

Adaptive Camouflage

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Abstract

Adaptive camouflage is a type of defense mechanism in which an object is rendered either hard to see or invisible to a particular observer. The possible applications of this technology are desirable for both civilian and military use alike. In this paper, I report a review of several possible methods of achieving this goal, as well as multiple ways of implementing them.

1 Introduction

The official title of the project is “Adaptive Camouflage,” and as you can imagine, there are any number of ways that I could take the project in. Over the past ten weeks I have investigated several possible methods of achieving this goal. I researched some more than others, and I will provide an introduction to each one here. In addition, I will include supplementary information for the direction in which I spent the most time.

1.1 Mimicking Nature

An obvious starting place for actively controlling camouflage would be to try to mirror the mechanisms of nature that produce the same result. This is available in a whole slew of animals, the most well known example is the chameleon. While the color changing abilities of this animal are impressive, it is typically agreed upon that it does not occur as an attempt to counteract a predatory threat. [1] Rather, it comes with the introduction of stress or temperature change. [2] The chameleon may change color as a result of the introduction of a predator, but it is a result of physiological processes, rather than psychological. [3, 4]

There are many who would disagree with this, and it would not be entirely unwarranted. [5, 6] Other studies suggests that the color changing abilities of the chameleon can be attributed towards facilitating social signaling. [7, 8]

But this is not to say that there do not exist animals that are able to change their color on de-

mand for the purposes of camouflage. Most notably is the cuttlefish, which can quickly and accurately shift its color almost instantaneously. Intriguing research demonstrates the dynamic color changing abilities of the cuttlefish by introducing them to a variety of checkered backgrounds and measuring their response. [9]

In both of these animals, the mechanisms that are employed to induce color change involve manipulation of the pseudo-transparent chromatophore cells atop various layers of reflective iridophores and leucophores. [10] A small sack of pigment within the chromatophore is manipulated via small muscles resulting in color change. [11]

The technical challenges that would arise from attempting to mimic this phenomenon are daunting and cumbersome; delving more in to biology than physics or chemistry. Although these animals do present curious behaviors that would be desirable to reproduce, neither my background or the physics department at Kansas State University have the necessary resources to pursue it.

1.2 Invisibility Through Metamaterials

Another possible way of achieving adaptive camouflage can be pursued through the use of metamaterials. In short, metamaterials are a type of material that gain their properties from their structure rather than their elementary constituents. [12] These metamaterials have proved to present revolutionary abilities; for example, they may be engineered to

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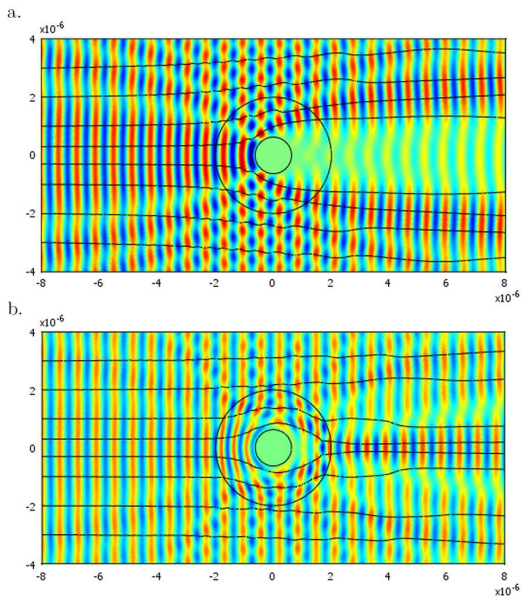


Figure 1: (a) A metal cylinder scattering impinging microwaves. (b) The same metal cylinder surrounded by a cloak made of metamaterials. The microwaves can clearly be seen curving halfway around the cylinder before returning along their original path.

have a negative index of refraction. [13, 14] Using metamaterials, it is possible to control the electric permittivity and magnetic permeability in such a way that electromagnetic waves can be manipulated in ways previously thought impossible. [15]

In fact, John Pendry at Duke University demonstrated that it is possible to create a “cloak of invisibility” by creating a gradient of the magnetic permeability, varying from the 0 at the inner radius to 0.27 at the outer radius. [16] In 2006 this theory was confirmed when Pendry and his team successfully diverted microwaves around a metal cylinder surrounded by metamaterials, rendering it invisible (See **Fig. 1**). [17] However, these results are only valid at one frequency in the microwave region.

Vladimir Shalaev of Purdue University has suggested a similar design employing nanorods radially distributed resulting in a cloak that functions within the optical spectrum. [18] However, no such device has yet to be created.

