Chemical Inflation for Assisted Assembly

Utilising state-changing reactions as a medium for material activation, animation and surprise

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Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of Master of Science in Media Arts and Sciences at the Massachusetts Institute of Technology

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ABSTRACT

This thesis aims to utilize an output method for pop-up fabrication, using chemical inflation as a technique for instant, hardware-free shape change. By applying state-changing techniques as a medium for material activation, we provide a framework for a two-part assembly process, starting from the manufacturing side, whereby a structural body is given its form, through to the user side, where the form potential of a soft structure is activated and a form becomes complete. The process discussed in this thesis is similar in nature to existing chemical reaction home-activation kits, such as hand warmers or cold packs, however, with the inclusion of volume-change and automatic assembly, this method gives way to alternative application possibilities and component-free construction. Along with structural configuration, this thesis provides material development for the application of volume changing membranes for the purpose of material surprise and transformation.

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There is the sky, which is all men’s together.
- Euripides
As a means to ignite curiosity and surprise within a material interface, behaviors that seem inherently unexpected or contrary to the material’s innate properties can act as catalysts to inspire awe. For example, seeing a Cuttlefish transform to blend into its background seems somewhat magical when we observe it in comparison to our conceptual understanding our own skin. Intriguing characteristics allow us to think outside the realms of possibility, thus inspiring unexpected thought and opportunity. Leading us into the world of ‘Radial Atoms’, a place where logic is elastic and atoms dance to create poetic transformations.

To explore this concept of material surprise, this thesis looks at the use of chemical behaviors to augment physical properties through the use of inbuilt energy potential, adding unexpected effects to otherwise inert forms. The specific effect we explore within this thesis is inflation, by utilizing the CO2 released as a bi-product of the reaction between Sodium Bicarbonate and Citric Acid. By applying an unexpected attribute to an otherwise familiar material, we are able to imbue a sense of wonder and surprise to the experience of using a product.

Inflatable structures within the field of design have been explored in many capacities from structure, to buoyancy, to air travel. In the scope of this thesis, I will be exploring the use of self-inflating structures from two perspectives, one, as a means to promote surprise through animation and shape transformations, and two, as a functional tool for distributed assembly processes.
INTRODUCTION

Motivation

Within the field of HCI, the exploration of reconfigurability and responsiveness has typically been applied to the digital aspect of computation (1), with emphasis on interactivity within screen-based and robotic interactions. More recently, researchers developing Tangible User Interfaces have identified the potential to apply the same design principles to physical materials (2), whereby materials themselves can respond and reshape to multiple degrees, in response to digital information. Projects such as inFORM (3) pioneered such thinking through promoting the idea of physical pixels able to reconfigure as freely as photons on a screen.

However, as exciting as these radical new materials seem, there are limitations to their functionality, specifically to a wider audience. These come down to practicalities such as the need for external hardware, for example cumbersome motor systems (3), noisy air compressors (4), and motion tracking systems (5). Thus we are designing for a world in which the technology has not yet caught up. There are great benefits to this way of thinking, in that we can shape a future yet to come, however, if we apply this vision-based thinking to practicalities of today, we can also achieve some pragmatic, yet advanced results. As an example of such works, bioLogic (6) tackled the
idea of creating a dynamic surface utilizing the expansion properties of Bacillus Subtilis Natto Bacteria that responds to heat and moisture to generate dynamic air-vents for runners. This advanced and scientifically profound work stemmed from the forward thinking vision of the Radical Atoms philosophy, but when applied to an everyday problem such as overheating when exercising, this radical vision becomes an implementable solution. Another example, which is somewhat less directly implementable, but uniquely visionary is the project M-Blocks (7) from Distributed Robotics Lab at MIT. This research looks at how to dynamically reconfigure building blocks using kinetic motion and magnetism.

What is special about both these examples is that fact that the energy potential is stored within the materials themselves. They are designed so as to be maneuverable within different contexts, meaning their form is not constrained by external hardware or a fixed base station. These properties can be considered ‘magical’, in the sense that their behavior is surprising or unexplainable from the outside, get highly controllable from the ‘inside’.

In this way, by activating a material, we are releasing stored energy into a per-defined structure, which in turn imbues a user with surprise.

**Aims**

This thesis provides both a theoretical exploration of material activation, from the perspective of design, fabrication and manufacturing, through investigation of existing programmable material systems into two-part manufacturing/assembly systems, whereby the user becomes a viewer, while being as much a part of the assembly process as the factory. Based on this theoretical approach, I provide tested examples in the form of 1) integrated ener-
gy-potential through chemical-inflation, 2) pop-up assembly through geometry investigation, 3) programmability of form through volume with instant small-to-large shape change, 4) an understanding of the relationship between energy-potential and material membrane deformation.

By using the specific example of chemical inflation, we utilize a hardware-free inflation method, where shape-change can be activated autonomously, surfaces can be seamless without the need for external-to-internal airflow channels, and no external pressure source is required (either by breath or by pump): transformation is in-built. By exploring the programmability of materials through inflation, via activated morphing actions, this thesis provides a study of primitive form, actuation and geometry, for the purpose of design, fabrication and mechanization, through the control of chemical behaviors.

**Contribution**

This thesis offers the following contributions:

- An integrated system for fabrication utilizing bi-products of a chemical reaction for inflation of materials.
- A new perspective on material transformations through chemical activation.
- A design space for manufacturing processes using programmable inflation.
- A solution for small-to-large shape change for economic transportation.
- Dynamic material with stored energy-potential.
Thesis Outline

The following chapters describe the evolution of ideas in this thesis:

Chapter 1 gives a background to the research through an analysis of existing work in the field of programmable materials, inflation, and material morphology.

Chapter 2 looks at the use of material behaviors within form-giving and objects construction

Chapter 3 documents a number of active chemical reactions we considered and tested for the purpose of material transformation.

Chapter 4 looks at fabrication in terms of human construction and assisted assembly, taking into consideration practicalities such as transportation and user-construction.

Chapter 5 explores the proposed design space through an analysis of primitive forms, movements and materials utilisable within inflating structures.

Chapter 6 presentation of Auto-Inflatable{s}, showing background research, testing and performance.

Chapter 7 summary of development of project with Ferrero MPG, from brainstorming to manufacturing hand off.

Chapter 8 Introducing future directions looking at the project across scales, specifically within architectural applications and disaster relief zones.
A brief history of inflatable structures within design and robotics

Over the past centuries, dating back to as early as the 1700's and possibly earlier, experimentation with the mechanical properties of air has become a well explored subject, especially in areas such as transportation, architecture, and more recently robotics. The qualities of air, being something intangible, lightweight and inexhaustible (8) as well as providing pressure, buoyancy, and the ability to elevate structures, means that air, when controlled, has the ability to add characteristics and capabilities to tangible structures that would be otherwise inconceivable.

The desire for man to fly provided great impetus for the investigation of air properties, and the discovery of the simple fact that hot air rises lead to some of the earliest examples of air utilization within unmanned flight. In 1709, Bartolomeu Lourenço de Gusmão presented an unmanned hot-air balloon to the King of Portugal (8), which managed to elevate 4 meters into the air. This was the first of many attempts by different inventors to commandeer the air above ground.
Beyond air travel, and the world above, the fascination with air at the ground level continued to grow (9), becoming a much used (but endless) resource for activities such as driving, cycling, boating, ball games, sleeping, and even eating. By applying the attributes of this invisible resource using aerostatics (10) within engineered membranes, we have seen the built world transform to make everyday experiences increasingly comfortable and adventurous (9).

The natural world is also a great source of wonder for observing the utilization of air. Transformative animal behaviors such as: defense - e.g. the puffer fish, mating - as in the case of the frigatebird when trying to attract a mate, underwater breathing - such as the Argyroneta aquatica, an underwater spider that creates its own atmosphere by living inside a self created underwater air bubble, all exemplify the evolutionary uses of morphing structures.

