

# **Method for Real-Time Physics Simulations**

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# 1. Abstract

Simulating the physical behavior of complex systems has been a necessity of humanity since the birth of engineering. The ability to design reality in the virtual world allows the future to be built with precision, and the past to be understood from a vantage point of the present. Human achievement has placed within reach, the ability to accurately and quickly predict reality

By harnessing the computational power of a piece of silicon that can fit onto the palm of a hand, physics simulations with scalable accuracy can be performed. Analyzing current methods of simulation has lead to improvement in traditional techniques and produced a unique set of heuristics and algorithms to more completely follow the laws of the universe. These improvements propose a new process for simulating solids, liquids, and gases.

## 2. Introduction

Fields of science and engineering, ranging from rocket design to bioengineering, are in need of an accurate and fast method to simulate the behavior of complicated systems. Developing a model capable of achieving this goal will result in an explosion of efficiency within the technological revolution of the 21<sup>st</sup> century.

Research on this subject has led to several conclusions. First, the model needs to be physically accurate. This means that construction of the system in the virtual world must be scalable to an equivalent system in the physical world. Second, the simulation must obey Newton's laws of motion. So concepts such as momentum, inertia, velocity, and force must be accounted for. Third, there must be heuristics that govern the behavior of a system under particular circumstances. These heuristics can range from modeling the plasticity of a material, to setting requirements for atomic bond formation. Finally, once these basic requirements are met, a numerical method needs to be able to stably, accurately, and quickly, compute the change in the system over time.

Putting these conclusions together lead to a method, known as the quanta-bond method, which simulates the atomic structure science is familiar with. The system being simulated is constructed by placing a quanta – equivalent in concept to an atom – in space. Quanta are then connected through bonds – equivalent in concept to a atomic bonds – that serve as the structures glue, holding the system together. The model can then be scaled. If exact accuracy is desired, every atom in a system can be modeled as a quanta. If accuracy is only mildly important, a clump of atoms can be modeled as a single quanta. Once the system is constructed, Newton's laws of motion are applied to individual quanta, which thereby directs the entire system to follow suit. Integration is then performed on each quanta of the system, calculating its vector of motion for a particular change in time. As each step in time is performed, the defined set of heuristics for the system is applied to each quanta.

Varying the degree of accuracy will change the amount of time required to perform the simulation. Simulations that advance time forward only a small amount per step, and have a larger quanta-to-atom ratio, will require more time to compute, reducing

the simulations real-time performance. Thus, the resulting computation produces a scalable and accurate physics simulation for any complex system.

## 3. Related Work

Computational engines for physics simulations have been created using many different methods for both high precision and real-time results. High precision simulations have been used to model weather patterns, wind tunnels, tire tread performance, and other areas where accurate data is a necessity. Real-time simulations are commonly used in video games and by computer animators where only the appearance of accuracy is needed. The quanta-bond method of simulation was based on the following past methods of simulation.

### 3.1 *Particle Method*

Particle methods of simulation make the assumption that all objects within a system are non-spinning spheres of finite mass. This simplified view of the world defines a method that can be updated with simple explicit Euler numerical methods. While the particle method requires only a very small amount of time to compute the next moment, they fundamentally do not account for asymmetric bodies or spinning objects.

Since the particle method is so intuitive and simple to implement, it is commonly seen throughout a variety of applications. It is often found in video games because of the low accuracy requirements and the real time performance it provides.

Despite the simplicity, the particle method was a piece of the foundation in the quanta-bond method. Each particle's motion is so easily described and quickly updated, that building something complex out of these simple particles was a desirable attribute.

### 3.2 *Rigid Body Dynamics*

Methods based on rigid body dynamics provide precise results for objects that are asymmetrical and change only in orientation and position [1]. The accuracy of this method makes it an ideal candidate for scientific purposes.

Unfortunately, the accuracy of rigid body simulations is limited to a strict set of circumstances. If an object can flex, or break apart, or exhibit characteristics not seen in solid objects, the model must be modified or it will fail. Furthermore, the method requires

a complex set of partial differential equations to be solved for each update in the simulation. The partial differential equations are written to include not only Newton's laws, but also concepts such as rotational momentum and non-uniform force application. All these requirements yield stiff differential equations that must be solved using implicit methods. In other words, the resulting simulation is unlikely to meet real time requirements.

The complexity seen in rigid body dynamics underscores the importance of a simpler method. If a simulation using rigid body dynamics needs to allow for more volatile objects, new parameters need to be added to the already complicated equations. Despite the accurate results of this method, it leaves something to be desired – a method that can take a simple set of rules that work together to produce wide ranging and complex results.