I was able to precisely model Pendry’s design in Autocad, however since our department does not have the resources to actuate such a device, I did not pursue the idea further.

1.3 Invisibility Through The Optical Theorem

Yet another possible means of achieving adaptive camouflage is through the Optical Theorem. The

[†]In particular, it should be noted that oftentimes nanoparticles are also classified as quantum dots, which describes the mechanical regime in which they follow.

Optical Theorem relates the forward scattering amplitude to the total cross section of the scatterer. [19] Mathematically, it can be expressed as

$$C^{ext} = \frac{4\pi}{k_1 |E_0^{inc}|^2} \text{Im} \{ \mathbf{E}_0^{inc*} \cdot \mathbf{E}_1^{sca}(\hat{\mathbf{n}}^{inc}) \} \quad (1)$$

where $k_1 = \omega \sqrt{\epsilon_1 \mu_0}$ and C^{ext} represents the scattering cross section. [20] With this in mind, recall that our goal is to actively camouflage (or similarly, “cloak”) a given object. If we assume our object to exhibit particle-like properties, then we can also assume that **Eq. (1)** applies. If we wanted to cloak such an object, i.e. make it so that it does not remove any energy from the incident wave, all we would have to do is make the scattering cross section equal to zero. [21]

There are several instances in which **Eq. (1)** will result in zero; most notably when

$$\mathbf{E}_0^{inc*} \cdot \mathbf{E}_1^{sca}(\hat{\mathbf{n}}^{inc}) = 0 \quad (2)$$

This only occurs when the two elements of the scalar product are orthogonal to one another. [22]

Although research in this area would be interesting, I do not believe that I am familiar enough with the concepts involved to make any progress in the field.

One of the key components in the last and most investigated method of achieving our goals involve gold nanoparticles (NPs) and gels. I will include an introduction to them below, as well as their relevance in **Sections 2.1** and **2.2**.

1.4 Nanoparticles

Nanoparticles generally contain 10^6 atoms or less. As a result, their properties differ from that of bulk samples made of the same particles bonded together.[†] [23] In particular, Michalet et al. suggests that semiconductor nanoparticles demonstrate exciting new applications, particularly in biology and medicine. [24] Specifically, it has been recently shown that nanoscale semiconductor materials tend to exhibit bandgaps that are strongly size dependent; increasing with decreasing cluster size due to quantum confinement effects. [25] Furthermore, it has been shown that these semiconductor nanoparticles can be made (via surface passivation) to be strongly photoluminescent. [26]

In other experiments, gold nanoparticles were coated with silicon dioxide (a semiconductor) and placed on a glass substrate creating a thin film. The

color of the films tended to shift towards longer wavelengths when the interparticle separation was increased (See **Fig. 3** in **Section 2.1**), and also when the shell thickness was increased. [27] Specifically, it was found that the extinction spectrum is dominated by quadripole and octipole absorption as well as scattering, which explicitly depends on the particle size. The plasmon absorption maximum tends to shift towards longer wavelengths when the particle diameter is increased. [28]

Su et al. demonstrated that this idea was applicable to gold nanoparticles without a semiconductor shell. [29, 30] In the paper, the surface plasmon excitation in pairs of identical gold nanoparticles were studied. They found that the resonant wavelength peak of two interacting particles is shifted to longer wavelengths when compared to that of single particles, which they attributed to near-field coupling. [29]

1.5 Smart Gels

A gel can be defined as a “jelly-like” substance, one that is more or less a solid material, and is formed from a colloidal solution. [31] Gels exhibit many mechanical properties similar to that of natural rubbers: a high deformity and reversibility. [32] Microscopically, gels consist of a three-dimensional flexible cross-linked polymer network with a solvent that fills in the gaps. [33] Depending on the particular solvent used, the polymer chains can either attract each other and cause a more dense gel, or repel and cause a less dense gel (see **Fig. 2**).

Gels may be synthesized that exhibit a change in properties when introduced to a stimulus. Such a gel is often referred to as a “smart gel,” although they are also referred to as polyacrylamide gels. [34] The stimuli can vary greatly, as can the result it produces. Some common stimuli are temperature, pH, visible light, UV light, external pressure, fluid composition, antigens, DC electric fields, as well as magnetic fields. [35–39]

If we can impregnate gold nanoparticles into a smart gel and then change its volume (i.e. the inter-

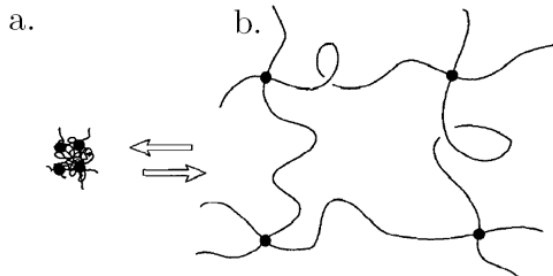


Figure 2: (a) A collapsed gel. (b) A swollen gel.

