term challenge has been to realize robust and fast space-time solutions. Towards this goal, works have explored the benefits of approximate dynamics [Liu and Popović 2002; Kass and Anderson 2008; Barbič et al. 2012; Hildebrandt et al. 2012], and approximate optimization [Popović et al. 2000; Chenney and Forsyth 2000; Twigg and James 2007].

In seeking interactive control over timing we turn to the greedier formulation of constraint-based dynamics. Barzel and Barr [1988] introduced this approach for driving rigid-body dynamics, coining the term dynamic constraints in contrast to the variational method of spacetime constraints. Recent works have adapted dynamic constraints for thin-shell simulations [Bergou et al. 2007] and further integrated it with traditional rig-based systems [Hahn et al. 2012]. All three papers have pioneered new workflows for combining keyframing and simulation. Our work goes further by allowing stylized shape transitions between different topologies and parameterizations. We also introduce an approach for reusing simulation (or their parts) on another shape. Instead of tweaking parameters, animators can now copy-paste simulations from one shape to another. Deformation Transfer [Sumner and Popović 2004] delivers this operation for static deformation, but not dynamic simulation. We show how to integrate example-based simulation, dynamic constraints, and deformation transfer in an animation system that delivers automation and enables stylization.

3 Methods

We construct a novel, interactive, physics-based tool to create animations with an intuitive example-based workflow. Here we present the pieces that together form a simple-to-use, handle-focused interaction tool where timing and shape are directly controlled by the artist and simulation fills in remaining degrees of freedom interactively. In addition to keyframes, artists can use examples to attract simulation, or to guide it through extreme artistic transitions. When desired, final results can be reused on another shape, simultaneously preserving the motion and adapting to new geometry.

Workflow A typical session begins with a set of artworks that are then equipped with handles. Handle locations determine the triangulation and define the rigging of artwork meshes. Artwork layers are then additionally attached, if desired, by setting positional constraint correspondences between handles. For timing control, per-handle keyframing begins the roughing out of an animation. Interactive preview of the current animation is then available at all times. To further embellish the animation, artists can add example shapes by editing existing artworks and so support desired deformation via example-based simulation. If a desired animation is not realizable by a smooth deformation of an artwork mesh, new artworks are imported, and handle and/or vertex correspondences are set by direct selection on the meshes. With correspondences in place, artist-directed shape transitions are generated to map between artworks and enable exaggerated, physically based animation. Finally, artists can copy and paste to retarget animation from one artwork to another by selecting desired regional correspondences between the two.

3.1 Background

We begin with a set of artworks each given as an arbitrary subregion \( \Omega \in \mathbb{R}^2 \) discretized as a triangle mesh with \( n \) rest pose vertices \( x_i \in \mathbb{R}^2 \) and corresponding deformed vertices \( x_i \).

**Linear Blend Skinning** We equip each artwork mesh with control handles and corresponding affine transforms \( T_j \). The deformation map from handles to mesh vertices is completed by skinning weights \( \alpha_{ij} \in \mathbb{R} \) specifying the influence of each handle \( T_j \) on vertex \( x_i \). Linear blend skinning (LBS) deformation of mesh vertices
Vectorizing the affine transforms $t_j = \text{vec}(T_j)$ and concatenating give us handle state $t = (t_1^T, ..., t_m^T)^T$ per artwork. Concatenating vertices as $x = (x_1^T, ..., x_n^T)^T$ we then define the LBS map equivalently in matrix-vector form as

$$x = Ut. \quad (2)$$

**Variational Time Stepping** Time stepping to state at time $t$ with implicit Euler can be cast in variational form (see e.g., Martin et al. [2011]) by minimizing the incremental potential

$$\min_{x'} \frac{1}{2\tau^2}(x' - x^p)^T \tilde{M}(x' - x^p) + \sum_k E_k(x') + \sum_i f_i^T x', \quad (3)$$

where $x^p = 2x^{t-1} - x^{t-2}$ is a predicted state, $\tau$ is timestep size, $\tilde{M}$ is the discretized mass matrix, $E_k$ are internal forces, and $f_i$ are external forces, such as gravity. Stationarity of (3) with standard elastic energies in $E_k$ is equivalent to standard implicit Euler equations of motion. However, as we can add arbitrary energies to the incremental potential, the variational form enables a simple, flexible and easily generalizable framework for artist-directed dynamics.