Trapped air has also been utilized for synthetic applications such as packaging (11). In 1957 in the US, Bubble wrap was invented by the engineers Alfred Fielding and Marc Chavannes. Initially the product was sold as greenhouse insulation, however, in 1960, the protective usage of Bubble Wrap was discovered. Being lightweight and temporary, this material is ideal for shipping and protection. Thus proving the versatility of trapped air is vast.
Within the field of HCI, the uses of trapped air has been explored in projects such as AeroMorph (12), by utilizing pneumatic systems to reconfigure membranes, to give form and feedback in response to digital information. The dynamic control of this I/O system provides unique qualities to a digitally controlled interfaces that allows for quick and unique morphological properties.

The use of air within pneumatic systems has also found its way into robotics, now that the development of soft robotics systems has begun to grow (13). This sub-field of robotics looks at the utilization of highly compliant materials, similar to those found in living organisms, to allow for increased flexibility and adaptability for alternative use-cases as well as improved safety when working around humans. The use of air within such a system is a useful actuation tool, as mechanical damage can be limited and system parts can be made to be lightweight. I will go into more detail about related work in the following chapters.

Life jackets and rafts found within airplanes and boats use fast releasing CO2 canisters that when pierced by a release mechanism with rapidly release CO2 into the body of the vest to create a securely inflated, highly preasurised membrane to enable flotation within water. The canisters themselves are also highly preasurised and therefore the release is immediate.

Airbags used within cars create inflation using a reaction between Sodium azide (NaN3) and potassium nitrate (KNO3) which react very quickly to produce a large pulse of hot nitrogen gas. The release mechanism works by a circuit passing an electric current through a heating element which ignites a chemical explosive causing the release of a large volume of harmless gas, typically either nitrogen or argon.
Transformative structures within an assembly process

The development of ‘smart’ or technically advanced materials is a process of synthesis, piecing together structural or molecular elements with complementing behaviors, or tuning their attributes to fit alternative needs (14). The ability to control morphological transitions through embedded logic or energy, gives rise to radical possibilities within the field of design. Within the specific context of two-part assembly, or distributed labor, for example within flat-pack furniture, control of morphological transitions can provide guidance mechanisms that aid in user-assembly. Within the context of this thesis, I am especially interested in how user-directed assembly can be implemented and aided by the use of inflating materials. By incorporating transformative elements into a design, are we able to add both emotion (in the sense of fulfillment) as well as function to the experience of using an artifact.

A key point to note within this thesis is the fact that by using engineered materials with transformative abilities, one of the solutions we are providing is that of economic transportation. As a society we have become accustomed to moving and transporting goods, so the importance for space economy is obvious. Therefore, by incorporating elements into a design that allow for efficient transpiration, as well as easy assembly though inbuilt energy assistance, this projects is incorporating a solution as well as a user experience through the use of self-actuating and animating materials.

To actuate, or transform a material, energy of some sort is required. In this case there are two options, external energy input or internal (stored energy) input.

Examples of stored-energy can be observed on a biological scale, when we look for instance at how a cell stores energy as Adenosine triphosphate (ATP) molecules. The transformation of this stored energy provides cells with
the ability to grow, transform and multiply. Although this process is very different from the mechanical processes I am discussing in this thesis, pointing out the correlation between the micro and macro world is a useful tool for conceptualizing processes characterized within the broader spectrum of life itself.

When we look at piece-by-piece construction of something like a house for instance, each brick provides a part to a whole, constructed by an outside energy source, in this case the human. Piece-by-piece construction of this kind treats the building material as single, solid atoms. Within HCI, the emphasis of reconfigurability is there so as to provide task-related feedback, rarely does a single-state provide a suitable mechanism for conveying transformable information. However, when a material can provide a multiplicity of states, we are able to provide information, or engineer functionality in different formats.
Programmable materials

Lessons from nature have inspired designers and scientists for generations everywhere from architecture to swimsuits. The evolutionary perfection of the organic world provides solutions that are both aesthetic as well as structurally profound.

Exploration of programmable materials has seen a range of outcomes in various forms, from biologically controlled movement to woods, to air.

Current programmable materials, what they can do, and how they’ve inspired me:

Within academic research, investigation and experimentation of programmable materials has taken various directions, here I shall discuss related work that covers a variety of techniques, with applications within HCI, assembly, and wearables.

Within the Tangible Media Group, the development of programmable materials stemmed from the Radical Atoms vision, whereby interfaces would no longer be limited to GUIs (Graphical User Interfaces) and TUIs (Tangible User Interfaces), but instead interfaces would be able to conform and reconfigure to fit the needs of the user (Ishii 2012). As a consequence, a number of projects have emerged.

PneuUI is an enabling technology designed to build shape-changing interfaces through pneumatically-actuated soft composite materials. The computational aspect of this project is the control of the air released into a predefined membrane. By being able to computationally control the output of an air compressor, soft membranes can be controlled to act upon specific command.
JamSheets (15), utilizes layer jamming as an enabling technology for designing deformable, stiffness-tunable, thin sheet interfaces. This project works in opposite to PneUI, in that instead of inputting air to create feedback, air is being pulled out to create stiffness.

![Figure 10. JamSheets samples, Tangible Media Group](image)

BioLogic (6) is uses grown living bacteria actuators that when exposed to moisture will swell to create movement. By applying the bacteria to a substrate material in specific logical geometries, curling and bending action can be generated to give ‘life’ to an otherwise lifeless material. The in-built mechanics of this system uses the combination of millions of micro movements (swelling) of cells to create a perceivable change that is visible to the human eye.

![Figure 11. BioLogic teabag application, Tangible Media Group](image)

M-Blocks (7) is a Momentum-driven, Magnetic Modular Robot system for novel self-assembling. Each module moves independently to traverse planar unstructured environments (Romanishin 2013)

![Figure 12. M-Blocks prototype, Distributed Robotics Laboratory](image)

The modules achieve these movements by quickly transferring angular momentum accumulated in a self-contained flywheel to the body of the robot.
Programmable Wood (16) from the Self Assembly Lab is a novel printing and composite material technology with the aim of overcoming prior limitations of manual wood forming. By extrusion printing flat sheets of custom wood composites, the group are able to combine the transformative qualities of wood and moisture by engineering geometric forms that can control the morphology of the transformation.

As an example of simplifying assembly processes, the Programmable Table, also from the Self Assembly Lab, provides a stylish example of how by engineering geometries and material composites, something like flat-pack furniture can be designed to be smarter and more intuitive for user assembly.

Some of the limitations we see with current programmable and transfigurable materials are issues such as the need for external energy sources (specifically for the examples of pressure changing membranes), stimulants such as water or heat, and external energy sources and battery power.

Other factors to take into consideration are aspects such as degrees of freedom and multiplicity of states. For instance, is the material binary with just two states, or does it allow for multiple angles of movement/structure/controllability? Tying this into the core project of this thesis, by looking at the pressure for inflation as something that can provide programmable qualities in both volume and movement, reference can be taken from the exemplified works above to show how this added degree of conformability (inflation) can be included to produce both new elements of surprise to a materials capabilities, as well as new functionalities such as changes in buoyancy, stiffness, and flexibility.
Assembly lines (automation + human power)

In the previous pages I have provide examples of existing research that has direct relation to the proposed design space in-which the work in this thesis is directed, which I will go into more detail in later chapters. What I would like to highlight here is that the work produced in this thesis fits within the body of existing work of programmable and transformable materials by way of transformation control-lability.

Next I would like to introduce the concept of material transformation through assembly lines. The process of an assembly line takes a material (or various materials) as inputs, and transforms them through the use of external machinery to produce reconfigured material outputs. Through the development of programmable materials, the idea that materials will be self-transforming has become an explored fantasy, and within such a world, assembly lines will become increasingly distributed. If we can design a system, or material, that allows for half the fabrication labor to be completed outside of the factory, then the use of programmable materials becomes a useful tool for adding value both in economy of transport and user participation.