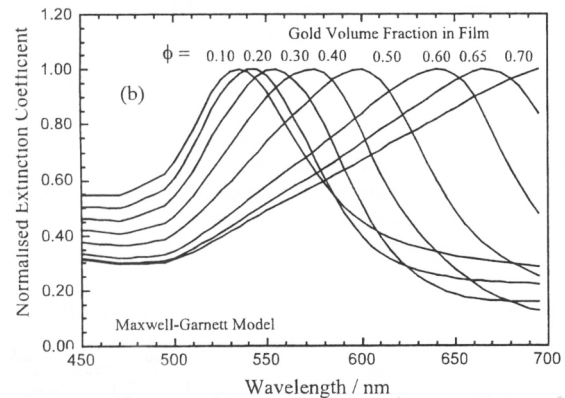


Figure 3: Calculated and normalized extinction spectra as a function of volume fraction.

particle separation), then we should be able to shift the color of the gel at will. This is the last and most investigated method of achieving adaptive camouflage. The nanoparticles are responsible for the wavelength of the transmitted spectrum (color), while the medium in which the nanoparticles lie (the gel) is responsible for changing the transmitted spectrum on demand.

2 Theory

Since this project is a blend of two seemingly unrelated fields, for clarity purposes I will discuss the theory of each subject in turn. In doing such, I will begin with the relevant theory behind the gold nanoparticles.

2.1 Gold Nanoparticle Theory

It might be of relevance to ask how a pair of gold nanoparticles may interact differently when compared to that of one. This can be explained by a dipolar interaction mechanism. This electrodynamic interaction, which occurs when the two particles are in sufficient proximity of one another, has been investigated. [30, 40] Additionally, recent studies by Tamaru et al. have been conducted involving pairs of touching gold nanoparticles. [41]

The relevant effects induced by these interactions can be explained by either a weakening or strengthening of the restoring forces of the plasma electrons that come as a result of the presence of a charge distribution from a neighboring particle. [30] An excellent illustration of this concept is depicted in terms of volume fraction above in **Fig. 3**. [27]

2.2 Gel Theory

Volume transitions in gels are predominantly a result of competition among two types of forces in the gel: attractive forces, which act to collapse the gel,

and repulsive forces, which act to expand the gel. [42] The most overpowering repulsive force within the gel is the Coulombic interaction between constituents of the polymer network having the same charge. This can be induced by ionizing the polymer chains via a (sufficient) potential difference.

Another factor contributing towards the expansion of the gel is the osmotic pressure created by the counterions present in the polymer network. This force can be utilized to induce volume transitions when the free ions in the gel move towards their respective counterelectrode. The attractive forces can vary greatly; some of the predominant forces are van der Waals, hydrophobic interaction, ion-ion interactions between opposite kinds of charge, and hydrogen bonding. [32] Additional aspects of the volume transitions of gels can be explained by Flory-Huggins theory. [43]

As stated previously, smart gels may be synthesized to respond to a variety of different stimuli. Since the stimuli can vary greatly, it is important that we focus our attention on only a couple at a time, rather than all simultaneously. At first inspection, using a DC electric field to initiate volume transitions seems as though it would be easy to control as well as implement. Although, another likely stimulus that may be of relevance is temperature. The majority of the research has been investigating the use of DC electric fields.

There are several explanations that detail the process which governs the volume transition in gels subsequent to the introduction of a DC electric field. The most widely accepted explanation is that a stress gradient is created along the direction of the applied field, which is due to the electrical responsiveness of the charged sites in the gel. [42] This summarizes a point made previously, that the volume transition of gels can be controlled via the Coulombic interaction between the polymer chains in the network (which can be changed via changing the degree of ionization across the constituent molecules). This changes the ratio of positive and negative charges, and causes the gel to either collapse or expand, respectfully.