### 3.2 Timing Control

Artists should be able to easily control the timing of any spatial region, in any subset of frames, with an arbitrary trajectory. We then want simulation to promptly fill in any unspecified portions of trajectory with physically plausible motion. In setting keyframes, artists should not need to concern themselves with physical limitations, mesh connectivity or unnecessary restrictions on their ability to set partial keyframes. Control of timing in animation should thus be intuitive, interactive and sparse as desired.

For usability we project our dynamics directly onto a reduced LBS handle space. Forming a reduced dimensional time stepper in the handle subspace enables artists to employ a small number of handles to rig, control, simulate and, as we will see later in Section 3.4, retarget animations with a consistent low dimensional representation. To project dynamics onto the handle subspace we construct the reduced variational time stepper utilizing (2) to get

$$\min_{t'} \frac{1}{2\tau^2}(t' - t^p)^T \tilde{M}(t' - t^p) + \sum_k E_k(Ut') + \sum_i \tilde{f}_i^T t' + \sum_p f_p(t'), \quad (4)$$

where $t^p = 2t^{t-1} - t^{t-2}$ and reduced mass and external forces are given by $\tilde{M} = U^T MU$ and $\tilde{f}_i = U^T f_i$ respectively.

With reduced dynamics in hand, the variational stepper (4) now includes energies $E_p$ directly on handles. We will use these handle energies as our means of directing dynamics. For example, to enable arbitrarily sparse timing control of keyframes in space and time, we simply add, per timestep, soft constraint potentials

$$E(t') = \frac{1}{2} \sum_i \beta_i \|t'_i - k'_i\|^2, \quad (5)$$

to the stepper energy (4) where $k'_j$ is a desired handle value at time $t'$ for handle $j$ specified by the artist with weighting strength $\beta_j$. We will include other potential energies in $E_p$ later in this section.

### 3.3 Artist-Directed Shape Transitions

As with timing, artists should likewise be able to directly control the deformation shapes generated by simulation in (4). Example-based simulation [Martin et al. 2011; Koyama et al. 2012; Coros et al. 2012; Bouaziz et al. 2014] constructs elastic materials drawn to rest subspaces formed from artist provided poses. Dynamics are then attracted to the nearest shape in the subspace at each timestep rather than a single rest shape. Example-based materials are a natural and intuitive starting point for our system as they allow artists to drive deformation dynamics by simply creating artwork examples.

Starting with a base rest-pose mesh $\bar{x}$ and a set of additional rest shape artworks $x^k, k \in [2, e]$ deformed from $\bar{x}$, an example manifold $\mathcal{E}$ of realizable shapes is constructed. We start with a standard elastic potential $E_l(x, \bar{x})$ that is attracted to a single rest shape $\bar{x}$. The corresponding example-based elastic energy that attracts instead to the closest rest shape in the example manifold is then

$$E_E(x) = E_l(x_w, x) \quad \text{s.t.} \quad x_w = \arg\min_{x \in \mathcal{E}} \|x - \bar{x}\|^2. \quad (6)$$

**Example Manifold in Handle Space** We construct our example manifold directly in handle subspace to continue to enable animation manipulation and creation directly on handle DOFs.

