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CALTECH UNDERGRADUATE RESEARCH JOURNAL

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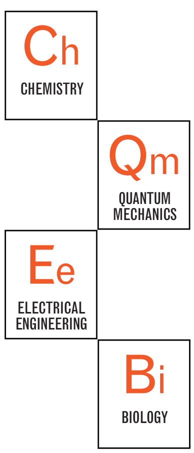

Interview

Research

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FROM THE EDITOR

Scientists are not isolated from the world in a vacuum; they work to improve lives through their discoveries. Although the day-to-day grind in a research lab may be focused on only one chemical reaction, one cell culture, or one electronic device, the research we conduct has wide applications to not only other scientists in the field, but also to the world as a whole.

However, there is no way for any of our research to have an impact outside the academic environment without effective communication. Without this communication, research may as well have not been conducted. From informal conversations with other lab members to publications in world-renowned journals like Science and Nature, science is built upon a large variety of interactions. Talking with a colleague can provide you with new insights or prompt new questions to get to the heart of an issue. Submitting to a peer-reviewed journal will enable others to learn from your conclusions, build upon them, and incorporate them into their own applications. What may seem at first like a simple reaction could actually be utilized within a greater synthetic scheme for a new therapeutic. An isolated signaling pathway could be implicated in a disease that affects millions worldwide. The bounds are endless: there is always more to be discovered, new details to be elucidated.

That is why science is so exciting - the work never truly ends. When a paper is published, when your Summer Undergraduate Research Fellowship is complete, the work does not stop. Publishing is a great milestone, but is not an end in itself. It is simply a way to share with others what you have poured many weeks, months, possibly years into understanding. Because of your hard work, you are the expert. And in your communication, you can show others a result no one else has thought of before!

In this issue of the Caltech Undergraduate Research Journal, four bright researchers share with us their contributions to their respective fields. What may have started as a simple curiosity had led them to discuss their thoughts with other scientists in the field. Through research and open communication, they arrived at new insights that can improve our world. Their work towards increasing security on our communications networks, exploring alternative energy, understanding the basis of Type I Diabetes, and implementing quantum mechanics for computing all have the potential to affect millions of lives. Showcasing their impressive work gives them an opportunity to continue the dialogue and ask us: what can we contribute to the discussion?

Best Regards,

Andrew Freddo
Co-editor-in-chief, 2008-2009

feature interview

By Andrew Freddo

Neha Das

What initially drew you to Caltech?

Caltech seemed like a place that would push me to my limits, and I am never one to back down from a challenge. The environment during Prefrosh Weekend was almost electric – it was amazing to meet so many intelligent and motivated people. Being surrounded by people like that motivated me, and I knew about the amazing faculty and resources so I realized that Caltech was the place for me.

What are your career goals?

Currently I intend to pursue pediatric dentistry and hope to practice as well as study jaw development. Ideally I would end up working in an academic institution, which would allow me to both treat patients and do research concurrently. A balance between these two pursuits will be a little tricky to manage, but I cannot imagine living without either component in my life. Dentistry will allow me to interact with people and have a positive impact on their lives while research will be an outlet for my insatiable curiosity.

Where are you now?

Right now, I am a first year student at UCSF's School of Dentistry.

What types of research did you participate in at Caltech, and how did this affect your career goals?

In Dr. Jacqueline Barton's lab I helped synthesize a rhodium based compound that intercalates into guanine-guanine mismatches during the summer after my freshman year. Everyone in the lab was really nice, but I was doing organic synthesis without knowing anything about organic chemistry so I did not really understand everything I was doing. During my junior year, I took a developmental biology course with Dr. Bronner-Fraser. I really enjoyed the material and wanted to take another shot at work in lab. I worked in that lab until I graduated and also for a year after I graduated, and I cannot even begin to express how much I loved it there. My experience there is definitely a major part of my motivation to continue to do research on jaw development while I practice dentistry.

What was one of the largest obstacles you had to overcome in transitioning from Caltech to the professional world?

After I left Caltech, I had a rather rude awakening. The rest of the world is not as honest as the student body there. If you talk to anyone about the Honor Code, they assume that there was rampant cheating and that people that don't believe that are just naive. I disagree completely. I have faith in the students of Caltech and am confident that the vast majority abides by the Honor Code simply because of the type of people that choose to go to school there. The problem is that the rest of the world tends to favor a different code of ethics, and this undoubtedly requires some adjustment after you leave.