This can be explained in terms of the energy gain from the formulation of ion pairs in the contracted state of low polarity (competing with the expanded state in which most of the counterions are dissociated). An increase in ionization increases the thermodynamic advantages of the collapsed state with ionomeric multiplet structure over the swollen polyelectrolyte state. [44]

Another way that we can imagine a volume tran-

sition from an electrical stimulus is as follows. Since the polymer network is negatively charged, the positively charged surfactant molecules tend to bond to its surface. This decreases the difference in osmotic pressure between the gel interior and the solution, causing localized contraction. We are able to focus the surfactant binding selectively, therefore controlling the contraction to one side of the gel by introducing a DC electric field. [45]

It is also possible to control the pH of the gel indirectly using a electric field through a process called electrodiffusion. This same process can be used to control the intermembrane ionic strength. Furthermore, electrokinetic processes can cause mechanical deformations in the hydraulic permeability of polyelectrolyte gels subjected to DC electric fields. [46]

3 Experimental Section

Two separate experiments were conducted in parallel: one to study the effect of the amount of sodium hydroxide added (**Table 1**) and another to investigate the effects of adding nanoparticles (**Table 2**) during synthesis.

The water-soluble nanoparticles were used without modification.[‡] Exactly 2ml of the nanoparticles were placed in a large test tube along with 6ml of a 50/50 solution of ethanol/distilled water. The contents were centrifuged for three hours to collect the nanoparticles at the bottom of the test tube. The solution was then removed and replaced with 1ml of distilled water. The precipitate was then deaggregated with an ultrasonic cleaner, and the solution used below.

The polyacrylamide gels were synthesized by free radical polymerization. [47] Acrylic acid (AA), acrylamide (AAM), N,N'-methylenebisacrylamide (BAAM) and Sodium Hydroxide (NaOH) were placed in a 30ml beaker according to concentrations listed in **Table 1**. The total volume was then brought to 25ml and stirred until fully dissolved. N,N,N',N'-tetramethylethylene diamine (TEMED) and ammonium persulfate, the initiators, were then added to the solution. The respective concentrations are listed in **Table 1**.

Table 1: Varying NaOH

No.	AA (mol)	AAM (mol)	BAAM (mol)	NaOH (mol)
1	0.05	0.05	0.0005	0.005
2	0.05	0.05	0.0005	0.010
3	0.05	0.05	0.0005	0.015
4	0.05	0.05	0.0005	0.200

[‡]Nanoparticles were provided by Sreeram Cingarapu and Ashely Cetnar.

Table 2: Introducing Nanoparticles

No.	AA (mol)	AAM (mol)	BAAM (mol)	NaOH (mol)	NP (μ l)
5	0.05	0.05	0.0005	0.015	100
6	0.05	0.05	0.0005	0.015	200
7	0.05	0.05	0.0005	0.015	300
8	0.05	0.05	0.0005	0.015	400

correspond to **Table 1** while 5-8 correspond to **Table 2**. The second set of samples had added to them various concentrations of the preprepared nanoparticle solution.

The samples were then injected into a 2mm ID test tube using a glass syringe. The test tubes were then placed in a small beaker and heated on a hot plate at 60°C for three hours.

After the gels had fully polymerized, they were extracted from the tubes by gently shattering the vials with a hammer. The gels were then individually placed in separate test tubes filled with distilled water and were allowed to reach equilibrium.

Once in equilibrium, the gels were cut into sections 2cm long and placed between two zinc electrodes separated by 3cm in a vat of distilled water. A potential difference of 50V DC was then induced and the volume transitions recorded.

4 Results

The gels with varying concentrations of sodium hydroxide were all uniformly transparent (**Table 1**), while the gels with nanoparticles took on a progressively darker shade with increasing concentrations (**Table 2**).

It was found that at first the volume change for all gels was slow, with less than 2mm deviation from the original size within the first hour. However, upon

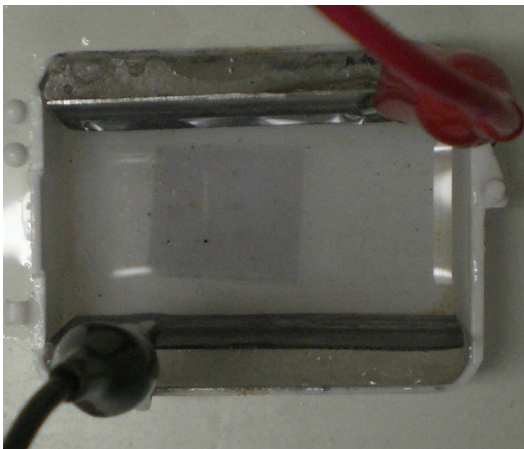


Figure 4: Our experimental setup. The outline of the gel impregnated with the gold nanoparticles is visible between the electrodes.