It is clear that of the examples introduced previously, a number require external stimulus to fulfill their designed function. If we look at the manufacturing process of products, more often than not, a product is distributed from a factory as a completed item, shipped as a whole, whereby the interaction from the user is simply unboxing and placing the item in its place. Sometimes setup is required, such as in the case of digital products, such as plugging in, turning on etc. Through the development of the research in this thesis, the chemical inflation requires activation, which is what is needed to complete the product’s function. This element of interaction is what brings the product to life, adding surprise to the material and eventual structural rigidity.
Feedback

The notion of feedback is important to explore when discussing transformability of materials, specifically in relation to user-assembly. The activation that causes a material change requires clear feedback to convey information to a user, communicating that an event has taken place. Within the case of programmable materials, there are two main stimulants that cause an event to take place:

1. Environmental stimulation
   As in when either an ambient stimulant such as sunlight or heat causes a physical change to occur.

2. User stimulation
   This could be a specific action or force that a user applies, such as shaking or pressing, that triggers a physical change.

Within HCI, feedback is most often designed into a system, e.g. if you press a button, a color change (for instance) will communicate to the user that something has happened. When dealing with materials, designing feedback is not always as simple due to factors such as the compliance of the material or the physical properties that it contains.

To design feedback into a material, the action that the material will perform is essential the premise of the information being conveyed. When we look at inflation, the contortion of the membrane tells a user if something is full (under pressure) or empty. When you blow up a balloon for instance, the deformation of the membrane can communicate if it is going to pop from too much pressure, or if it is faulty due to being unable to inflate. By incorporating this type of feedback information into a design, we can create functional user experiences through the subtleties of a material transformation.
Brief intro

Radical atoms suggest re-conformability, dynamism and programmability of physical materials. From a designers perspective, multiplicity of form is not always a desirable attribute, however the incorporation of dynamic components or state-change can provide application possibilities beyond the rigid surfaces we are used to handling and working with.

By incorporating shape and volume change into the fabrication process, we open up possibilities for a new typologies of form, manufacturing and transportation. Work previously done in PneUI (5) explored this use of dynamic change of membrane through non-perminant interactive feedback. By considering the manufacturing side of product creation as the process of pre-forming a structure, we can think about the user-side as the ‘final touches’, where a product is transformed into its final structure. Along with this functional approach to the use of transformative materials, we can also take advantage of the experience of transformation as an interactive/reactive tool to garner wonder.
Inter-material interaction

The term Inter-material interaction was coined by Follmer and Leithinger in 2013. What they refer to is the interplay between digital ‘material’ and the physical material that we can touch and manipulate, more specifically the augmentation of otherwise inert physical objects with kinetic capabilities (Follmer, 2013). Within this chapter I will refer to inter-material interaction as the interplay between invisible/intangible gases and physical instances, whereby the gas, to an extent, substitutes the digital as a programmable, or controllable, medium upon which to affect a physical body.

The interplay between material states creates behaviors that can be advantageous for applications such as energy production, such as within turbines. Gaseous or liquid behaviors upon soft and rigid structural dynamics can provide outputs, such as kinetic energy, when the movement of the gas particles is strong enough to push a solid structure. Equally with the use of water, kinetic motion can be generated. Pressure buildup is another example of an effect that can have beneficial qualities, for instance by utilizing a barometric effect or filling a balloon membrane with air to increase side and rigidity.

Rigidity and flexibility

The relationship between hard and soft structures and membranes is something we can observe most notably in the human body, as Chelo and Ziegelbaum explain in their paper on Shape Changing Interfaces (17) form and its ability to change in nature are the result of a harmonious orchestration between elements with disparate and changing physical properties. They go on to explain in D’Arcy
Thompson’s words, ‘the human body is neither hard nor soft, but a combination of muscles, bones, tendons, and ligaments that make up the complete load-bearing actuation structure that allows us to walk, resist the pull of gravity, or write this document’. This is an important message when designing artifacts for our tangible environment, especially when dealing with interfaces, as it reminds us that a shell does not necessarily have to be hard, and that is the combination of materials working in unison that create a functional whole.

Figure 15. Illustration from the Anatomy of the Arteries of the Human Body with its applications to pathology and operative surgery, by Richard Quain.

**Programmability of volume**

The ability to control volume from within a deformable structure allows for a unique programmability of space that would otherwise be constant or externally influenced. By having access to this negative space, and the ability to add constraints to its form, we can develop a range of primitive elements that can be used to add parametric properties such as: shape, structure, movement, comfort, and aesthetics to otherwise inert or single-dimensional materials. In relation to the expansion of volume for material programmability, the relationship to muscle movement becomes a distinct action comparison that when com-
combined with rigid and flexible structures can give rise to the types of anatomical movements visible in nature. As well as being able to generate movements with organic similarities, the benefit to utilizing air for this purpose is it's invisibility and lack of density, which means that no extra weight or structure needs to be included, and therefore minimal impact is applied to a membrane.

The project Sticky Actuators by Ryuma Niiyama, looks at how by applying per-fabricated actuation membranes to existing structures, animation effects can be applied to per-existing objects to bring inert materials to life. By imbuing unexpected behaviors such as movement into a familiar object, we can transform the characteristics of an existing structure into something wildly new.

### Actuation

Actuation within HCI provides a powerful mechanism for responsive feedback, so as to be able to communicate, as well as transform the functionality of an interface. Animation (as a result of actuation) is something we perceive and perform constantly, so by being able to imbue a physical change into an experience though actuation, the space in which an interface exists broadens. Thus, we are now in a position whereby what defines an interface expands into areas such as product design and material engineering.

### Material Yield

To create a structure with inflation capabilities, a membrane needs to contain a gas. The transformation of the membrane when exposed to pressure from gas buildup can create yield stress. Once a yield point is met, when a material will no longer deform elastically, it will deform plastically, creating a permanent structural change to the material. In the three-dimensional principal stresses ($\sigma_1, \sigma_2, \sigma_3$) an infinite number of
yield points form together a yield surface (18). By taking yield stress into account when designing a transformable structure, permanent deformation and bi-directionality can be a parameter to be considered, so as to be able to construct surfaces that deform with pre-defined behaviors. For instance, by predefining the atmospheric pressure build-up that will be contained within a membrane, in conjunction with establishing a membrane structure that will deform plastically, inflation can be used to create functional structures with lasting transformations. Another way to look at this would be by utilizing qualities of composite layers, whereby a combination of plastic and elastic transformations can be engineered to create 2-dimensional sheet materials that transform into permanent and semi-permanent structures.
Chapter 3. State-changing Chemical Reactions

To generate the material transformations I have spoken about in the prior chapters, we took advantage of the output produced through simple chemical reactions to activate a specific material behaviors. I will go into more detail later in the thesis to explain specifically what reaction and effect we utilized for the outcome we made, however I will bring to light in this chapter a number of reactions we explored and took into consideration for their output behaviors.

To make clear, the difference between a physical reaction and a chemical reaction is composition. In a chemical reaction, there is a change in the composition of the substances in question; in a physical change there is a difference in the appearance, smell, or simple display of a sample of matter without a change in composition. Although we call them physical “reactions,” no reaction is actually occurring. In order for a reaction to take place, there must be a change in the elemental composition of the substance in question. Thus, we shall simply refer to physical “reactions” as physical changes from now on.
Types of chemical reactions we explored

Acid-Base Reactions (Gas Producing)

Type #1

*Metal carbonate (or bicarbonate) + Acid reaction*

This reaction could be considered an acid-base neutralization reaction. Compounds with carbonate (CO₃²⁻) and bicarbonate (HCO₃⁻) ions act as a base because they will accept hydrogen ions from acid molecules. This lowers the amount of hydrogen ions in the aqueous solution produced by the reaction and neutralizes the acid. The products formed include water and a salt but the difference between this type of reaction and neutralization reactions is that carbon dioxide gas is also produced.