For each example pose $x^k$ of an LBS rigged artwork, we have the corresponding handle state $t^k$ and interpolation weight $w^k \in \mathbb{R}$. Identifying $x^k = $ $\bar{x}$ and recalling the LBS subspace construction, the blend shape $x^E \in \mathbb{R}^{2n}$ in the example manifold at $w = (w^0, ..., w^e)^T$ is simply

$$x^E(w) = U \left( \sum_{k=0}^e w^k t^k \right), \quad (7)$$

so that the blend-shape handle rig is correspondingly

$$t^E(w) = \sum_{k=0}^e w^k t^k. \quad (8)$$

The handle-space, example-based energy is then simply minimization on weights $w$

$$E_E(t^k) = E_l(x^E(\alpha), Ut^k) \quad \text{s.t.} \quad \alpha = \arg\min_{w} \|U(t^k - t^E(w))\|^2, \quad x^E(w) \in \mathcal{E}. \quad (9)$$
Example-Based Materials and Transition Maps

While an example-manifold enriches the range of animations we can create with simulation, we observe that artists quickly run up against the barriers imposed by a single example-based elastic-material. Simulated example-based materials capture a wide range of deformations but can not realize shapes that are not realizable by a smooth deformation of the rest-pose mesh. Artists, however, naturally explore and would like to enrich simulations with arbitrarily shaped artworks to support jumps over topology changes and often large exaggerations. On the other hand, artists also have a clear sense of how correspondences should be maintained between shapes across such large jumps.

To support the artist’s inclination to create keyframe artworks with arbitrary exaggerations, we extend example-based simulation with a transition map. Artists can now construct a set of example-based manifolds \( \{A, B, C, \ldots\} \) each from an independent artwork with a possibly varying topology and/or handle rigging. We treat each example-based manifold as a single deformation family of shapes that can be derived from one another using provided handle rigging. We then define transition mapping between these disconnected manifolds that are otherwise unreachable from one another due to rips, differing handles, or extreme deformations.

Each deformation family \( A \) can have its own unique mesh topology, vertices \( x^A \) and handle rigging \( t^A \). Our system then requires the artist to specify a correspondence across the rest shapes of the deformation families by matching a subset of handle-to-handle parameters (e.g., position, rotation) with \( \Omega_{(A,B)} t^A \leftrightarrow \Omega_{(B,A)} t^B \) and/or vertex-to-vertex correspondences with \( \Psi_{(A,B)} x^A \leftrightarrow \Psi_{(B,A)} x^B \). For example in Figure 2, the correspondence between the rest shape of a square and the rest shape of a “crocodile” is specified by pairs of handles (illustrated with the same number).

Given current state \( t^A = t^t \) in the current deformation family \( A \), we maintain a time varying closest shape correspondence to each family \( B \) by weighting the least squares correspondences with the elastic energy of the example-based material \( B \) given by \( E^B_k \). The handle configuration \( t^B \) that realizes this closest point shape in \( B \) is then a transition candidate and is found at each timestep by

\[
t^B = \arg \min_t \left\{ \left\| \Omega_{(A,B)} t^A - \Omega_{(B,A)} t^B \right\|^2 + \left\| \Psi_{(A,B)} U^A t^A - \Psi_{(B,A)} U^B t^B \right\|^2 + \lambda E^B_k (U^B t^B) \right\} = \mathcal{K}_{(A,B)} \mathcal{M}_{(A,B)} t^A + \mathcal{S}_{(A,B)} \mathcal{M}_{(B,A)} U^B t^B,
\]

where we set \( \lambda = 10^{-2} \) to weight shape correspondence against internal deformation energies.

An artistic transition from current example material \( A \) to \( B \) is then applied if the transition is candidate minimizes internal energy over all possible deformation families so that

\[
E^B_k (U^B t^B) < E^A_k (U^A t^t)
\]

and

\[
E^B_k (U^B t^B) \leq E^C_k (U^C t^C), \quad \forall C.
\]

Upon transition we update state with \( t^t \leftarrow t^B \) while the velocity-like term \( t^B = 2t^t - t^{t-1} \), required for time stepping with the variational solve of (4), is updated to the new deformation family using the previously computed candidate transitions to \( B \) from the last two time steps. Observe that we have constructed our transition to a new family if the deformation energy strictly decreases and so effectively have found an improved representation for deformation in the new family. This formulation is reminiscent of strategies employed in variational adaptive remeshing [Mosler and Ortiz 2007] where a similar metric is applied to argue when a jump to a new basis is warranted by better minimization of deformation energies.