In which ways is Caltech similar to and different from your current work environment?

Caltech and UCSF are actually pretty similar. I'm really impressed with the students currently in my class, and they are just as motivated as my classmates from Caltech. The difference is really in the material more than anything else. Anatomy is a lot of memorization so multiple choice is inevitable, and I have to learn a lot of hands on techniques. We would never have anything like the seven-hour finals of Caltech.

If there were one piece of advice that you could tell current students in planning their future, what would it be?

Find something that makes you happy and that can excite you for a long time. Don't do something just because people expect it of you – at the end of the day, you need to make sure you can look back at your life and feel like you've lived it the best way you can.

Anything else you'd like to comment on?

Good luck everyone!

feature interview

By Andrew Freddo

Helen Lee

Helen graduated from Caltech in 2008, and is originally from Los Angeles, California. She received her B.S. in Chemical Engineering and Business, Economics, and Management. While at Caltech, she participated in Ballroom Dance, and now spends her free time helping out with a volunteer consulting group, Inspire Inc., practicing martial arts, and preparing to hike the Grand Canyon!

What initially drew you to Caltech?

One of the biggest draws about Caltech is the research facility and opportunities on campus. I'm a big advocate of "learn-by-doing" because I think the only way to really understand concepts and theories is to experiment, get your hands dirty, and make some mistakes.

But beyond that, the people really drew me to Caltech. I knew coming to this school, I'd be working with smart, driven, intellectually curious students. When I had the chance to actually meet people, I was pleasantly surprised. Beyond very smart people, I also sensed a very strong community (maybe hardened by surviving through tough classes!) and saw the mutual support that everyone was so willing to impart. That's hard to find.

What are your career goals?

Would it be too idealistic of me to say that I want to change the world somehow? To be quite honest, my hope is that I can make a difference in the world someday (small or big). If my career can take me in that direction... well, then I would call that living a successful life.

Where are you now?

These days, I'm working at a management consulting firm, Bain & Company, as an associate consultant. We basically use an analytical approach to helping companies solve their business problems. An associate consultant's role varies from case to case, but generally we are responsible for a lot of the data and analyses. This ranges from building complicated models to forecast market trends or company valuations to working as the point person with analysts from the client company. I guess that's what keeps it interesting. Our job is to adapt to each new situation as needed.

What types of research did you participate in at Caltech, and how did this affect your career goals?

I participated in a diverse set of bioengineering research projects while I was at Caltech (with a stint of aerospace research right before I started Caltech)... and I had some really great learning experiences with each project. However, going through the research process and even interning as a research associate during my sophomore summer made me realize that though ground-breaking research could potentially change the world, I wasn't patient enough for it.

So I opted for testing out the business path and see where that would lead me.

What was one of the largest obstacles you had to overcome in transitioning from Caltech to the professional world?

Communication. It's a skill that isn't really emphasized at Tech because there's a belief that if you're smart, understand the theory, and can do the work, that should be enough. In the professional world, if you can't communicate what you found, need, or want to do to the rest of your group or your superiors, you won't get anywhere.

It's tough – to be able to concisely move people to action through what you communicate. It's definitely something that I'm still figuring out myself.

In which ways is Caltech similar to and different from your current work environment?

Caltech is similar to Bain in a lot of ways. We all use whiteboards here, we sit around and brainstorm together in our teams to figure out problems, we work collaboratively but competitively, and so on. We even use the motto "work hard, play hard" and dream up fun little video shorts for our annual company offsite if you can believe it! It always makes me nostalgic for the videos we made as a House during Rotation. Granted, Bain still differs from Caltech just like any industry job differs from collegiate life, but I'd like to think that we try to maintain a fun culture (and not take ourselves too seriously!).

If there were one piece of advice that you could tell current students in planning their future, what would it be?

Make more mistakes. There's a belief that failing is wrong – and that often keeps us on a very safe path because we're too scared to venture out, try something totally new, and fall on our face a little. But that's the only way we can really figure out what's right or not right for us.

In college, you can take on an incredible amount of risk and make mistakes without too many permanent consequences. You won't have that same flexibility to explore such a diverse set of career options once you're no longer in school.

What's stopping you, as students, to discover something innovative? To start your own business? To go abroad and volunteer for a summer? To...(you fill in the blank)?