### 3.3 *Soft Body Dynamics*

Methods based on soft body dynamics are similar to the quanta-bond method being proposed. These methods simulate soft, deformable objects in real time with varying precision. Generally, soft body methods make use of a mass-spring model to perform the simulation of objects such as clothes, liquids, and hair [2].

A mass-spring model functions like it sounds. Masses are laid out in space, and connected with springs to resist motion. The finer the resolution of masses and springs in a deformable object the more accurate the resulting simulation will be. Updating a soft body simulation commonly makes use of an explicit integrator, such as Runge-Kutta, to solve the simple partial differential equations from the mass-spring system.

Relying on an explicit integrator works well for liquids and clothing since the spring constant is small, making the differential equations that need to be solved fairly loose. In order for a solid to be simulated, the spring constant must be significantly increased, producing very stiff differential equations. These equations can't be solved stably with a Runge-Kutta integrator. The quanta-bond method makes use of an implicit method in order to solve these stiff differential equations.

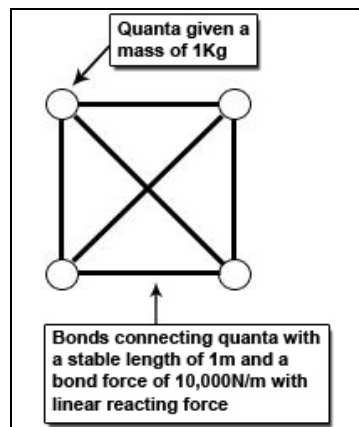
## 4. Research

Basic ideas from previous work done on particle systems, rigid body, and soft body dynamics have been used to develop a unique method, known as the quanta-bond method, which takes a simple set of rules and combines them together to produce complex results. Analysis on this method begins with the understanding of the basic concepts.

### 4.1 Concepts

Any valuable physics simulator should first be able to model systems at the smallest possible level. Ideally this simulation would work with the hypothetical Higgs boson particle, since it could be considered the building block of all matter. Performing a simulation at this size is unreasonable for several reasons, most prominently though because of the extremely high resolution required for any object being modeled. Basing the method at the atomic level is the most appropriate, since equations of motion for atoms are simple and precise. Lets examine the construction of a simulation.

Each system being simulated is constructed in terms of quanta and bonds. Quanta are added to a system to represent a single atom, or a clump of atoms. If quanta had to be assigned with a one-to-one ratio between atoms, the computers resources would quickly be depleted when simulating large complex systems. Quanta maintain values representing their mass, position, velocity, and acting forces. Once the quanta are laid out in space, they can be connected with bonds. Bonds can behave like springs with one of two options: the reacting force of the bond can grow linearly, or it can fall off inversely as the bond stretches. A bond can connect exactly two quanta to each other, and is defined to have a resting length, a bond force constant, and a dampening coefficient. The resting length is the length at which the bond exhibits no force on either of the connected quanta. The bond force constant is the amount of force applied to the quanta as the bond is stretched. The dampening coefficient is the



**Figure 1: 2D solid box modeled with quanta and bonds**

amount of energy lost as the bond applies force to the connected quanta. Figure 1 demonstrates the construction of a solid 2D box using quanta and bonds. Once construction of a system is complete, it is ready to be simulated.

Progressing a simulation of a system forward in time is done in iterations, called timesteps. Each timestep updates the position and velocity of quanta within the system. This process is divided into two parts: the timestep projection, and the timestep application. When the timestep is projected, the change in position and change in velocity is computed for each quanta. Before those changes are applied to the actual position and quanta of a simulation, the heuristics are applied. After all necessary heuristics have been applied to the quanta and bonds, the timestep completes by applying the computed changes to the system.

All these concepts come together to form the quanta-bond method of simulation. The simple concepts build upon each other to make the method versatile in its ability to simulate systems under a vast number of conditions.

## 4.2 Equations of Motion

Quanta within a simulation are updated according to a strict set of equations of motion. These equations take into account only velocity and forces acting on a quanta. In fact, the equations of motion are strikingly similar to the equations of motion used in the particle method; the key difference is that they quanta are connected together with bonds.