3.4 Simulation Copy and Paste

Iterating to a complete, satisfying animation will always take time and effort. While our system so far enables the rapid design, edit, and refinement of animations, we also wish to be able to copy and paste carefully crafted motions to new artworks.

We propose “copy-and-paste physics” to enable this easy transfer and reuse of artistic assets. The first step is to create the desired correspondence between source animation artwork and a target asset artwork. As in artistic transitions there are many possible and often equally desirable correspondences available between artworks. We currently support an interactive tool that allows artists to guide and explore various copy and paste correspondences.

Here again handle level DOFs and LBS subspace provide a quick and intuitive interface for creating and working with correspondences between artwork assets. Artists select corresponding handles between artworks and then set thresholds for the blend weights to define region-to-region correspondences. For example in Figure 3, to copy and paste from a cat to a squirrel, we select one handle at the middle of the cat body and set the weight threshold to 0.4. All vertices with weight greater than 0.4 in the cat body are automatically selected (illustrated as the green region).

With regional correspondences completed we can copy and paste with a TRACKS [Bergou et al. 2007] constraint to enforce region-to-region centroid matching between source \( S \) and target \( T \) artworks. The handle-space TRACKS constraint to match centroid of target artwork to the centroid of a source animation per user specified regions \( K \) is then

\[
 ge(t) = ||S^k_M S^k t^k - S^k_M T^T U^T t||,
\]

where \( S_K \) is the selection matrix that extracts the \( r \) vertices in region \( K \) and \( M \) is the Petrov-Galerkin mass matrix [Bergou et al. 2007] computing the weighted average.

However, when the scales of source and the target objects vary, target objects will be undesirably stretched and squeezed by centroid translation constraints alone. Moreover, the translation of a centroid does not fully describe nor prescribe the deformation of corresponding regions. We demonstrate these issues in Figure 4 (center panel) and observe that constraining centroid translation alone can not and will not induce a similar deformation to the source.

We require additional, readily available constraints on the local deformation to make the constraint mapping robust between disparate
shapes. For each correspondence region $K$, we find a close-as-possible affine map $A_K$ that deforms the rest shape $x^S$ of the region to its current shape:

$$\min_{A_K} \|A_K \Delta(x^S) - \Delta(x^S)\|^2,$$  

where the matrix operator $\Delta$ composes column-wise per vertex in region $K$ with the vertex to centroid difference $\Delta(x) = [x_1 - c_k(x), \ldots, x_r - c_k(x)]$, where $c_k(x)$ gives the centroid of region $K$.

The corresponding constraint to match the transform in the target is then

$$h_k(t) = \|A_K \Delta(Ut^T) - \Delta(Ut^T)\|.$$  

For direct copy and paste while simulating, we construct and add the corresponding constraint penalty energy

$$E(t) = \frac{1}{2} \sum_k (\gamma_k g_k(t)^2 + \eta_k h_k(t)^2)$$

simplifies to a quadratic program (QP) in the projection

$$E_k(t^i) = E_I(x^E(\alpha), Ut^i)$$

$$s.t. \alpha = \arg\min_{w} \sum_{(i,j)\in\text{edges}} \|B_{i,j}(t^i - \sum_{k=0}^{e} w^k t^k)\|^2,$$

where $B_{i,j} = [S_j - S_i] U$, the matrix $S_i$ gives the $\mathbb{R}^{2 \times n}$ selection that extracts vertex $x_i \in \mathbb{R}^2$, and the bound constraints in the QP ensure that example blend shapes lie within the convex hull of the example domain. We further approximate the QP with Koyama et al.’s [2012] boundary projected solution in which smallest negative weights are iteratively eliminated by zeroing and an even redistribution among remaining weights. While a fully optimal bounded QP solution would be a simple extension we found the boundary projected solution sufficient in all our tests.