Making fuel by modeling nature: Increasing the rate of hydrogen production with improved dinuclear cobalt catalysts

Author: Carolyn N Valdez
Co-Mentor: Jillian L Dempsey, Harry B Gray

The production and utilization of a clean, abundant, and renewable energy source is widely accepted as one of the key challenges facing mankind today. Population growth and further industrial maturity of underdeveloped nations will increase our current demand for energy. Although fossil fuels may power the planet today, they are being rapidly depleted and their detrimental effect on our environment is being realized. The harmful effect of CO_2 emissions and numerous economic concerns necessitate the use of alternative energy.

Many scientists favor using sunlight as a source of energy because of its abundance—more solar energy hits this planet per hour than is consumed on Earth in a year. Solar cells (photovoltaics) are used today to produce thermal and electrical energy, but we are still unable to store this captured energy. In the interest of addressing this storage problem, perhaps we can model nature's energy storage system. As the phosphate bond in ATP is used to store energy, maybe we can similarly utilize the high energy H—H bond in H_2.

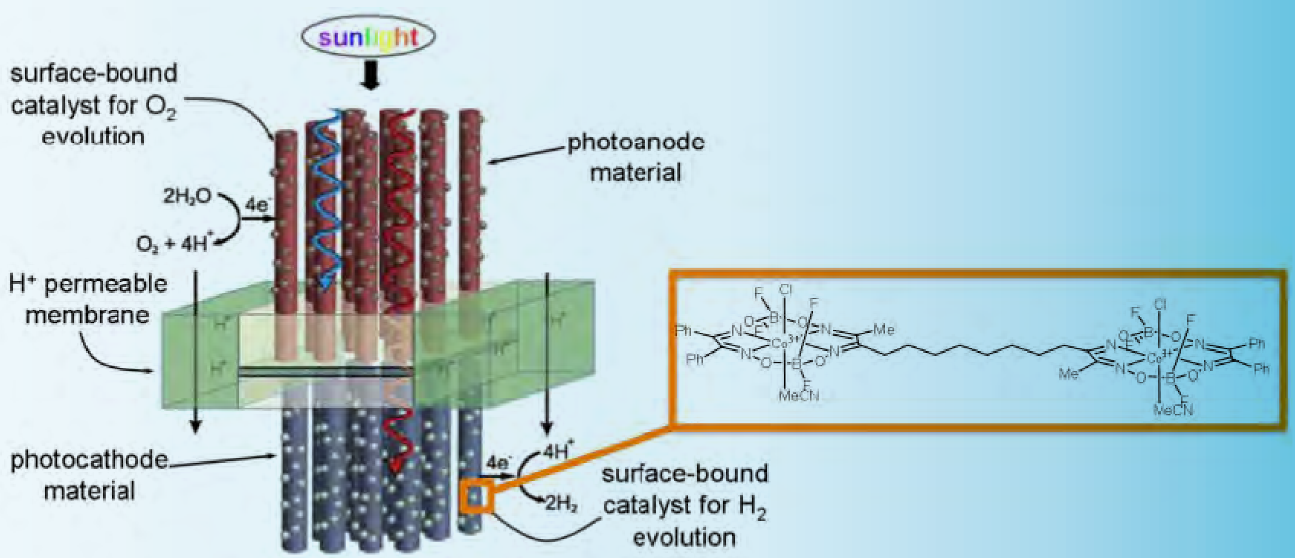


Figure 1
A three-component solar fuel cell that acts as a water-splitter and may one day be used as a source of clean energy. The components include (a) Membrane assembly that captures sunlight to produce separated electrons and holes (b) A catalyst to facilitate the 2-electron reduction of water to H_2 and (c) a four-electron catalyst to oxidize water to form O_2 (Adaptedfrom the CCI Solar website).