Examination of a simple two quanta, one bond system is necessary before diving

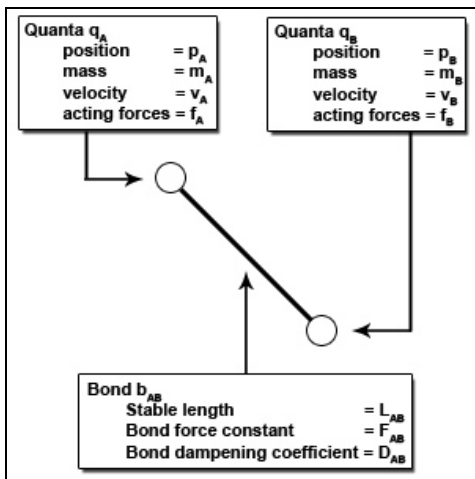


Figure 2: Simple 2 quanta 1 bond system

into the equations of motion for a full mesh of quanta and bonds. This simple system can be seen in Figure 2, where each quanta has a given position in space, a mass, a velocity, and the amount of force acting on it. A vector in 3 dimensional space represents these quantities. The bond connecting quanta  $q_A$  and  $q_B$  is defined by three dimensionless quantities: the stable length, the bond force constant, and the dampening

coefficient. Using these quantities it is possible to define the desired behavior of motion, which can be described as follows:

1. Forces acting on a quanta cause it to accelerate at a rate proportional to its mass.
2. If the distance between the positions of two bonded quanta is less than the stable length of the bond, a repulsive force is equally applied to the quanta.
3. If the distance between the positions of two bonded quanta is greater than the stable length of the bond, an attractive force is equally applied to the quanta.
4. If the bond is applying a force to the quanta, it either linearly increases or inversely decreases with respect to the stretched length of the bond.
5. The change in position of each quanta during a timestep is a product of the forces acting on it and the current velocity.
6. The change in velocity of each quanta during a timestep is a product of the forces acting on it.

This behavior of motion yields a second order partial differential equation. From the perspective of quanta  $q_A$ , the equation is:

$$\textbf{Equation 1: } p_A'' = \frac{1}{m_A} [f(p_A, p_A', p_B, p_B') + f_A]$$

$$\textbf{Equation 2: } f(p_A, v_A, p_B, v_B) = F_{AB} (L_{AB} - \|p_B - p_A\|) - D_{AB} (v_A - v_B)$$

$$\textbf{Equation 3: } f(p_A, v_A, p_B, v_B) = F_{AB} \left( \frac{1}{L_{AB} - \|p_B - p_A\|} \right) - D_{AB} (v_A - v_B)$$

Where the function  $f$  computes the force acting on quanta  $q_A$  from the bond between quanta  $q_A$  and  $q_B$ . The force function will compute a force that either increases linearly or falls off inversely as distance increases. Converting this second order partial differential equation to one of first order simplifies the work of the numerical solver used by the quanta-bond method. First order equations can be achieved through substituting the quanta's velocity for the change in position, yielding the following first order equations:

$$\textbf{Equation 4: } p_A' = v_A$$

$$\textbf{Equation 5: } v_A' = \frac{1}{m_A} [f(p_A, v_A, p_B, v_B) + f_A]$$

For the two quanta, one bond system, these equations account for all the behaviors necessary for successful simulation. This simple system is too primitive to be useful, so expanding on these equations is necessary.

Allowing systems with considerably more complex arrangements of quanta and bonds requires different equations of motion. Nonetheless, these new equations stem directly from the simple system's equations defined above. Specifically, in order to allow any amount of quanta to be bonded in any possible configuration, the equations only need to account for the forces applied by all the bonds connected to the quanta. Summing the different forces from each bond connected to a specific quanta fulfills this requirement, bringing forth the following, more versatile equations:

**Equation 6:**  $p_i' = v_i$

**Equation 7:**  $v_i' = \frac{1}{m_i} \left[ \sum_j f(p_i, v_i, p_j, v_j) + f_i \right]$  where  $j$  represents each quanta bonded quanta  $i$

Solving the differential equations presents a new problem. Each quanta in a simulation requires a new equation to be solved – this equation is coupled to the motion of every other quanta. Since the exact solution is, at the least, very difficult to find, a numerical method is required that is capable of approximating the solution to the system of coupled differential equations.

### 4.3 Integrating

Integration on the equations of motion is the heart of the quanta-bond method. Not only does the method need to be stable when presented with stiff equations, it needs to be accurate and fast. In order to achieve these goals, a hybrid implicit integrator was used.

Finding the change in velocity for a given quanta is the major requirement for the integrator. Once the change in velocity is known, the change in position can be quickly computed. By assuming that the connected quanta don't move when solving for a quanta's change in velocity, the coupled system of equations becomes decoupled. This

results in an acceptable loss of precision but maintains the key features of an implicit integrator -- stability and large step size – while at the same time reducing memory costs and increasing speed. Furthermore, this decoupled approach allows for the quick modification of a quanta's velocity and acceleration vectors since the bonded quanta ignore its motion anyways. This also reduces the number of computations used in some heuristics, such as collision detection.