### 4 Results

Artist-directed dynamics delivers the benefits of both keyframing and simulation. We first demonstrate the features and workflows of our system for artistic creation. We then use the Twelve Principles of Animation [Thomas et al. 1995] interpreted by a professional animator [Lodigiani 2013] to evaluate the system from each perspective: (1) how keyframing enhances simulation and (2) how simulation enhances keyframing.

#### 4.1 Artistic Creation

We use the following five different scenarios to demonstrate the process of artistic creation using our system and showcase the main features of our method: handle control, example-based dynamics, artist-directed shape transition, and simulation copy and paste. Please see the accompanying video for the resultant motion.

**Articulated Figure.** First, we demonstrate that our method applies to articulated characters (Figure 5). We create a walking cycle by keyframing the handles at the hands and the feet of the articulated character, as shown in Figure 6 (nine keyframes per walking cycle). We demonstrate a variety of ways to enrich the simple walking cycle, such as changing the physical properties of the character, modifying the spacing and timing of the handles, or adding examples. For example, we delay the motion of the head by keyframing the handles on the head differently (Figure 1 (a)), or create a “sad” walk and a “sneaky” walk by using example poses (Figure 1 (b)).
mainly due to physics simulation, such as the responsive motion on the bottom part of the ball. The motion of the other part of Sam is legs of Sam so that the legs stretch and squash in a similar way as by physics. We also copy and paste the motion of the ball to the motion of the other parts of Lola such as legs and head are governed the bouncing ball to the ball on which Lola sits. The reactive motion of new characters: Lola and Sam. We copy and paste the motion of simulation copy and paste, we reuse the simulation results on two and squash example poses and set the keyframes on top and bottom stretch out before contacting the ground. To do so, we add stretch and squash more when it is in contact with the floor. To accentuate the height of the floor in the particle simulation. This change makes the motion of the bouncing ball accordingly. For example, we increase the velocity, and coefficient of restitution, we achieve different motions simply adjusting the simulation parameters, such as initial height, governed by the physical simulation and contact constraints. By controlling speed with keyframes; or, when more convenient, by adjusting needs to refine precisely, our technique allows an artist to control speed with keyframes and corr. The timing and spacing principle. As shown in the accompanying video, the results are shown in Figure 8 and the accompanying video.

4.2 Evaluation

Our system is designed for limitless customization. We try to explore this range comprehensively in context of the Twelve Principles of Animation. To do that objectively, we attempt to recreate animations of the ten relevant animation principles, which were independently created by another animator [Lodigiani 2013]. The animations of the ten relevant animation principles, which were independently created by another animator [Lodigiani 2013]. The results are shown in Figure 8 and the accompanying video.

Timing and Spacing. The dramatic impact of careful speed customizations can be seen in the animation that illustrates the timing and spacing principle. As shown in the accompanying video, the large box moves in different timing and spacing to give the animation a different feel, such as “punch” and “push”. In our approach, both the timing and spacing can be controlled precisely and directly by specifying trajectories for some subset of handles.

Slow In Slow Out. Slow-in and slow-out, another physically inspired principle, emerges automatically as simulated objects move in response to external forces and collisions. The slow-in slow-out spacing on one of the boxes creates the illusion of faster arrival in addition to making that box appear heavier. When that movement needs to be refined precisely, our technique allows an artist to control speed with keyframes; or, when more convenient, by adjusting the mass, coefficients of friction, and other simulation parameters.

Figure 6: Keyframes used in the articulated character walk example. The artist only specifies keyframes for a subset of handles (handles at hands and feet) which are shown as blue dots. Nine keyframes are used to create a walking cycle. Their timing is visualized by the black lines at the bottom. The artworks are adapted from Angryanimator.com (http://www.angryanimator.com/).
Figure 7: Illustration of retargeting a cat’s trunk and limb motion to a squirrel and a rabbit. The artworks are adapted from The Catterwall (http://thecatterwall.tumblr.com/) and Cartoon Animation [Blair 1994].