An example of this reaction would be when a solution of sodium carbonate and a solution of hydrochloric acid are combined:

\[
\text{Na}_2\text{CO}_3 + 2 \text{HC} \rightarrow 2 \text{NaCl} + \text{CO}_2 + \text{H}_2\text{O} \ [\text{molecular}]
\]

Type #2

*Metal sulfide + Acid reaction*

This reaction looks like a metathesis reaction, where positive parts of the compounds exchange negative parts. The products formed by this category of reaction include hydrogen sulfide gas and a salt. An example of this reaction would when a solid copper sulfide and solution of hydrofluoric acid are added together:

\[
\text{CuS} + 2 \text{HF} \rightarrow \text{CuF}_2 + \text{H}_2\text{S} \ [\text{molecular}]
\]
Type #3

*Metal sulfite + acid reaction*

This reaction also looks like a type #1 gas-forming reaction, except we replace the carbonate (CO₃) with a sulfite (SO₃). The products formed by this category of reaction include a salt, water and sulfur dioxide gas (instead of carbon dioxide).

\[
\text{metal sulfite} + \text{acid} \rightarrow \text{salt} + \text{SO}_2 + \text{H}_2\text{O}
\]

An example of this reaction would when a solution of potassium sulfite and solution of nitric acid are added together:

\[
\text{K}_2\text{SO}_3 + 2 \text{HNO}_3 \rightarrow \text{KNO}_3 + \text{SO}_2 + \text{H}_2\text{O} \text{ [molecular]}
\]

Type #4

*Ammonium salt + Strong base reaction*

This reaction looks like a metathesis reaction, where positive parts of the compounds exchange negative parts. The products formed by this category of reaction include hydrogen sulfide gas and a salt.

\[
\text{ammonium salt} + \text{strong base} \rightarrow \text{metal salt} + \text{NH}_3 + \text{H}_2\text{O}
\]

An example of this reaction would when a solution of ammonium chloride and solution of potassium hydroxide are added together:

\[
\text{NH}_4\text{Cl} + \text{KOH} \rightarrow \text{KCl} + \text{NH}_3 + \text{H}_2\text{O} \text{ [molecular]}
\]
Color Change

Example #1

*Oxygenic photosynthesis*
Photosynthesis causes the production of chlorophyll turning leaves green color. Anthocyanins, produced during autumn, turn leaves red. Carotenoids provide the yellow, brown, and orange hues.

\[6\text{CO}_2 + 12\text{H}_2\text{O} + \text{Light Energy} \rightarrow \text{C}_6\text{H}_12\text{O}_6 + 6\text{O}_2 + 6\text{H}_2\text{O}\]
[equation for photosynthesis]

Example #2

*Rusting Iron*
Color change from iron to yellow
\[4\text{Fe} + 3\text{O}_2 + 6\text{H}_2\text{O} \rightarrow 4\text{Fe(OH)}_3\]

Example #3

*Copper with air*
Copper metal is stable in air under normal conditions. At read heat, copper metal and oxygen react to form \(\text{Cu}_2\text{O}\).
\[4\text{Cu(s)} + \text{O}_2(g) \rightarrow 2\text{Cu}_2\text{O(s)}\]

Temperature Change

Type #1

*Thermite Exothermic Reaction*

Type #2

*Sodium or Other Alkali Metal in Water*

All alkali metals dropped in water will produce an exother-
mic reaction, generating varying degrees of heat. As you move down the group in the periodic table, the energy output of the reactions will increase. The example below shows the reactions between sodium metal and water.

\[ 2 \text{Na} + 2 \text{H}_2\text{O} \rightarrow 2 \text{Na}^+ + 2 \text{OH}^- + \text{H}_2(\text{g}) \]

**Type #3**

**Chemical Fire**

Potassium permanganate + glycerin + water

As an example of an exothermic reaction, if Fe$_2$O$_3$Fe$_2$O$_3$ is mixed with Al and ignited (often with burning Mg), then the thermite reaction is initiated, generating heat as a product of a very exothermic reaction.

- **Application: Fireworks**

\[ \text{Fe}_2\text{O}_3 + 2\text{Al} \rightarrow 2\text{Fe} + \text{Al}_2\text{O}_3 + \text{Heat} \]

**Changes in Odor**

Formation of Precipitate

\[ \text{Ba}^{2+}(\text{aq}) + \text{CO}_2^-\text{aq} \rightarrow \text{BaCO}_3(\text{s}) \]

\[ \text{Ba}^{2+}(\text{aq}) + 2\text{CO}_3^-\text{aq} \rightarrow 2\text{BaCO}_3(\text{s}) \]

Changes in odor can provide applications for signalling through alternatively perceived ambient feedback.
Controllability

Temperature is a major factor that affects the rate of a chemical reaction.

The two distribution plots shown here (fig. 18) are for a lower temperature $T_1$ and a higher temperature $T_2$. The area under each curve represents the total number of molecules whose energies fall within a particular range. The shaded regions indicate the number of molecules which are sufficiently energetic to meet the requirements dictated by the two values of $E_a$ that are shown.

The activation energy needed for the chemical reaction to be triggered can have a direct impact on the rate at which the reaction will occur. So temperature is a variable that we can control to an extent if we want to speed up or slow down the rate of change in a material. This may not always be possible to control based on the medium or substrate we are working with, however it is an important variable to take into consideration when testing transforming effects.

Potential Use Cases

Applying chemical reactions to inert materials to imbue life, or give new qualities to a substrate or membrane, can provide hardware-free transformations for the purpose of surprise, wonder and delight. As each reaction provides differing output qualities at varying intensities, finding specific applications for each type of reaction becomes an exciting task. Many applications have already been applied to products such as the use of exothermic reactions for hand-warmers, or color-change for pH detection. By exploring the potential for these kind of ‘magical’ transformations, we can imbue the Radical Atoms vision of the Tangible Media Group into the every-day experiences through analog transformations.
Chapter 4. Assisted Assembly

By utilizing known behaviors of organically occurring phenomenon like chemical reactions as I discussed in the previous chapter, we can exploit these behaviors for design purposes, for instance with the intent of completing structures. By controlling aspects of a solid geometry in combination with a controlled reaction we can ‘turn random energy into non-random things’ - Skylar Tibbits

Flat-pack furniture

The development of mass manufacturing gave rise to the ability to produce precise, repeatable parts in vast quantities, to be assembled and distributed out of view of the consumer. In the 1800s, when society saw the first signs of factory production, distribution of large quantities of fully constructed products was cumbersome, especially with the main mode of transport being horse drawn carts and primitive railroads. Obviously the inefficiency of this lead to innovation, considering better transportation and assembly methods, and according to U.S. patent records, the first true flat-pack, or self-assembly, furniture design was invented by Erie Sauder in 1951.

This kind of two-part assembly process looks at the deconstruction of a product for production in a factory, and in-turn, an assembly system that provides a user with a set of instructions to assemble that item in-situ.
We can think of this in the same way as we think about DNA. The product has a pre-programmed structure, or sequence of nucleotides, designed of parts connected by joints and screws.

Within the field of design and manufacturing, innovation of the assembly process can provide a more efficient means, both to the consumer and to the manufacturer, for assembly and delivery, however as a consumer, the idea of assembling an item on one’s own may not always be appealing. Therefore through innovation in the area of self-assembling parts, or ‘assisted self-assembly’ we can begin to imagine scenarios where quality products can be shipped efficiently and constructed through minimum effort to high degrees of accuracy. Moreover, with the development of such functionality, products do not have to be limited to the consumer realm, but can provide easy and accessible parts to relief zones, engineering bases and even space travel.