Table 3: Magnitude of Deflection

No.	NaOH (mol)	NP (μ l)	Final Length (mm)
1	0.005	0	7.5
2	0.010	0	9.0
3	0.015	0	10.0
4	0.020	0	14.0

upon leaving the gels in the field for around 12 hours warranted a greater transition. The exact amount of the transitions for the various gels are listed in **Table 3**. Since the gels from **Table 2** correspond to the same amount of sodium hydroxide as the third sample in **Table 1**, as expected they all had roughly the same magnitude of contraction. For this reason I did not include them in **Table 3**. All gels reverted back to their original size within 12 hours.

In addition to measuring the deflection, in future experiments it would be desirable to conduct a UV-Vis spectroscopy survey on samples containing varying concentrations of the nanoparticle solution both before and after contraction. However, thus far, no such experiment has been conducted.

5 Discussion

There were several obstacles that we had to overcome in order to achieve the results in **Section 4**. The gels were not difficult to synthesize; although the physics department was unable to fulfill our requirement for a scale capable of measuring the small quantities associated with their production. Dr. Christer Aakeröy was able to accommodate my request by allowing me to work in the lab of one of his graduate students, Kanishka Epa, who was very eager to help me in any way that he could.

One of the most cumbersome problems that I encountered was not being able to get the nanoparticles to go into the gel. Initially, we tried to include the nanoparticles during the synthesis of the gel, replacing small amounts of distilled water by the nanoparticles. However, it quickly became apparent that the nanoparticles acted as a catalyst or possibly an initiator to the gel. Within a few minutes, the gel began to coagulate, but would not fully polymerize no matter how long it was heated. This is an interesting result, since the gel normally remains in a liquid state indefinitely unless heated. This effect was observed multiple times, even when infinitesimal amounts of nanoparticles were added during the synthesis.

Another method we tried was first synthesizing the gels as normal, and then placing the completed gels in a solution containing nanoparticles and al-

lowing it to reach equilibrium, hoping that it would absorb some of the particles through osmosis. We found that this also did not work; the gels reached equilibrium by absorbing the water in the solution, leaving the nanoparticles on the outside. This leads us to believe that the nanoparticles are too large to fit through the interstitial regions of the polymeric network in the gel.

This is hard to believe since as discussed in the **Section 1.4**, these particles tend to be rather small. It would seem natural then to believe that somehow the particles are aggregating together to form larger clumps of particles that cannot be absorbed into the gel.

This may in part be explained by the Derjaguin-Landau-Verwey-Overbeek (DLVO) potential. [48] The DLVO potential is a purely repulsive effective potential between charged colloidal spherical macroions. [49] This is expressed in terms of zeta potential vs pH in **Fig. 5**.[§]

As can be seen in **Fig. 5**, if we vary the pH of the nanoparticle solution so that it is no longer neutral, then the magnitude of the electrokinetic potential increases and the particles deaggregate.

In accordance with this theory, we determined that by adding sodium hydroxide to the nanoparticle solution, we were able to deaggregate the particles to a large extent. However, recall that sodium hydroxide is a strong base, meaning that it tends to completely dissociate in water forming an excess of hydroxide ions. Also recall that sodium hydroxide plays a key role in the synthesis of the gel: the volume transition depends sensitively on the concentration of the polyions, $-\text{COO}^-$ and Na^+ in the gel. By varying the

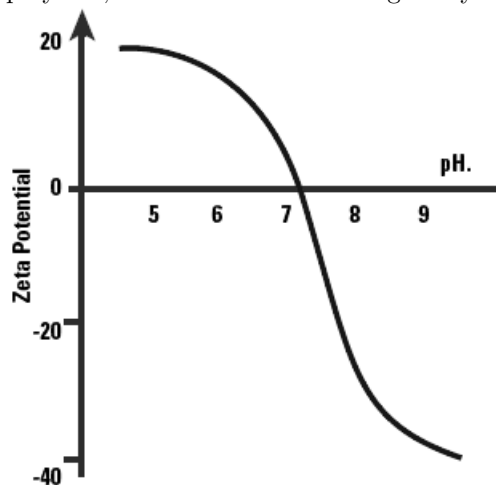


Figure 5: The DLVO Potential

[§]The zeta potential describes the electrokinetic potential present in colloidal systems. [50]

concentration of the sodium hydroxide during the synthesis, we inherently also change the transitional properties of the gel, decreasing in magnitude with increasing concentration of sodium hydroxide. For this reason, we could not use this method to deaggregate the nanoparticle solution.