Implementing this solver requires some modification to the equations of motion. The new equations can be found below.

**Equation 8:**  $\Delta p_i = P_i(t_0 + h) - P_i(t_0)$

**Equation 9:**  $\Delta v_i = V_i(t_0 + h) - V_i(t_0)$

**Equation 10:**  $\Delta p_i = h[v_i + \Delta v_i]$

**Equation 11:**  $\Delta v_i = h \left[ \frac{1}{m_i} \left( \sum_j f(p_i + \Delta p_i, v_i + \Delta v_i, p_j, v_j) + f_i \right) \right]$

Where:

- ◇  $t_0$  is the current time
- ◇  $h$  is the size of the timestep
- ◇  $P_i(t)$  and  $V_i(t)$  return the position and velocity of quanta  $i$  at time  $t$

Equation 11 presents two problems. First, there are two unknowns:  $\Delta p_i$  and  $\Delta v_i$ .

Substituting equation 10 for  $\Delta p_i$  produces a solvable equation. The second problem is that the force function  $f$  is non-linear. By replacing  $f$  with its first order Taylor series, the method can once again sacrifice a bit of precision for large gains in speed. Correcting these problems yields the final equation for a quanta's change in velocity:

**Equation 12:**

$$\Delta v_i = h \left[ \frac{1}{m_i} \sum_j \left( f(p_i, p_j, v_i, v_j) + \frac{\delta f(p_i, v_i, p_j, v_j)}{\delta p_i} (h[v_i + \Delta v_i]) + \frac{\delta f(p_i, v_i, p_j, v_j)}{\delta v_i} (\Delta v_i) \right) + f_i \right]$$

The accuracy of this numerical method depends on the size of the timestep -- the smaller the timestep, the more accurate the results. However stiff the equations, the solution remains stable. Unfortunately, as the stiffness of the equations increase, the size

of the timestep must decrease to maintain an equal level of precision. Despite this, the solver provides visually accurate results in real time, and realistic results with timesteps that produce less than real time results. Behavior and comparison of this numerical method with explicit and coupled implicit methods was analyzed to insure this method provided the best compromise between precision and speed.

#### 4.4 Integrator Behaviors

Three integrators were considered for use with the quanta-bond method. While the hybrid implicit integrator achieved the best balance between precision and speed, it is worth reviewing the capabilities of the two other possibilities. The other possibilities offer advantages over the hybrid method in certain specific cases.

Fourth order Runge-Kutta was the fastest method considered. This explicit method performed considerably well with loose equations and small timesteps. However, making the equations just slightly stiff causes the method to completely lose stability. Because of this limitation, the Runge-Kutta candidate was ruled out quickly since it was unable to even complete many basic tests.

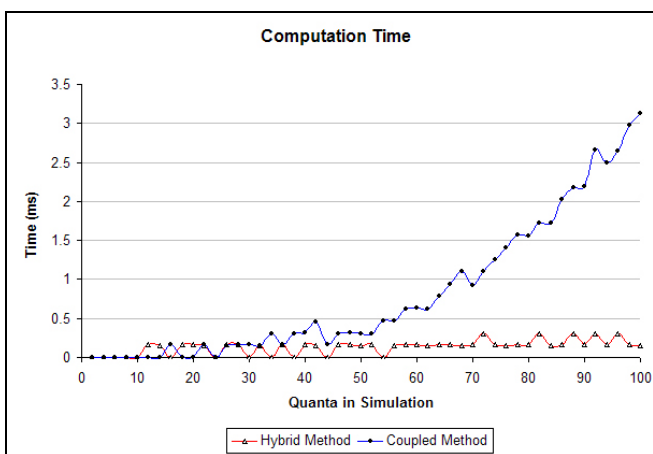
The most promising alternative to the hybrid method is an implicit method that doesn't assume bonded quanta remain still while finding a quanta's change in velocity – an integrator that leaves the equations coupled. In order to achieve this, each bonded quanta's change in position and change in velocity need to be taken into account while updating each quanta. This leads to a slight modification of the hybrid method's equation for change in velocity:

$$\text{Equation 13: } \Delta v_i = h \left[ \frac{1}{m_i} \left( \sum_j f(p_i + \Delta p_i, v_i + \Delta v_i, p_j + \Delta p_j, v_j + \Delta v_j) + f_i \right) \right]$$

As with the hybrid method, taking the first order Taylor series of the above equation and making the appropriate substitution for  $\Delta p$  creates a solvable non-linear equation. Unlike the hybrid method, however, the change in velocity for a specific quanta can't be found

individually – a system of equations must be solved. The system of equations was solved using Gaussian-Elimination.