**Material conformability**

Within the physical world, we think of materials as having various states: solids, liquids, gases. Within these categories there are also variants, such as density, rigidity, softness, texture, color, and so on. A single material can have a variety of perceivable states. In the 19th century, a Swedish engineer by the name of Christopher Polhem invented a ‘mechanical alphabet’, or a set of primitives, consisting of mechanical parts which he believed could be used to construct any mechanical object. The idea that with a set of base parts, any mechanism could be brought to life became a foundational pedagogy amongst engineers. However, one limitation of Polhem’s ‘alphabet’ was that all the parts within the repertoire are made of solid, rigid materials. If we consider the world in which we exist, and more specifically the body that we possess, it is an
amalgamation of soft tissue, bones, tendons, liquid and gases. This does not reflect the mechanical design of Polhem's engineering corpus. In more recent years we have seen the development of systems such as soft-robotics come to prevalence, where the understanding of flexible geometry has broadened the fabrication possibilities and structural outcomes of engineered mechanisms.

In similar fashion, Italian designer Enzo Mari contributed a contemporary milestone in design by establishing a format for 'do-it-yourself' furniture, published in his 1974 book 'Autoprogettazione'. This ethos was in contrast to the popular formalism of the time, and provided a democratization of design by provoking an alternative to the capitalist paradigm of mass consumption; building your own furniture, when required.

**Pre-programming geometry**

To assist assembly, design elements such as pre-defined geometries can guide a user through affordance-based direction, such as perforations to non-verbally advise a user where to make a fold. As well as being a guiding mechanisms, pre-programmed geometries can act as guides for automated actuation/transformations. Projects such as Popapy (28) use the material attributes of flexible polystyrene plastic in combination pre-defined folds with thin aluminum sheets, to embed state-change potential into a material.

Along with defined geometries, the combination with material properties is what gives transformable qualities to a structure. To define the properties of a solid material, and thus encode logic into its structure, the properties of, in the case of Popapy, a polymer, depends on the processing history of that material. Key variables in defining a material's properties include temperature, method and speed of processing.
As an example, the extrusion process of polystyrene begins with the raw material which is melted at 190°C and extruded through a slot die. The resulting film exits the die at a temperature above its glass transition point, around 100°C. The extruded material is soft and rubbery. The forced flow through the die causes stretching in the direction of the flow, but to produce a biaxially stretched film, further stretching in the direction perpendicular to the machine direction is required. The stretched film is then taken up by several rollers. These rollers are usually chilled to quickly cool, or quench, the soft film. It is this rapid cooling of the film that gives the material the ability to maintain its stretched shape. Upon the energy input of heating, the polymer chains that have been stretched through the cooling process return to their initial, more random configuration. This is the state of ‘memory’ that the material has.

The behavior of the biaxially-oriented polystyrene is unusual. Most objects soften or melt when heated, or sometimes they decompose if the temperature is high. The polystyrene shrinks dramatically, but its mass stays the same. The decrease in the area is compensated for by an increase in the thickness.

In its ‘relaxed’ state, the composite material is simply a flat sheet without obvious definition, when activated, however, through heat energy provided by a domestic microwave, the 2D structure transforms into 3D geometry. The pre-programmability of this system is embedded directly within the material; there is a stored kinetic potential encoded within the structure. Within the system the energy source is external, in that it requires activation through an energy-consuming peripheral (in this case the microwave). Something that I’m keen to promote through this thesis is the potential for a contained energy source, and therefore no need for external power to stimulate a transformation.
Chapter 5. Proposed Design Space

Inflatables and their functionality

Inflatable structures, more specifically within this context, pressurized membranes, come with a number of attributes that contribute both to aesthetic quality and mechanical functionality. From an aesthetic perspective, the quality of a material to be somewhat ephemeral; lightweight, transparent, with organic curvatures, is something unique that is difficult to replicate in other materials, therefore this quality can be employed within specific use-cases where these attribute are required, for instance within transportation or assembly, the ability to transport something lightweight that can be inflated to add rigidity and structure would be beneficial to reduce energy consumption through unnecessary volume transportation. From a mechanical perspective, the types of actuation and movement possible within a membrane structure provide benefits for instance in flexibility of joint types and actuation of irregular shapes. They also allow for lighter weight components and internal actuation of sold membranes.
Shape Primitives

By utilizing the structural movement generated by inflation, we have a number of characteristics that can be employed to serve various functionalities. In this section I will be looking at the use of inflation for hinging, folding, rigidity, small-to-large structural change, surface pattern and movement. I will also be looking at the use of air for insulation, flotation and buoyancy.

Hinging

By applying the deformation gradient achieved by pressure buildup within an airtight membrane, hinging can be achieved through expansion, applying force on attached parts.

The hinging angle is dependent on the stiffness/flexibility of the inflated membrane. Stiffness, k, of a body is a measure of the resistance offered by an elastic body to deformation. For an elastic body with a single degree of freedom (DOF) for example, stretching or compression of the inflatable membrane.

\[ k = \frac{F}{\delta} \]

F is the force on the body
\( \delta \) is the displacement produced by the force along the same degree of freedom (for instance, the change in length of a stretched spring)

The angle and strength of force is also dependent on the geometry, by designing a system where we can decrease the total length of the outer surface of the airbag membrane, we can generate hinging actions that can control simple as well as complex shape transformations.

Examples of simple mechanical hinge movement:
**Folding**

Origami techniques can be employed to generate 2D to 3D structural change of more complex forms. By applying pressure within specific points of a flat surface, structures can be automatically folded into place through pre-defined folding logic.

**Soft + rigid structures**

By combining a soft membrane with a rigid structure, large and strong, as well as complex structures can be assembled through the input of air.

---

Figure 24. Mechanical hinge designs

Figure 25. Folding Patterns

Figure 26. Design for soft + rigid components
Small-to-large shape change

By optimizing airflow within a structure, for instance by decreasing the inner volume of a structure, structural form can be generated with minimal pressure. This technique is specifically beneficial for small-to-large structural change. The images below show primitive shapes that can be generated in this way.

Surface pattern

Surface patterns can be created by using the heat-pressing technique to create continuous tubular structures. To maintain airflow throughout a membrane, the patterns must be non-isolating, thus allowing a constant flow of air. The repetition of these patterns allows for structural changes that create textured and tactile patterning for both aesthetic and practical functions.
Movement

By controlling the time and order in which CO2 is released into a membrane array, complex movements can be created in order to generate autonomous animation and motion.

The examples below show how by ordering airflow through the channels via multiple valves and passageways, a single structure can obtain alternative movement possibilities.

Insulation

Air provides strong thermal insulation due to its lack of density. By providing a region within a void in which thermal conduction is reduced using air, temperature can be regulated. But utilizing the controllability of the sodium bicarbonate and citric acid reaction, thermal insulation can be included in a use-case for this technique. Something to note is that initially, due to the reaction being endothermic, there is an initial drop in temperature when the chemicals react, however, this is only temporary, and by taking this into consideration as a constraint, can be controlled to provide the required thermal regulation.
As an example of thermal regulation, figure X shows an image of the Eden Project designed by the architect Nicholas Grimshaw and engineering firm Anthony Hunt and Associates. The construction of the ‘biomes’ (the term used to describe the form of the geodesic structures) is made from a tubular steel (hex-tri-hex) with mostly hexagonal external cladding panels made from the thermoplastic ETFE (Ethylene Tetrafluoroethylene). The use of glass was avoided due to its weight and potential dangers. Instead, the cladding panels are created from inflated membranes made of several layers of thin UV-transparent ETFE film, which are sealed around their perimeter. The resulting cushion acts as a thermal blanket to the structure, by creating an insulating air pocket between the outer and inner environment.

**Floatation / Buoyancy**

One of the qualities of inflated membranes is that they have the ability to float. This unique quality provides applications beyond land, out onto water and into the sky. By utilising this parameter, the design space for solid structures can be opened up to include off-land applications as well as light-weight structural applications. By reinforcing a membrane with an internal (or external) anatomy, we can begin to think about the application of self-inflating structures for assembly at sea or in-air. By activating a network of inflatable structures intertwined with solid anatomies could create assembly on water or in air a viable solution to applications such as ocean clean-up or rescue.