Upon re-examining our nanoparticles, it occurred to us that there is a relatively high concentration of ligands compared to that of the actual gold nanoparticles (30:1). It then became of relevance to inquire as to whether or not this excess is changing the inherent properties of the nanoparticles, causing them to aggregate.

Subsequent to speaking with the individual who originally synthesized our particles, we were told that it may be possible to remove the excess ligands by mixing the nanoparticles with equal parts of ethanol and water. After centrifuging, the nanoparticles should collect at the bottom, at which point the liquid could be removed and replaced with water. After mixing the particles uniformly with the water via an ultrasonic cleaner, the particles were thought to be deaggregated.

Including these dissolved nanoparticles in the synthesis of the gel did not result in an exothermic reaction, and warranted a gel impregnated with nanoparticles. This was the procedure used to synthesize the gels in **Table 2**.

While this was indeed a large step in the right direction, it was not enough to bring everything together. Recall from **Fig. 3** that the volume fraction must be extremely large in order to warrant observable spectral shifts in thin films ($\phi = 0.10 - 0.70$). [27] Unfortunately, the final volume fraction of the particles inbedded in the gel is several orders of magnitude less than this, even after the volume of the gel has decreased.

The relevant question then becomes is it possible to have a volume fraction of our nanoparticles as high at $\phi = 0.70$ while still retaining the transitional properties of the gel. This is something that we did not have time to explore; but at first inspection, this may be a large roadblock in the road for this project in the future. In order to achieve a volume fraction this large, we would need to shrink the volume of the gel over three orders of magnitude.

6 Conclusions

Even though we did not end up creating a system with tunable optical properties, we took several large steps in the right direction. Since most accomplishments

in science are made from these small steps, we are satisfied with our progress. Still, it is important that we discuss the issues we ran into so that we may continue building on our ideas in the future once we figure out how to solve them.

One of the largest problem that we encountered along the course of this project was our inability to get the nanoparticles embedded into the gel. We were later able to solve this problem by methods described in **Section 5**.

Secondly, we found that even though at first we were using stainless steel electrodes, we would get iron oxide fragments in our distilled water. We later replaced the stainless steel electrodes with ones made of zinc; however this did not alleviate the problem. Instead of iron oxide, the zinc electrodes produced a slimy goo, not unlike ectoplasm. This problem has yet to be solved, although a possible solution would be replacing the zinc electrodes with ones made of platinum or perhaps titanium.

It also may be helpful to create a larger testing device; at the moment, we are only able to fit one sample in at a time. And since the volume transitions tend to be very slow, it takes an extremely long time to collect data. Creating a larger testing chamber, or possibly several small ones, will greatly improve the efficiency of our research.

The largest unresolved problem details the abilities of our system to yield the necessary volume fraction in order to exhibit significant spectral shifts. Before this can be answered, we need to investigate the full potential of the gels in our system. If we can get them to collapse to three orders of magnitude less than their original size, then we will be one step closer to our goal.

Overall we feel as though our time was well invested, although it should be mentioned that we did run out. Unfortunately, it took us so long to get the nanoparticles into the gel that we didn't have enough time to properly measure any optical changes. In the future it may be of interest to do multiple systematic studies (as opposed to one) of this and compare the results.

This is not to say that it was all for nothing, however. The experience proved to be fruitful in multiple respects. One of the most valuable things that I will take away from this experience is the ability to be efficient in research.

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References

- [1] LH Kleinholz. Studies in Reptilian Color Changes. I. A Preliminary Report. *Proceedings of the National Academy of Sciences of the United States of America*, 22(7):454–456, 1936.
- [2] C. Gordon and W. Fox. The Normal Daily Rhythm of Color Changes in the Lizard, *Anolis Carolinensis*, When Exposed to the Contrasting Background Color. *Herpetologica*, 16(4):233–235, 1960.
- [3] M.A.C.E. Hadley and J.M.G. Oldman. Physiological Color Changes in Reptiles. *Integrative and Comparative Biology*, 9(2):489–504, 1969.
- [4] AE Best. The discovery of the mechanism of colour-changes in the chameleon. *Annals of Science*, 24(2):147–167, 1968.
- [5] D. Stuart-Fox, M.J. Whiting, and A. Moussalli. Camouflage and colour change: antipredator responses to bird and snake predators across multiple populations in a dwarf chameleon. *Biological Journal of the Linnean Society*, 88(3):437–446, 2006.
- [6] M. CUADRADO, J. MARTIN, and P. LOPEZ. Camouflage and escape decisions in the common chameleon *Chamaeleo chamaeleon*. *Biological Journal of the Linnean Society*, 72(4):547–554, 2001.
- [7] D. Stuart-Fox and A. Moussalli. Selection for Social Signalling Drives the Evolution of Chameleon Colour Change. *PLoS Biol*, 6(1):e25, 2008.
- [8] K.E. Barnett, R.B. Cocroft, and L.J. Fleishman. Possible Communication by Substrate Vibration in a Chameleon. *Copeia*, 1999(1):225–228, 1999.
- [9] C.C. Chiao and R.T. Hanlon. Cuttlefish camouflage: visual perception of size, contrast and number of white squares on artificial checkerboard substrata initiates disruptive coloration.

