Elastic and Plastic Deformations with Rigid Body Dynamics

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Left: *Simulation of a wood column bending & breaking with our system (1.29 sec/frame, 230 fragments, 3.2K bodies, 89K constraints).* ***Right***: *Volume fracture often results in concave fragments; our decomposition yields no inter-fragment overlap; our custom constraint network.*

We present a fast and robust method of simulating flexible materials that offers significant advantages over existing methods. Our approach supports complex geometry (concave features, holes, self-intersections), requires no topology restrictions, boasts fast collisions, maintains volume, is numerically-stable for large time steps, and supports dynamic plasticity. Our approach provides an intuitive solution for modeling the complex dynamics of deformable solids with a predictable and production-friendly workflow.

Decomposition

Complex fracturing of detailed meshes often results in concave geometry, which is difficult for collision detection. A common approach is to use simulation proxies created using approximate convex decomposition. Unfortunately, this produces overlapping proxy geometry when decomposing multiple interlocking concave fragments, resulting in a degenerate initial simulation state.

Instead, we propose a two-step decomposition scheme that ensures there will be no intersections across neighboring fragments. First, each mesh is converted into a narrow-band level set. For this, our conversion algorithm is robust to non-manifold polygonal surfaces and can efficiently produce monotonic signed distance fields from arbitrary models. Second, we use a custom sphere packing algorithm to efficiently fill the narrow-band level set volume with adaptively-sized overlapping or non-overlapping spheres. Both steps take full advantage of multi-threading hardware.

Modeling Material Behavior

Each sphere within a fragment is connected to each of its neighbors via ball and socket joints [2011]. This constraint was chosen because of its computational efficiency and numerical stability. Combining these spheroidal constraints with collision constraints in a rigid body dynamics framework also mimics the behavior of a physical spring, which can only compress to a limit.

Different material behaviors are modeled by controlling stiffness values on each constraint, number of connections for each body, and number of constraints between pairs of bodies. The constraint pivots are typically arranged in a trigonal (or higher degree) bipyramid. This configuration prevents flexing and twisting between fragments. Connections across fragments follow the same structure, but are allowed to break if constraints cannot be satisfied within user specified thresholds.

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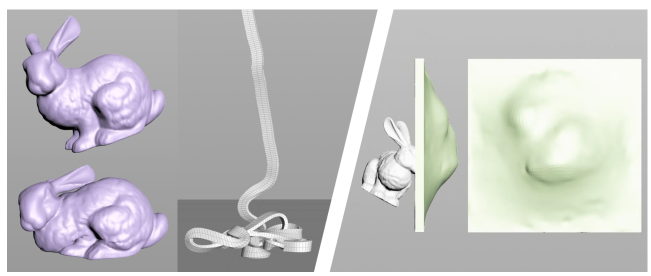
Our system also supports plasticity, or the propensity of a material to undergo permanent deformation under stress. For instance, metal will typically behave in an elastic manner (returning to its original shape), yet upon extreme load the metal will assume a new rest state. This is implemented by updating constraint parameters on the fly once the deformation passes the elastic limit. Users have complete control over this phenomenon, and can also modify any constraint properties mid-simulation for artistic effect. Furthermore, our decomposition scheme facilitates a post-simulation fracture workflow, where the original geometry is fractured based on the final state of the simulated proxy geometry.



Elastic deformation: *falling bunny: 0.27 sec/frame 200 bodies, 2.5K constraints; falling rope: 0.28 sec/frame, 300 bodies, 900 constraints;* ***Plastic deformation***: *wall impact: 2.4 sec/frame, 4.2K bodies, 63K constraints.*

Simulation and Skinning

The decomposition and fracturing tools are built using the OpenVDB library [2012]. The simulation system, called Rumble, is based on the Bullet Physics engine [2011]. Artists can typically iterate quickly, as the simulations are often less than 1 sec/frame.

After the simulation, we bind the original geometry to the simulation geometry with a constraint-weighted linear defomer, using a basis from a user-defined neighborhood. Visually, this results in seamless inter-fragment connections, until the corresponding constraints are broken. Further, we have decoupled simulation and geometric resolution (users are free to augment geometry detail prior to binding), making the technique ideal for production demands.

References

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