Figure 31. Inflated, plastic cells supported by steel frames
Materials

From the research we found that Mylar, the trade name for BoPET, is the most efficient CO2 barrier out of the materials we tested, and therefore provides a good membrane either as a standalone material, or as the inner portion of a composite material.

BoPET (Biaxially-oriented polyethylene terephthalate) is a polyester film made from stretched polyethylene terephthalate (PET) and is used for its high tensile strength, chemical and dimensional stability, transparency, reflectivity, gas and aroma barrier properties, and electrical insulation. A variety of companies manufacture boPET and other polyester films under different brand names. In the UK and US, the most well-known trade names are Mylar, Melinex and Hostaphan.

Mylar comes with many different coatings that can add to both the aesthetic as well as adding mechanical properties to the material. We found that metalized Mylar and more specifically, metalized Mylar (commonly used in helium balloons) with a matte outer coating, has the ability to maintain a pressurized state for many weeks after initial CO2 inflation. One of our test has lasted for 2 months at 1atm pressure.
Other composite materials that we have tested include TPU backed Nylon and rubber. We have also tested a latex, TPU, Mylar composite, which provides mechanical strength with marginal flexibility. These materials are discussed later in the thesis within the specific context of Auto-Inflatables.

**Design criteria**

Fabrication from the perspective of user-assembly has been formalized and distributed, most notably in recent years, through the development of flat-pack furniture. In this way, structures that inhabit large cubic areas can be transported en masse in efficiently deconstructed formats, thus reducing both the carbon footprint of the product delivery, and the cost of manufacturing, by allocating labor in-part to the consumer. To improve the experience of this kind of delivery and assembly process, self-actuating systems can offer aid in 2D-to-3D, or small-to-large, user-directed construction. To establish this process further, we consider a number of ways in which to utilize stored energy within a material with kinetic potential, as well as external energy sources for activation.
Design space

Inflatable assembly can be applied in various ways, from structural primitives, such as pre-programmed material elements, to geometric forms with multi-state structural potential. In the context of this thesis I am focusing on small-to-large structural change, with elemental control of structural form. From an application perspective, space utilization is one of the most useful traits of this technology, given that volume can be generated out of air, thus providing a light-weight solution to storage and transportation of physical artifacts.

Aside from functionality, the aesthetic properties of inflated membranes provide an ethereal and surprising quality to a structure that is unique to this medium. The combination of a both rigid and cushioned membrane provides an almost skin-like texture, which for a solid artifact can add a semiotic value to an object that can be evocative of nature.

With the development of soft structures becoming a prevalent feature in the field of robotics, we can see that there is a clear desire for an aesthetic push in the direction of texture diversity within transformable artifacts. Through the research done in this thesis, we have found a number of appropriate solutions to surface membranes which will provide functionality as well as character for CO2-retaining inflatable structures.
Summary: Primitives Toolkit for the design of inflatable structures

This tables provides a toolkit of primitive elements that can be combined to create a range of functionalities for self-inflating structures.

<table>
<thead>
<tr>
<th>3D Forms</th>
<th>Movement</th>
<th>Texture</th>
<th>Pressure</th>
<th>Membrane</th>
</tr>
</thead>
</table>

- Weak
- Strong
Chapter 6. Designed systems as proof of concept

Auto-inflatable

As a means to explore the idea of self-contained material surprise, we developed a system for material expansion that utilizes the CO2 release of the chemical reaction between Sodium Bicarbonate (NaHCO3) and Citric Acid (C6H8O7). A pressure build up of the CO2 released from the reaction is trapped within an airtight bag/structure, creating a volume change strong enough to inflate and give solid form to a previously soft and flexible membrane. The benefits to a system like this is that it takes very little material to create an expansion, the details of which will be explained in the following chapter.

Basic Reaction

Citric acid [C6H8O7] and sodium bicarbonate [NaHCO3] (aka baking soda) react to form sodium citrate [Na-3C6H5O7], water, and carbon dioxide [CO2]

\[ C_6H_8O_7 + 3NaHCO_3(s) \rightarrow 3H_2O(l) + 3CO_2(g) + Na_3C_6H_5O_7(aq) \]

| Citric Acid | Baking Soda | Water | Carbon Dioxide | Sodium Citrate |
Technical Specifications

One of the core challenges, beyond the controllability of the reaction itself, is the choice of membrane material. Most plastic materials are relatively permeable to carbon dioxide (19). Because the inflatable product needs a combination of properties like low permeability to CO₂, strength, low price and perhaps the ability to be printable, the most reasonable options for the purpose of the research are thermoplastic polyesters and coated thermoplastic polyurethanes.

To define the most suitable membrane material in terms of impermeability to CO₂, based on the existing research documentation we found, we narrowed our own testing materials down to three main options, Mylar, Polyvinylidene chloride, and TPU, the consolidated documentation of each is below:

1. Mylar:
According to the chemical and physical properties sheet, the permeability of Mylar (amorphous polyester) is 16 cc/100in² /24hr/atm/mil, from another source, it is 5.86 cm³*mm/m²*24hr*atm.

A metalized sheet should be an even better solution, and exists as an off the shelf product such as Mylar MC2.

Mylar can be corona treated for easy printing and coating, and some varieties come ready for printing on one side. A heat sealable variety is needed for our requirements so as to be able to create air-tight membranes through a heat-sealing process (20) (21).
2. Polyvinylidene chloride (PVDC):
Polyvinylidene chloride is commonly used as a food packaging agent, often referred to under the brand name Saran. It is made of a synthetic resin produced by the polymerization of vinylidene chloride. A major disadvantage of polyvinylidene chloride is that it will undergo thermally induced dehydrochlorination (22) at temperatures very near to processing temperatures. This degradation easily propagates, leaving polyene sequences long enough to absorb visible light, and change the color of the material from colorless to an undesirable transparent brown. However low permeability to water vapour and gases makes it a good barrier for membrane applications.

3. TPU:
We have tested nylon fabric coated with TPU as the heat sealing layer. The direct source of TPU we used is unknown, but was comparatively quite permeable to CO2, and inflated structures lost their gas content after a couple of days. According to (23) polyester-TPU, polyether-TPU and polycarbonate TPU exist and have lower permeability to CO2. According to our calculation (data is not readily available and comes in different conventions), permeability is about 70-300 cm³·mm/m²·24hr·atm, or 13-60 times more permeable. (24)

We do not recommend using TPU alone if long inflation time is desired. Creating a composite structure with fabric such as nylon and mylar could provide both the required CO2 barrier, and the strength and aesthetics required.
Inflation characterization and chemical ratios

It is hard to quantify general inflation time since it heavily depends on the inflatable structure, mixing/water separation mechanism, liquid volumes and distribution of chemicals.

From our experimentation, it seems like the rate of inflation is mainly determined by:

1. Water getting in touch with both chemicals.
2. Dissolution of the chemicals in the water.

We have conducted experiments using square 10cm x 10cm bags. According to the tea bag problem solution, the inflated volume of such a bag should be ~0.19L, so for 1atm of gas pressure we used:

<table>
<thead>
<tr>
<th>Inflated volume (L)</th>
<th>Sodium bicarbonate (g)</th>
<th>Citric acid (g)</th>
<th>water (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19</td>
<td>0.700</td>
<td>1.5</td>
<td>1-2</td>
</tr>
</tbody>
</table>

Since baking soda is the limiting reactant (it will determine how much CO2 will be released in the reaction over all) its quantity should not exceed a certain amount per desired pressure, which can be calculated according to the desired volume to inflate, V(L).