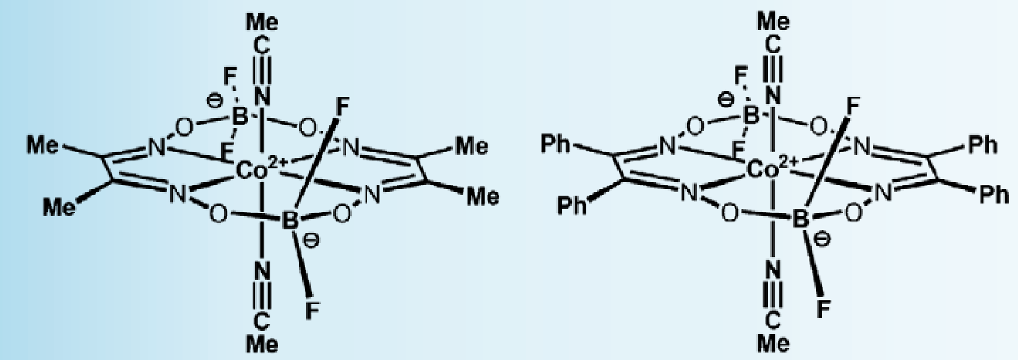
Dihydrogen is even more appealing due to its ability to give up both electrons to form water as the only byproduct of combustion. Yet there are still a few fundamental challenges that we must overcome before hydrogen will be accessible for use as the world's main source of fuel. The current production of hydrogen is costly, inefficient, and storage methods are inadequate. Although industry generates a vast amount of H_2 today, the production is largely based on the burning of fossil fuels, something we want to avoid. Therefore, finding another method to generate hydrogen is of significant interest. Once a method for producing dihydrogen is obtained, preferably in the form of a surface-bound catalyst, it may be used in the Center for Chemical Innovation's proposed solar fuel cell shown in Figure 1.

BASIS FOR THE CATALYST

An ideal hydrogen evolving catalyst operates at the smallest overpotential possible. A catalyst with a large overpotential, measured in voltage by electrochemical methods, requires more energy than thermodynamically expected, rendering it inefficient and expensive. Fortunately, long ago nature developed an efficient catalytic system in bacteria.

These natural energy factories, or hydrogenases, can be found in cyanobacteria and the chloroplasts of plants and green algae. Hydrogenases are capable of either catalyzing the reversible two-electron oxidation of H_2, as H_2 $2H^+ + 2e^-$, or the two-electron reduction of two protons, as $2H^+ + 2e^-$ H_2. Attempts to mimic the bimetallic active sites of these enzymes have been met with challenges of large overpotentials and slow rates. These enzymes rely on the exquisite electronic tuning nature provides with a protein environment, and an exact mimic cannot function without the whole protein. Hence many simpler models of these hydrogen producing catalysts have been constructed to imitate hydrogenase's activity without the complications. However, most of these simpler catalysts are active at such a large overpotential that they could never be used in a functional solar cell, except in a few special cases.

Figure 2
Left: $Co(dmgBF_2)_2(CH_3CN)_2$.
Right: $Co(dpgBF_2)_2(CH_3CN)_2$.
These catalysts have been shown to electrocatalytically evolve H_2 at -0.55 V (1) and -0.28 V (2) vs. SCE (Standard Calomel Electrode).



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MAKING A SUITABLE CATALYST

Decades after it was first noticed that cobalt-based vitamin B12 complexes generated hydrogen in the presence of acid, a former Caltech postdoctoral student studied two analogous cobalt catalysts and showed that they successfully evolve H_2 at a much lower overpotential than other catalysts known in literature (Figure 2).

These cobalt complexes are supported by diglyoxime ligands, where $dmgBF_2$ is difluoroboryl-dimethylglyoxime and $dpgBF_2$ is difluoroboryl-diphenylglyoxime. The mechanism of their hydrogen production has been studied using flash-quench techniques. Shown below in Figure 3, after reduction and protonation of the initial Co(II) catalyst, a Co(III)—H bond is formed. The complex will then either (A) undergo a second protonation to permit the evolution of H_2or (B) undergo bimolecular hydrogen gas release (Figure 3). The simulations performed by Hu et al. as well as thermodynamic considerations suggest pathway (B) is likely the predominant pathway.