**Squash and Stretch.** Elastic simulation produces squash and stretch automatically. One can modify simulation properties to adjust these deformations, but as already observed that indirect approach can fall short of typically desired customization [Martin et al. 2011]. Furthermore, as seen in animated cartoons, even the elastic model may not be appropriate for some squash-and-stretch animation. This can be easily seen in the corresponding interpretation of squash-and-stretch, where the amount of deformation necessitates plastic instead of elastic deformation. In this example, we recreate the extreme squash and stretch effect, by repeatedly expanding and compressing handles at the top and bottom.

**Anticipation.** Preparing for action requires planning instead of simulation. Proper anticipation arises only when simulation is paired with control or corresponding (spacetime or dynamic) constraints. Our system adapts dynamic constraints, allowing the simulation to track trajectories that induce desired anticipation. We illustrate this principle using a square rotating about one corner. We set the orientation constraints on the bottom handle to turn the square back and forth at the beginning in preparation for the final tumbling.

**Follow Through and Overlapping Action.** Analogous to the earlier squash-and-stretch example, simulation yields movement with realistic follow through but without the control needed for further customization and exaggeration. Overlapping action then synchronizes deliberate and often keyframed actions, which initiate the movement, with the follow-through and other reactions that appear in response. We show how our system supports this synergy by emulating sample animation for the corresponding principle. First, we exaggerate the drag with a pin constraint, delaying the action at the top of the rectangle. As the animation progresses, we release the constraint allowing the elastic simulation to take over and recreate corresponding follow through. The initial movement, drag, and follow through can all be further customized either with existing or new constraints.

**Secondary Action.** Simulation is routinely used to add secondary animation automatically. Our system improves on this process with simpler synchronization of primary and secondary actions. In this example, the larger box follows the motion similar to the anticipation example, and we embellish it with the secondary action where the smaller box bounces on its top. The contact force between the big and small boxes is scripted. After the small box bounces twice, we constrain the two bottom corners of the small box so it stays on the big box. The animation of each box can be further refined and adjusted leaving it to constraints to maintain proper synchronization.

**Arc.** Most natural actions tend to follow arc trajectories. The handle trajectories in our system make it possible to express arc paths directly, as shown in the corresponding example. The arc motion for the top and bottom handles initiates the square-to-arc transformation, but because this transition is not a purely elastic deformation, our system also incorporates the arc as another example and uses our artistic transition method to create smooth transitions between these two examples. As one handle drags behind the other, the simulation transitions from square to arc automatically, and when they come back together, the simulation reverts back to the square.

**Exaggeration.** The need to jump to any example is most apparent in the illustration of the exaggeration principle. We refer the reader to the crocodile example described in Section 4.1.

**Straight Ahead and Pose To Pose.** Straight ahead and pose are the two classical animation workflows with complementary benefits and drawbacks. Pose to pose makes it easier to plan out timing, but the result may end up too choppy. Straight-ahead workflow leads to fluid animation, but the timing can wander and drift. We observe similar pros and cons with simulation and keyframing. A straight-ahead simulation of a box fails to catch the small box at the right time and the right place, while pose-to-pose keyframed animation looks too stiff without natural reactive motion. As with the two classical workflows, the hybrid approach leads to a better workflow in our system: one begins with keyframed trajectories with desired timing, and then refines animation either by removing the trajectories, so that simulation fills in fluid motion, or by adding trajectories to constrain simulation as needed.

**Appeal.** The goal of this principle is to establish a connection between the viewer and the animation. The simulation copy and paste feature of our system makes it easier to experiment with different appeals. An artist can draft first animation on a simple geometry,
then transfer it to another when seeking to improve appeal. As an example, we retarget the motion of a bouncing square onto Lola, a girl character from a popular story book. The correspondence is established by relating the regions around the handles on each object. Although Lola is sitting on a ball, the copy-paste approach works well for the square. The rest of the body is freely simulated, and could be further tuned with trajectories, examples, wind, and other simulation properties.