Comparisons will only be made between the hybrid implicit method and the coupled implicit method since Runge-Kutta fails to provide answers for many of the tests. Performance between the implicit methods is quite different. An experiment was devised to show the performance discrepancy. For each method, computation time was computed by taking the average completion time for a thousand timesteps of a simulation. After each average was calculated, two new bonded quanta were added to the simulation, and



**Figure 3: Performance comparison**

once again the computation time was computed. The results seen in Figure 3 show the exponential increase in time required to perform a timestep with the coupled implicit method. The hybrid implicit method undergoes a linear increase in computation time. For a small amount of quanta, the two methods perform about equally, under which

circumstances the coupled method would be superior. This superiority can be seen in the accuracy and stability of the method.

Precision between the two methods varies based on the number of quanta and the timestep used for the simulation. There are a number of things that affect the precision that are common to both methods. First, the Taylor series used to estimate the force around a given point consistently results in a value half of the actual force. Second, there is a constant accumulation of round off error, which, over time can result in slight but noticeable differences between the exact solution and the estimated solution. Using a sufficiently small timestep is usually enough to overcome these sources of error. To demonstrate this, two tests were run. These tests simulated a system simple enough that the exact solution was known – two quanta connected by a single bond. The relative velocity of each method was then compared to the known exact solution using both small and large timesteps. The results can be seen in large and small timestep plots seen below.

While there is a phase shift present in both methods, the amplitude and period of the solutions match the exact solution precisely. Sufficiently small timesteps cause the solutions from both the coupled and hybrid methods to be nearly identical. However, a large timestep causes the hybrid method to produce less accurate results, while the coupled method continues to be accurate. Stability is guaranteed independent of the size of the timestep, this is best seen in the large timestep plot. This stability occurs because even though the accuracy of the solution decreases with large timesteps, the solution consistently underestimates the actual value, resulting in a loss of energy instead of an increase. Stability of these methods is the next area of experimentation.

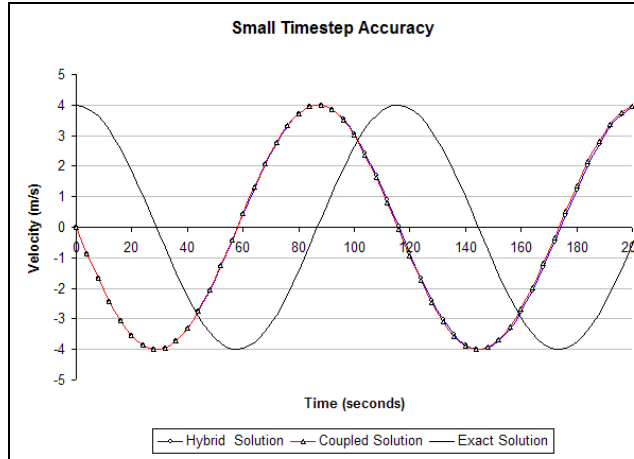


Figure 4: Solution with a small timestep

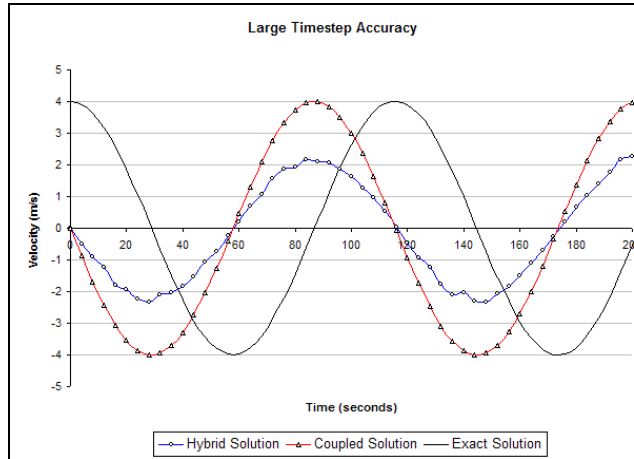
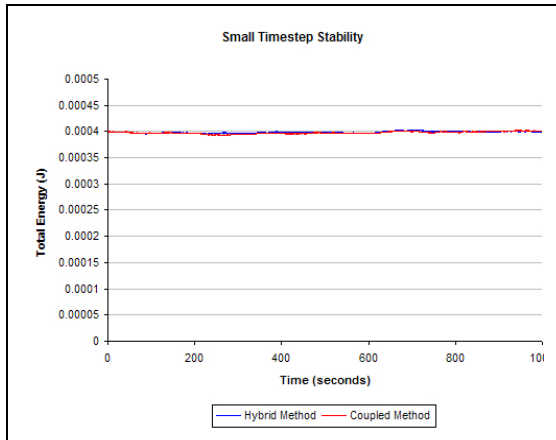