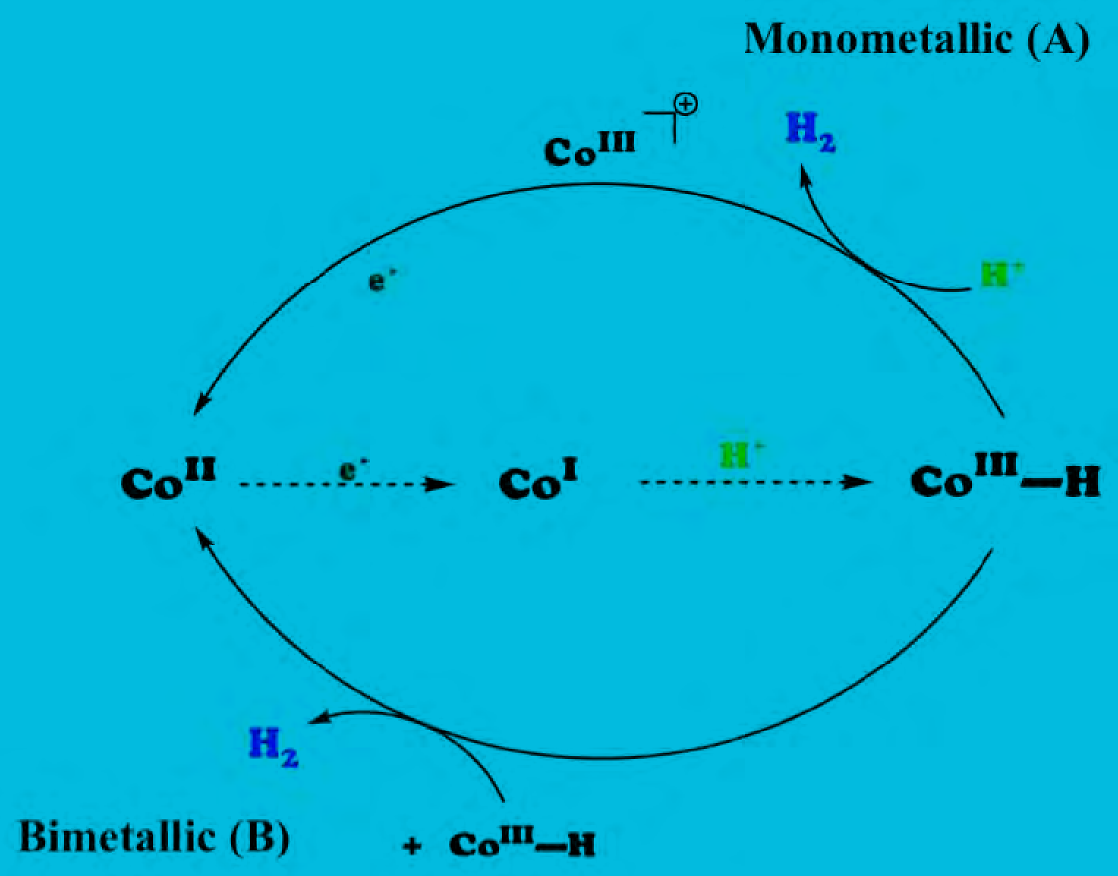


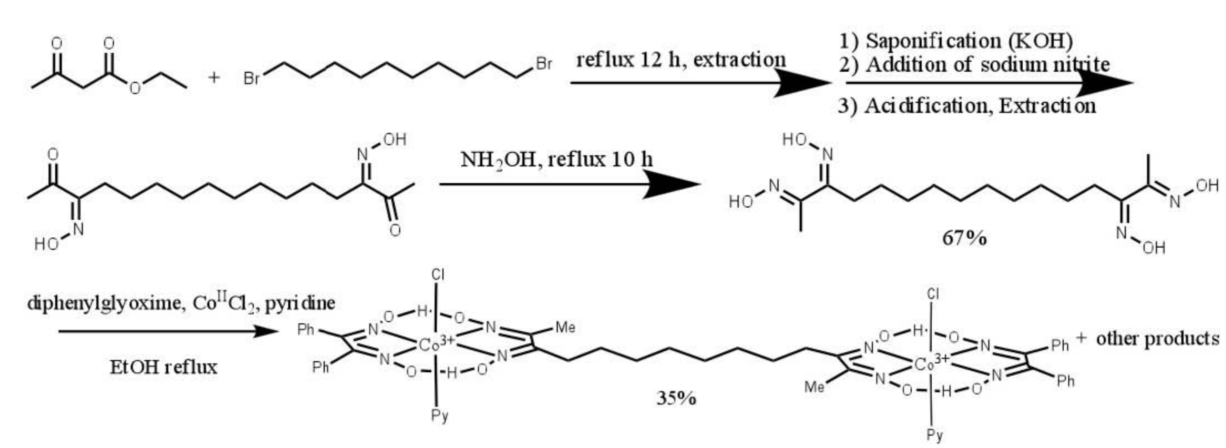
Figure 3
Two proposed pathways for hydrogen production.

Based on these mechanistic conclusions, we propose that the rate of hydrogen production may be increased with a dinuclear catalyst. Tethering two metal centers using a synthetic chain will increase the rate of cobalt collision, and eliminate any rate hindrance via diffusion. Additionally, modification of the linkers may give the catalyst water solubility or allow the molecule to be fixed onto the surface of a solar cell, but still allow two metal centers to be close enough to generate hydrogen.