4.3 Implementation

We implemented our entire framework in C++ with the Eigen library (eigen.tuxfamily.org) for dense and sparse linear algebra. We apply ten iterations of local-global steps to solve Equation 4 in all presented examples and applied Cholesky decomposition to solve the linear system. We employed a time step 0.02s which obtained realtime simulation performance across all examples.

5 Conclusion

We have introduced a unified framework for tightly integrating simulation and keyframing—two typically disparate animation workflows. Artists can now fluidly create, customize, and retarget an animation’s timing and spacing in a seamless and interactive fashion. The key to making this work was integrating recent developments in example-based dynamics for spacing with constraint-based dynamics for timing. We further introduced reduced dynamics on handle-based degrees of freedom to provide intuitive artistic exploration of 2D animation and extended the expressive range of
example-based dynamics with artistic transitions. The result is a system that satisfies the full range of classical animation goals, as codified by the Twelve Principles of Animation.

Our unified framework with the handle interface introduce new interaction possibilities. Instead of depending on kinematically keyframed trajectories alone, artists can also benefit from other simulations and procedural methods. They could design the center-of-mass trajectory with a simple particle system, before moving on to simulations and procedural methods. They could design the center-of-mass trajectory with a simple particle system, before moving on to limitations. Indeed, even animations of our own animation system can be further nested and composed by using any handle to key the motion of another. Overlapping actions and colliding interactions are most obvious applications, but we also go further to demonstrate simulation retargeting operations on our animations. With these features, artists have both the ability to customize any animation, and then compose and reuse the best of them by reapplying them onto other objects.

Future Work and Limitations While artist-directed shape transitions enable maps between disparate shapes they do not guarantee smooth transitions. Artist-directed transitions require suitable example shapes to satisfy animation goals. If artist-provided example shapes are too disparate or too far from desired deformations, results may not be pleasing or may stray from the envisioned animation sequence. As such, the system relies on artists to provide reasonable example shapes to achieve desired deformations. However, we observe that providing reasonable intermediate shapes for pleasing transitions generally follows from artistic intent and fits well with the workflow provided. As an example consider the process of creating the “Walking Arc” example (illustrated in the accompanying video), where a single simulated square is insufficient to capture the desired smooth transitions between a square and arc. If an artist selects a rectangle as a secondary shape for artistic transitions, the simulation remains unable to smoothly reach the desired inelastic deformation and the result is unsightly. If instead, the artist adds the desired end-shape arc as an example, artistic-directed transitions are then able to simulate the desired transitions smoothly.

Handle rigging also plays an important role in the success of an animation. As shown in the accompanying video, a square cannot be deformed into an arc with a too small number of handles. We expect that automated handle-rigging, targeted to satisfy artist intent, will be an important direction of future research. Alternatively, as discussed above, we also observe that artist-directed transitions can be applied in these cases to deform via intermediate shapes when a desired deformation cannot otherwise be achieved. Likewise, recent work on generalizing LBS with point handles [Wang et al. 2015] could also potentially be applied in our system to provide suitable DOF for desired deformations.

Simulation copy-and-paste builds on deformation transfer and TRACKS-based dynamic constraints. However, as with all dynamic constraint approaches, retargeting with constraints that violate a physical system’s symmetries will not and can not preserve momentum.

For evaluation we have developed a prototype system that is not comprehensive. In presented examples we currently apply pin constraints to mimic inelastic collisions. Frictional contact modeling can and should be added to the simulation dynamics in (4) for automatic contact handling. Similarly, rendered silhouettes are currently jaggy (see e.g., Arc examples) when low resolution meshes are employed. Boundary smoothing can and should be applied in such cases.

Finally, while the tools developed in this paper have been evaluated for the creation of 2D animation, we note that the core techniques we utilize, including projective dynamics and example-based materials, have been demonstrated on thin shells and volumetric shapes. This points to promising avenues for future work in 3D both to examine the system proposed here for its suitability for thin shells and to enable practical application on volumetric shapes.

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References