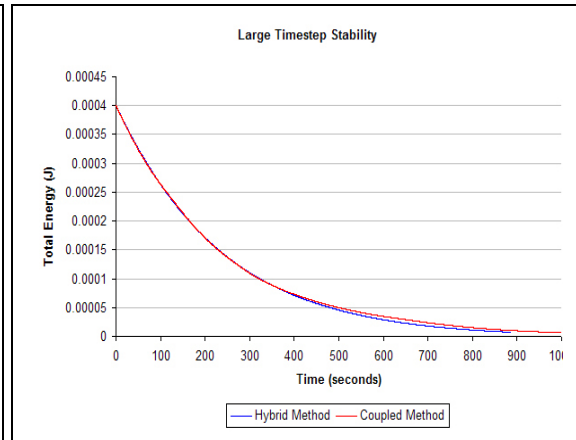
Figure 5: Solutions using a large timestep

Stability of a system is considerably important when trying to simulate solids. Without stability, the stiff equations required by solid objects could not provide appropriate solutions for simulation. Measuring the stability of a particular integrator involves measuring the energy of a system. In a closed system, the total energy – the sum of kinetic and potential energies – remains constant. If the solution is exact, this energy will remain constant. If a solution is unstable, the energy will increase well beyond the initial value of total energy. If a solution is stable, the total energy will be less than or equal to the initial value of total energy. An experiment was run with four quanta, each bonded together and given a specific initial velocity. Each method continuously measured the total energy as the simulation progressed in time. Again, with a small enough timestep, the solutions were

nearly identical and perfectly stable. When a large timestep was used, the coupled and hybrid implicit methods stabilized at nearly the same level just as rapidly. This is interesting, since when a simple system is simulated, the hybrid method stabilizes at near zero levels of energy extremely rapidly, while the coupled implicit method stabilizes at non-zero levels of energy after a long period of time. So, as the complexity of the system increases, the two methods perform nearly identically in terms of stability. This can be seen in the following graphs of stability with large and small timesteps.



**Figure 6: Stability with small timestep**



**Figure 7: Stability with large timestep**

Comparison between the two interesting methods of integration has found that the coupled implicit method is superior in every way except for efficiency. Because this superiority vanishes when a sufficiently small timestep is used, the efficiency advantages the hybrid method has over the coupled method become very significant. In complicated simulations, the timestep used in the hybrid method can be a thousandth the size of the timestep used in the coupled method, and provide superior accuracy and stability while operating at roughly the same performance. Because of this advantage, the hybrid implicit method was the chosen integrator for the quanta-bond method of simulation.

#### 4.5 Real World Comparison

Behind all the mathematics and algorithms, the optimistic goal of the quanta-bond method is the ability to simulate any complex system in the virtual world and apply the results to the physical universe. Such a solution produced from a simulation is said to be valid. Validity of the quanta-bond method can be broken into a couple pieces: validity of the algorithm, and validity of the calculation.

At the heart of the quanta-bond method is the concept that the atomic force between two bonded atoms behaves in the same way as a spring. Models of atomic bonds within molecules have traditionally assumed the bonds behave similarly to a spring [3]. In fact, within certain boundaries, it has been proven that the bonds behave exactly in accordance with Hooke's Law using atomic force microscopes [4]. If the quanta-bond method was used then to simulate every atom in an object, and the calculations were exact, the results of the simulation would be completely valid. Fortunately, this can also extend to objects where quanta are used to model clumps of atoms instead of an exact

**Equation 14:**  $k_{effective} = \left( \sum_i \frac{1}{k_i} \right)^{-1}$  where  $i$  represents each spring in the series

one-to-one mapping. Looking at a simple one-dimensional case, a series of springs can be replaced with a single effective spring using the equation below [5].

In order to expand into the second and third special dimension, parallel springs must also be taken into account. Parallel springs are considerable easier to replace, since the equivalent spring is just the sum of all the springs connected in parallel [6].

**Equation 15:**  $k_{effective} = \sum_i k_i$  where  $i$  represents each spring in the series

With the ability to replace any springs in series or in parallel with an equivalent spring, there are no reasons groups of atoms and atomic bonds can't be replaced with equivalent systems of quanta and bonds. This is a very important observation, because simulating every atom in an object individually is very exhausting of both memory and computation cycles. Reducing an object to just fractions of the number of atoms is perfectly valid, and is what makes real time simulation possible.