- Journal of Experimental Biology*, 204(12):2119–2125, 2001.
- [10] H.I. Nielsen. Ultrastructural changes in the dermal chromatophore unit of *Hyla arborea* during color change. *Cell and Tissue Research*, 194(3):405–418, 1978.
- [11] J.T. Bagnara, J.D. Taylor, and M.E. Hadley. The Dermal Chromatophore Unit. *The Journal of Cell Biology*, 38(1):67–79, 1968.
- [12] DR Smith, JB Pendry, and MCK Wiltshire. Metamaterials and Negative Refractive Index. *Science*, 305(5685):788–792, 2004.
- [13] V.M. Shalaev, W. Cai, U.K. Chettiar, H.K. Yuan, A.K. Sarychev, V.P. Drachev, and A.V. Kildishev. Negative index of refraction in optical metamaterials. *Optics Letters*, 30(24):3356–3358, 2005.
- [14] RA Shelby, DR Smith, and S. Schultz. Experimental Verification of a Negative Index of Refraction. *Science*, 292(5514):77, 2001.
- [15] MCK Wiltshire. Optical Materials: Bending Light the Wrong Way. *Science*, 292(5514):60, 2001.
- [16] JB Pendry, D. Schurig, and DR Smith. Controlling Electromagnetic Fields, 2006.
- [17] D. Schurig, JJ Mock, BJ Justice, SA Cummer, JB Pendry, AF Starr, and DR Smith. Metamaterial Electromagnetic Cloak at Microwave Frequencies, 2006.
- [18] W.C.U.K. Chettiar, AV Kildishev, and VM Shalaev. Optical cloaking with metamaterials. *Nat. Photonics*, 1:224–227, 2007.
- [19] R.G. Newton. Optical theorem and beyond. *American Journal of Physics*, 44:639, 1976.
- [20] M.J. Berg, C.M. Sorensen, and A. Chakrabarti. Extinction and the optical theorem. Part I. Single particles. *Journal of the Optical Society of America A*, 25(7):1504–1513, 2008.
- [21] M.J. Berg. Idea for the Monochromatic Invisibility of a Particle. mberg@phys.ksu.edu.
- [22] M.J. Berg and C.M. Sorensen. Possibilities in Invisibility in Electromagnetic Theory. mberg@phys.ksu.edu.
- [23] C.P. Poole and F.J. Owens. *Introduction to Nanotechnology*, pages 8–9, 226. Wiley-Interscience, 2003.
- [24] X. Michalet, FF Pinaud, LA Bentolila, JM Tsay, S. Doose, JJ Li, G. Sundaresan, AM Wu, SS Gambhir, and S. Weiss. Quantum Dots for Live Cells, in Vivo Imaging, and Diagnostics. *Science*, 307(5709):538–544, 2005.
- [25] L. Spanhel, M. Haase, H. Weller, and A. Henlein. Photochemistry of colloidal semiconductors. 20. Surface modification and stability of strong luminescing CdS particles. *Journal of the American Chemical Society*, 109(19):5649–5655, 1987.
- [26] Y.P. Sun, B. Zhou, Y. Lin, W. Wang, K.A.S. Fernando, P. Pathak, M.J. Meziani, B.A. Har-ruff, X. Wang, H. Wang, et al. Quantum-Sized Carbon Dots for Bright and Colorful Photoluminescence. *Journal of the American Chemical Society*, 128(24):7756–7757, 2006.
- [27] T. Ung, L.M. Liz-Marzán, and P. Mulvaney. Gold nanoparticle thin films. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 202(2-3):119–126, 2002.
- [28] S. Link and M.A. El-Sayed. Size and temperature dependence of the plasmon absorption of colloidal gold nanoparticles. *J. Phys. Chem. B*, 103(21):4212–4217, 1999.
- [29] KH Su, QH Wei, X. Zhang, JJ Mock, DR Smith, and S. Schultz. Interparticle coupling effects on plasmon resonances of nanogold particles. *Nano Lett*, 3(8):1087–1090, 2003.
- [30] W. Rechberger, A. Hohenau, A. Leitner, JR Krenn, B. Lamprecht, and FR Aussenegg. Optical properties of two interacting gold nanoparticles. *Optics Communications*, 220(1-3):137–141, 2003.
- [31] H. Kawasaki, T. Nakamura, K. Miyamoto, M. Tokita, and T. Komai. Multiple volume phase transition of nonionic thermosensitive gel. *The Journal of Chemical Physics*, 103:6241, 1995.
- [32] Y. Li and T. Tanaka. Phase Transitions of Gels. *Annual Reviews in Materials Science*, 22(1):243–277, 1992.
- [33] T. Tanaka, E. Sato, Y. Hirokawa, S. Hirotsu, and J. Peetermans. Critical Kinetics of Volume Phase Transition of Gels. *Physical Review Letters*, 55(22):2455–2458, 1985.