For example, for 1atm pressure (above the atmospheric pressure):

\[ M_{Na_2CO_3}(g) = n \times M_w = M_w \times \frac{PV}{RT} = 3.45 \times V \]

The amount of acid can be calculated like this:

\[ M_{citric \ acid}(g) > 2.3 \times M_{Na_2CO_3}(g) \]
This table can be used to facilitate the calculations:

<table>
<thead>
<tr>
<th>Volume (L)</th>
<th>Pressure</th>
<th>S.BC (g)</th>
<th>C.A (g)</th>
<th>Suggested Water volume (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1 atm</td>
<td>0.345</td>
<td>0.800</td>
<td>1-2</td>
</tr>
<tr>
<td>0.05</td>
<td>1 atm</td>
<td>0.173</td>
<td>0.285</td>
<td>0.5-1</td>
</tr>
<tr>
<td>0.01</td>
<td>1 atm</td>
<td>0.035</td>
<td>0.080</td>
<td>0.5-1</td>
</tr>
<tr>
<td>0.1</td>
<td>0.5 atm</td>
<td>0.175</td>
<td>0.400</td>
<td>0.5-1</td>
</tr>
<tr>
<td>0.05</td>
<td>0.5 atm</td>
<td>0.085</td>
<td>0.200</td>
<td>0.5-1</td>
</tr>
<tr>
<td>0.01</td>
<td>0.5 atm</td>
<td>0.018</td>
<td>0.040</td>
<td>0.5-1</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1 atm</td>
<td>0.035</td>
<td>0.080</td>
<td>0.5-1</td>
</tr>
<tr>
<td>0.05</td>
<td>0.1 atm</td>
<td>0.018</td>
<td>0.029</td>
<td>0.5-1</td>
</tr>
<tr>
<td>0.01</td>
<td>0.1 atm</td>
<td>0.004</td>
<td>0.008</td>
<td>0.5-1</td>
</tr>
</tbody>
</table>

The images below show a visual representation of the table above.

Figure 34. From right to left: Inflated bags of 0.2L at pressures of 1 atm (rigid) 0.5 atm (soft but inflated) and 0.1 atm (almost un inflated)

As these visual representations show, the difference between pressure makes a significant impact on the structural deformation of the inflated bags. By utilizing this level of controllability, the programmable aspect of the structure can be designed so as to define specific application outcomes. In the main application we explored looking at the development of toy surprises, the expansion aspects became an important way to control specific elements of the toy design through controlled deformation.
Materials tested for water/citric acid solution capsule

We have tried very thin gauge polypropylene and polyethylene for the bag material to encapsulate the citric acid solution. From our trials, polypropylene worked better. Both materials were bought as a sleeve roll, filled with the solution and heat sealed. This is an industrial procedure used for making pop-ice, soy sauce bags and so on. The material needs to be thin enough, or the seal weak enough, to break under reasonable pressure.

Water volumes needed to inflate different material volumes

The amount of water needed to cause a reaction is very small. But, there are two problems with small volumes of water:

1. Solubility. Water can dissolve ~1.5g citric acid/ml of water and about 1g/ml of sodium bicarbonate. So, for example, for a bag of 1L at 1atm, we will need 3.45g sodium bicarbonate, 8g citric acid, and ~8 ml of water.

2. Adhesion of water to the plastic container. If a very small amount of water is used, much of it will “stick” to the surface of the capsule, resulting in very little water reacting with the sodium bicarbonate.

Activation Techniques

CO2 is generated when all 3 components mix:

Water, Baking soda and Citric acid

Therefore, it is possible to separate any one of them from the others to obtain a controllable reaction. As previously
described, this also has an effect on the inflation speed.

**Slow inflation (1-2 min for full inflation):**
Powders are inside the external inflatable package, water is inside a capsule or added by the child through a valve or a hole in the package that can be blocked with a cap.

**a.** The powders are isolated in an absorbing pouch (like paper towel or fabric) inside inflatable package.

**b.** Powders are just freely dispersed inside inflatable package

**c.** The powders are isolated in a dissolvable pouch inside the inflatable package.

**Medium speed inflation (~1 min full inflation):**
One of the powders is dissolved in the water, the other is in powder form. Both the aqueous solution in a capsule and the powder are confined within the inflatable package.

**a.** Acid dissolved in water (higher solubility)

**b.** Baking soda dissolved in water (lower solubility)

**Fast inflation (<1 min, approximately 30 sec for full inflation):**
Both powdered reactants are dissolved in water, separately.

**a.** One bag inside another - resulting in a one step interaction

**b.** Two bags, one next to the other - two step interaction.

The rate of reaction can be tuned according to these guidelines and interactions can be tailored.
Design of inflated parts

The design of inflated parts is difficult because of the deformations that occur when a 2d shape inflates, wrinkles and deformations may occur.
While we do not have a computation tool to deal with this, there are some resources that can be helpful:

CAD
1. Within the Tangible Media Group, a design tool was created by Chin-Yi Chang for the project Prinflatable. The tool was made using the Grasshopper platform with a custom script for the Kangaroo plugin to simulate inflation behaviors within the Rhino 3D modeling environment. (25)

2. Disney research published a very related paper on CAD design of inflatable structures made of 2d material. (26)

Manual/computational design of curvatures and bending
Our research group has developed a number of different approaches for controllable bending and folding of structures.

\[ \theta = \arccos\left(\frac{a^2 + b^2 - w^2}{2ab}\right) \]  

(1)

Figure 39.

The figure above shows the equation necessary for designing a hinge structure to simulate fold mechanics of an inflated geometry.
Release Mechanisms

Existing release mechanisms for CO2 gas canisters commonly use a 2-part tab mechanisms that in a single pull will open the canister to allow for the CO2 execution. See fig. 40.a.

Based on this system, we designed a number of release mechanisms that look at different methods to pierce the water-filled polypropylene bag, by applying variations in gestural movement to the mechanisms such as pushing, pulling and twisting, which apply pressure to pierce a bag.

The importance of these actions is to ensure a specific and controlled action is performed so that accidental activation is avoided.
Fabrication Process

The manual fabrication of this work involves a number of steps to get all the elements of the design working in unison. To piece the parts together requires these main steps:

1. Laser cutting the membrane shape
2. Partially heat-sealing laser cut membrane
3. Pre-dissolving the citric acid in the water
4. Filling the polypropylene bag with water mixture and heat sealing
5. Placing measured quantity of sodium bicarbonate and water+ citric acid capsule in the pre-sealed membrane
6. Heat-sealing the air-tight membrane

Design possibilities with such a system

For our specific application we have been looking at the design of children’s toys that have the specific requirements of needing to fit within a small casual, be surprising and also safe to use. Beyond toys, there are also application possibilities in areas such as flat-pack furniture,
by using the combination of soft and rigid structures to control elements of the movement. As currently the designs we explored require a one-time behavioral change, the applications are specifically single-time, and therefore multiple feedback options are limited.

Figure 4. Folded ring  
Fig 5. Triggered flower

Auto-inflatables within HCl

By utilizing chemical reactions for construction purposes, we give way to unique, light-weight fabrication methods that can be self-evolving or human directed, through pre-programmable structures with in-build energy potential. In terms of interaction potential, the proposed system for chemical inflation, in its current state, does not allow for sensing, and is therefore the human interaction is simply an activation through a trigger behavior. This
is something that can be built upon to provide a wider range of interactive possibilities, which will be application specific. However, I would like to emphasise here that the uniqueness of this project is not in the interaction but in the material itself. The activation triggers a controlled transformation. The computation aspect of this project is within the controllability of the form; the artifact is therefore comprised of a single action with in-built transformation properties.

Auto-Inflatables therefore can be applied in HCI through various directions:

1. **Fabrication** - digitizing fabrication, movement through inbuilt dynamics
2. **Assembly** - using the attributes of small-to-large and soft-to-hard material change for assembly
3. **Simulation** - quick 2D to 3D iteration*

*Within the physical world there is, most-usually, a finite extent to editability. The physical prototyping process requires numerous iterations and mistakes before a final product is built, so inflation could provide a high-speed alternative to fully prototyped 3D structures.
Chapter 7. Design development with Fererro MPG toy company

As a proof of the working project, the technical and design research we conducted was further developed in collaboration with Ferrero MPG (Magic Production Group), one of the biggest global toy manufacturers. Working with the team we developed a functioning expandable toy with fully working capabilities which will be put into factory production within the next 3 years. This is a big success of the project as we have transformed something from a research idea to a deployable product.