Determining the computational validity of the quanta-bond method is a little more difficult. If a simulation is computationally valid, the stress across

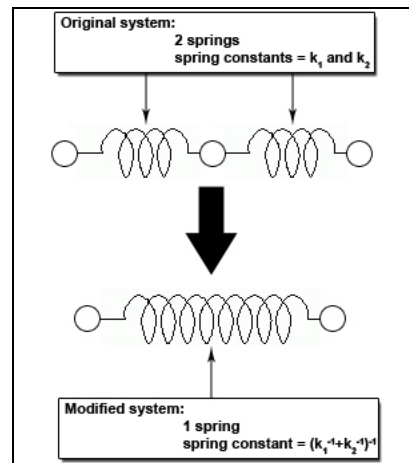
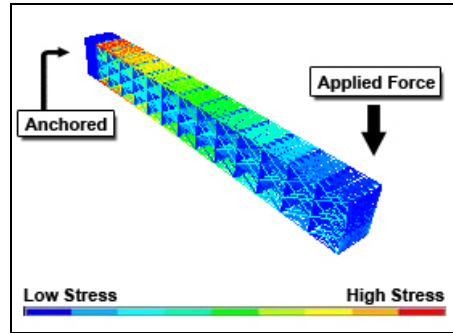


Figure 8: System reduction

an object should be correct, the physical movement should be correct, and the arrangement of quanta and bonds should be analogous to the real world structure. Each of these aspects was examined individually.

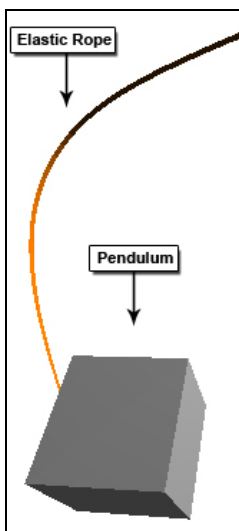
A Von Mises stress distribution [7] was generated and compared to an actual value to determine if the stress across an object is computed correctly with the quanta-bond method. To generate this stress distribution, a simple block was constructed with all the nearest neighbor quanta connected and bonded. One end of this block was anchored and not allowed to move. The opposite end has a force applied onto it. Each bond was then colored according to the stress distribution function and compared to an actual value for such a situation



**Figure 9: Computed Von Mises stress distribution**

[8]. The computed stress distribution can be seen in Figure 9. Comparing the two distributions, it's easy to see the very strong similarity. It is easy to conclude that the calculation of bond lengths – which results in stress throughout the object – is valid, and can be mapped directly to real world situations.

Determining if the motion of a system is correct was done subjectively, since daily experience is generally enough to notice realistic or unrealistic motion. The important behaviors to look for when examining the motion of an object are momentum,



**Figure 10: Pendulum in motion**

angular momentum, velocity, acceleration, and the shape of deformation. All but the shape of deformation can be examined through a simple pendulum system. This system was constructed by connecting a heavy, solid cube to an elastic rope. Force could then be applied to any location on the pendulum, and the results observed in real time. From the pendulum simulation, all behaviors expected were seen. An image system setup and the pendulum in motion can be in Figure 10. Shape of deformation was a little more difficult to observe subjectively, since it's not as common an experience in daily routine. The open source package “Getfem++ “ proved its usefulness in comparing Getfem++ solutions against solutions from the quanta-

bond method. Getfem++ exposes an API that can be used in finite element methods elementary computations. It offers functionality proven correct for performing exact and approximated integrations. Using the Newton method, the Getfem++ package computed the results of a large bar being twisted at one end. This system was reproduced using the quanta-bond method, and a bar was twisted the same distance as the Getfem++ bar. The final shape of the object from the two different methods was then compared. The results of the quanta-bond method, as seen in Figure 11, show the same shape and form as the Getfem++ solution [9]. Thus, it was concluded that the motion of a system behaved as expected and displayed all of Newton’s laws, so the motion computed by the quanta-bond method of simulation is valid.