- [34] M. Zrínyi, A. Szilágyi, G. Filipcsei, J. Fehér, J. Szalma, and G. Móczár. Smart Gel-glass Smart gel-glass based on the responsive properties of polymer gels. *Polym. Adv. Technol.*, 12:501–505, 2001.
- [35] T. Miyata, N. Asami, and T. Uragami. A reversibly antigen-responsive hydrogel. *Nature*, 399(6738):766–9, 1999.
- [36] A. Suzuki and T. Tanaka. Phase transition in polymer gels induced by visible light. *Nature*, 346(6282):345–347, 1990.
- [37] T. Hoare and R. Pelton. Functionalized Microgel Swelling: Comparing Theory and Experiment. *JOURNAL OF PHYSICAL CHEMISTRY B*, 111(41):11895, 2007.
- [38] X.Z. Zhang, Y.Y. Yang, T.S. Chung, and K.X. Ma. Preparation and characterization of fast response macroporous poly (N-isopropylacrylamide) hydrogels. *Langmuir*, 17(20):6094–6099, 2001.
- [39] G. Chen and A.S. Hoffman. Graft copolymers that exhibit temperature-induced phase transitions over a wide range of pH. *Nature*, 373(6509):49–52, 1995.
- [40] S.A. Maier, M.L. Brongersma, P.G. Kik, S. Meltzer, A.A.G. Requicha, and H.A. Atwater. Plasmonics: A Route to Nanoscale Optical Devices*. *Adv. Mater.*, 13(19):2, 2001.
- [41] H. Tamaru, H. Kuwata, H.T. Miyazaki, and K. Miyano. Resonant light scattering from individual Ag nanoparticles and particle pairs. *Applied Physics Letters*, 80:1826, 2002.
- [42] T. Tanaka, I. Nishio, S.T. Sun, and S. Ueno-Nishio. Collapse of Gels in an Electric Field. *Science*, 218(4571):467, 1982.
- [43] H. Suzuki. Stimulus-responsive Gels: Promising Materials for the Construction of Micro Actuators and Sensors. *Journal of Intelligent Material Systems and Structures*, 17(12):1091, 2006.
- [44] A.R. Khokhlov and E.Y. Kramarenko. Weakly charged polyelectrolytes: collapse induced by extra ionization. *Macromolecules*, 29(2):681–685, 1996.
- [45] Y. Osada, H. Okuzaki, and H. Hori. A polymer gel with electrically driven motility. *Nature*, 355(6357):242–244, 1992.
- [46] J. Kost. *Pulsed and self-regulated drug delivery*. CRC Press, 1990.
- [47] T. Tanaka, D. Fillmore, S.T. Sun, I. Nishio, G. Swislow, and A. Shah. Phase Transitions in Ionic Gels. *Physical Review Letters*, 45(20):1636–1639, 1980.
- [48] G.M. Kepler and S. Fraden. Attractive potential between confined colloids at low ionic strength. *Physical Review Letters*, 73(2):356–359, 1994.
- [49] N. Gronbech-Jensen, K.M. Beardmore, and P. Pincus. Interactions Between Charged Spheres in Divalent Counterion Solution. *Arxiv preprint cond-mat/9902059*, 1999.
- [50] R.J. Hunger. *Zeta potential in colloid science: principles and applications*. London; New York: Academic Press, 1981.