The project took a total of 6 months to complete in collaboration with the MPG team, below I will explain some of the core engineering factors that went into the development of the toy and the final outcomes along with comments from the Ferrero board.

Figure 44. Group brainstorm at Ferrero MPG HQ
Design workshops

We conducted a number of workshops with the innovation team from Ferrero/MPG where we discussed application of the self-inflating structures within toys. The kinder egg product from Ferrero proved to be a specifically applicable design space for such a techniques, as the requirements for the kinder surprise (the toy that come within an outer chocolate egg) are that it must firstly be small, secondly be safe, and thirdly be surprising. The self-inflating technique we discussed fulfils all those categories. Throughout our workshops with the team we explored the concept, the prototypes and specific applications such as inflating fairy wings, outdoor toys and transformable behaviors of the material. The outcome of the design workshops with the team brought a number of new ideas to the table such as the use of the inflatable membranes for applications such as outdoor toys, whereby the toy can be transformed from within a very small space to a large ball game or Frisbee for instance. The main outcomes were:

1. **Shape transformation**: Creating a fairy with wings that expand when activated.
2. **3D Geometry (Hinge Effect)**: Using computational bending curvature to create a dinosaur with transformable limbs in multiple directions.
3. **Size Impression**: Using the a stretchable membrane to create outdoor activity toys such as a Frisbee.

![Diagram of the inflatable toy components](image)
Core principles of chemical inflation for toy applications

For the collaboration with MPG, we decided upon five main principles that would frame the research. Toy safety was a key concern which we wanted to address, specifically within the context of toys with small parts. As one of the prerequisites of the toys developed by the MPG team is that they are made of small parts that can be transported in 40mm long capsules with a radius of 30mm, the toy parts that are transported tend to be small and therefore easy to be swallowed, posing choking hazards. What our research allowed for is a toy that can be shipped within the small capsule but transformed into a large toy upon activation of the chemical reaction. This provided a unique opportunity for Ferrero to develop large, non-swallowable toys and transform their product value with the addition of new toy possibilities. Therefore, the main principles we came up with for the application fulfillment are as follows:

- Safety implementation through increasing a toys’ volume
- Utilizing food-grade materials for CO2 release from chemical reaction to activate inflation
- Implementing techniques to control shape/movement
- Developing process and mechanisms for controlling reaction variables
- Opening up new toy possibilities such as role-play and active play through size increase and surprise transformation effects.

Based on the points, we turned our focus to one of the key quality control attributes, that being the development of a strong membrane material and production method that creates a secure barrier so as not to allow access to the inner chemical materials.
To do this we experimented with many material possibilities through compositing layers to create lightweight and flexible membranes with a tough enough tensile strength so as not to be broken with light to moderate force.

The composite we developed that performed best in our tests consisted of a layer of 0.1 mm thick Mylar, for its CO₂ containing properties, heat-fused with a 0.1mm layer of Thermoplastic Polyurethane, fused with woven Nylon (Fig. x).

![Diagram of composite process using heatpress and 3 material layers](image)

Ultimately, for a functional and deployable product to be successful, the finished membrane should maintain these properties:

![Diagram of capsule within membrane with key factors for membrane design](image)
Along with the development of the outer membrane, the development of a functional and industrial inner capsule was important. The properties of the inner capsule were that it should be resistant to decay from an acidic liquid, and breakable under the force of an intentional strength, capable of a child.

Our solution to this was to create a polyethylene capsule that we filled and heat sealed. We discovered that this is an existing industrial process which can be directly utilized, and therefore would not require the development of any new industrial techniques by Ferrero.

To ensure that no accidental activation occurs, we designed a system collaboratively with MPG for 4 toys that each display a unique characteristic of the inflation qualities. For each toy we designed a specific rigid activation part that integrates into the soft membrane.

The activation components comprise of two-part mechanisms that require a specific dexterous movement to be completed so as to pierce the polyethylene bag. This is very important because if accidental activation occurs we could risk the possibility of a child activating the toy in their mouth, causing inflation to block the airways.
Based on the initial release mechanism designs we made, the components we designed consisted of designs for four surprises: A fairy, dinosaur, Frisbee, and butterfly. The designs for the rigid components are seen here below.

The images below show the constructed prototypes consisting of the rigid release mechanism and the soft membranes for inflation.

As I mentioned before, each of the designs demonstrates different unique characteristics of the inflation properties. By this I mean that the transformation possibilities of inflation can be controlled by restricting different aspects of the 2D geometry, so that once inflated will provide unique transformation of the 3D structures.
From June 26th to 28th 2017 we conducted a workshop and presentation the Ferrero board members at their headquarters in Italy, where we presented the entire research process and proposed applications for to the team. The responses from the presentation were unanimously positive and the Ferrero group saw the benefit of the technology within their products.

The continuation of this research will be done in-house by the MPG team who will take the work we have achieved and find ways to industrialize the processes so as to be manufacturable.
Chapter 8. Future Directions

Having developed a reliable system for creating self-inflating structures that require a simple human interaction to activate a volume-change, and finding specific application within the toy industry, I would like to continue this research by pushing it in new directions more specifically directed towards assisted assembly within architecture, and disaster-zone relief. By exploring geometry transformation through inflation, with specifically controlled pressure gages, I believe the technology will provide beneficial assistance where quick-acting structural implementation is required.

One of the technical challenges for the continuation of this work on an architectural scale is the need for larger quantities of CO2 for the inflation, as well as a more durable and robust membrane.

To put this into motion I will be collaborating with a post-doctoral student from the architecture department to develop a release mechanism to instantly trigger inflation of large-scale structures for space applications. The main drawbacks we will need to overcome will be understanding the quantities of reagents needed for large-scale inflation, structural strength, speed controllability and transformation possibilities for large membranes.
Another application I will be prototyping is the development of an emergency response protective bandaging for use within disaster zones. From the research we have developed it came to our attention that this would make an ideal application as the material itself will be lightweight so easy to transport and quickly activated to provide relief and support to injuries acquired in extreme conditions.

We have begun to develop a prototype (see appendix) which works like a tape that can be discretely activated moments before being applied to the body. By utilizing the endothermic properties of the reaction also, the cooling qualities of the reaction can be used to its advantage to provide anti-inflammatory functionality in the period between first-aid to treatment.
Conclusion

In conclusion, the utilization of chemical bi-products for the purpose of shape-change and material augmentation provides a useful resource to provide hardware-free inflation methods. Limitations to the system rest in the fact that the process provides a one-time activation mode, which in the context of HCI does not allow for the fidelity of applications that a pneumatically controlled system would, however, the advantage of such a system is that it's one-time use can be applied to other areas such as construction, fabrication and immediate surprise, without the need of energy consuming devices. In the context of material curiosity, the implementation of surprise is something that is a unique characteristic and can be developed further to contribute to areas such as learning/education, as well as adventure and play.

By providing a material with stored energy potential, we are giving life to otherwise inert materials through movement and shape-change.
APPENDIX

Beyond the work done in collaboration with Ferrero, we have been developing a system for structural primitives using inflation as a hinging mechanism for structural bodies. We found that to create a structural transformation, we can utilise the minimum inflation necessary to add an inflated frame to a soft structure to give it an overall rigidity. Below is some of the documentation of this work.
Another application that I developed in collaboration with Chrisoula Kapelonis from the MIT Media Lab and Valentina Sumini from the MIT department of Civil Engineering is a tape for first responders and people in war zones to apply instant pressure to wounds using the chemical activation cells within a bandage. Images below show the documentation of this work.
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