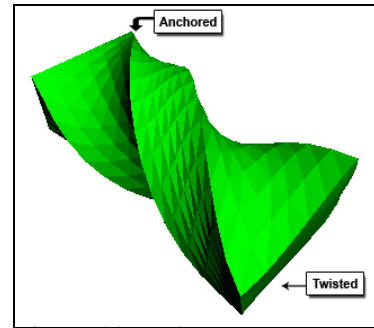


Figure 11: Twisted bar

Placement of quanta and bonds is the last area necessary before the quanta-bond method can be deemed valid. The atomic structure of matter generally forms in only a couple different ways. Symmetry plays the largest role in behavior of a material. Atomic structures that exhibit a high degree of symmetry, such as crystals or carbon nanotubes, result in materials with much more rigidity and durability. Structures that exhibit asymmetric properties, such glass or rubbers, make much weaker and more flexible

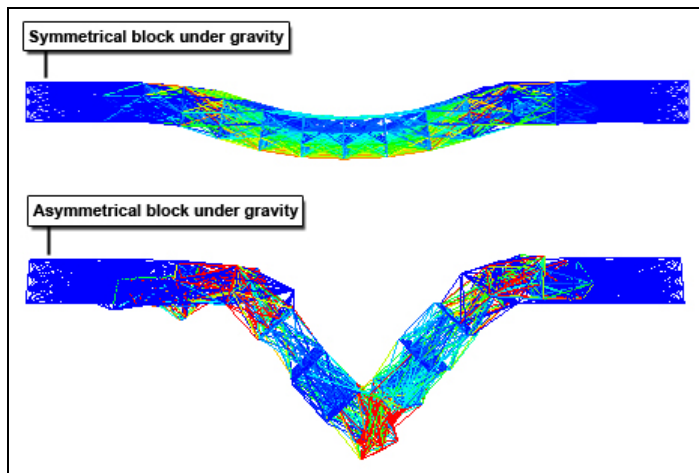


Figure 12: Symmetric and Asymmetric Structures

materials [10]. This behavior was perhaps best seen when testing the plasticity of a block. The block was initially arranged in symmetrical square form and experienced the force of gravity. As the block was stretched out, a heuristic was applied that randomly broke bonds that were undergoing extreme stress. When

the bonds broke, the arrangement of quanta and bonds quickly became asymmetrical, and gravity was able to flex the material much more than when the system was symmetrical.

Figure 12 shows this difference between symmetric and asymmetric arrangements. This experiment demonstrates the significance of different quanta and bond layouts, and matched what is seen in the real world. Since symmetric and asymmetric layouts behave similarly in both the simulation and in the real world, the quanta-bond layout is analogous to a materials atomic structure, and the quanta-bond method is valid in this area as well.

Through intense experimentation, the quanta-bond method was found to perform validly in both concept and computation. The accuracy of the results scales from low precision and real time to performance, to high precision and slow performance. The quanta-bond method is valid.

## 5. Further Research

Many aspects of the quanta-bond method were investigated, but there are still important questions that need to be answered. Throughout the research, the numerical method for integration was found to be sufficient, and the general concept and algorithms were found to work very well with any conceivable material. Nonetheless, there are several lines of research that need to be continued.

Waves need to be incorporated into the quanta-bond method. Concepts such as light, and magnetism are clearly absent from the model designed. Obviously, just using quanta and bonds isn't sufficient to model these fundamental necessities. Perhaps the addition of new bond types will allow for the integration of these concepts, but it has yet to be investigated.

When the timestep is kept constant, total energy of a system decreases as complexity increases. To balance this effect, smaller and smaller timesteps are needed to maintain perfect stability. Eventually this leads to an impossible situation, where the lack of real time performance is guaranteed. This is a fundamental problem with the integrator used. If the method of integration paid attention to the total energy of the system, perhaps this problem could be overcome. Once again, this idea has yet to be investigated.

Liquid simulations have yet to be analyzed. Most of the research was spent dealing with solid objects, and very little time spent examining the behavior of liquids with the quanta-bond method. While appropriate heuristics were determined for concepts such as plasticity, no heuristics were developed for liquids. In theory, the quanta-bond method is fully capable of simulating liquids, however, further research is needed.

By continuing research in this area, the quanta-bond method has the potential to become a vastly superior physics simulator when compared to any of the alternatives. This method should continue to be developed since it will be able to provide wide ranging and versatile results for any situation.

## 6. Conclusion

Throughout the duration of research, the quanta-bond method of simulation has continuously showed promise. Promise was seen in its ability to offer a finite set of simple rules that can be used to produce accurate results with complex systems. Promise was seen in its ability to offer real time solutions in situations where accuracy isn't a requirement. The method has shown that physics simulations should not try to hardcode the endless number of observed phenomenon in nature, but rather, to dig down to the building blocks of nature. Simulation at the tiniest level guarantees that none of these phenomenon will be excluded.

The quanta-bond method has evolved to the point where, just like the real world, design and structure of an object matter. To the point where concepts like stress and strain, plasticity and rigidity, are seen in simulations exactly as they are seen in the universe. Indeed, the quanta-bond method is reaching to place reality in the virtual world.

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