SYNTHESIS

Several possible synthetic bridges, or linkers, were considered. A long, flexible hydrocarbon chain was targeted as the first and most straightforward linker. Two synthetic pathways were considered (Figure 5). The first involves the monoalkylation of a symmetrical dioneusing an asymmetric protecting group. While this synthesis is useful for making complex compounds, producing the linked diacetyl in this way requires more steps than necessary for a simple alkyl chain and gives a low yield of product. The second, perhaps less elegant, but more practical synthesis utilizes commercially available ethyl acetoacetate (see Figure 4). We were able to obtain a high yield of the ligand, tetradecane-2,3,12,13-tetraone tetraoxime (TDTO). The catalyst was completed by metallating TDTO using cobalt and capped with difluoroboryl groups for stability and a further decrease in overpotential. The catalyst is synthesized with cobalt in the 3+ oxidation state, which cannot be oxidized, or decomposed, by air. Thus this catalyst, unlike those described above, is sufficiently stable to purify on a silica gel column. The pure catalyst was isolated from other products and is shown below, overlayed on the graph, in Figure 5.

Figure 4
Synthesis of the dinuclear catalyst. The first step involves SN2 attack, saponification and decarboxylation to generate the mixed dione. Refluxing with hydroxylamine will give the final linked dioxime (TDTO). Metallation with pyridine will give the metallated product, and addition of borontrifluoride in acetonitrile will replace the pyridine axial ligands with acetonitrile to generate the final catalyst.



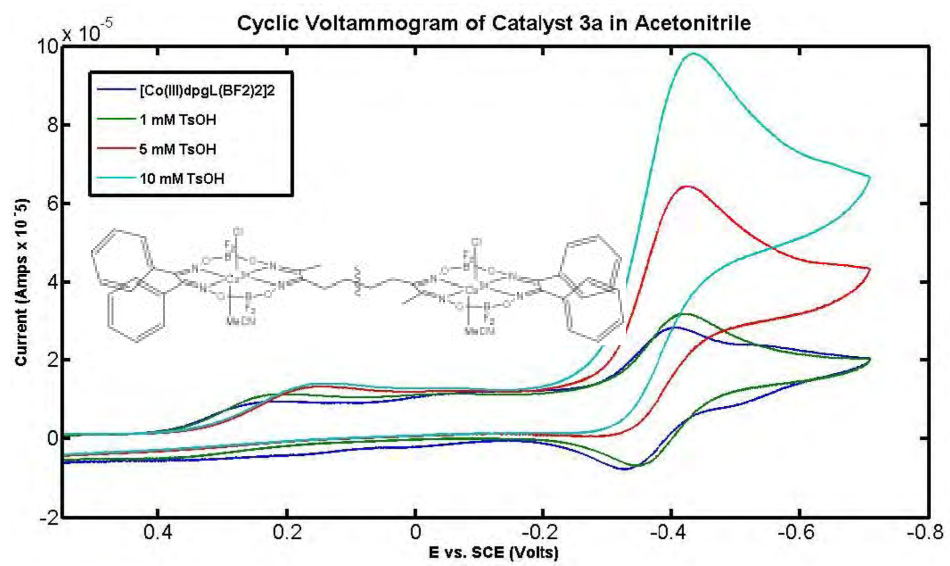


Figure 5
Cyclic voltammogram of [(MeCN)(Cl)(dpg)(BF2)2Co—L—Co(dpg)(BF2)2(Cl)(MeCN)] in acetonitrile. In the presence of p-toluenesulfonic acid we observe a catalytic wave at the CoII/I potential indicative of hydrogen evolution. The graph is overlayed with a diagram of the final pure catalyst.

ELECTROCHEMISTRY

To study the catalyst's ability to make hydrogen, we look at the electrochemistry. To measure the reduction potential, or how much energy the catalyst requires to convert protons and electrons to H2, cyclic voltammetry was used. The cyclic voltammogram was obtained of the crude catalyst (0.1 mM) in acetonitrile versus a saturated calomel electrode (SCE). We observe a scan by applying voltage until the catalyst is reduced and measure the resulting current, then reverse the voltage to study the opposite reaction. In general, for a cobalt complex we expect to see a peak as it is reduced from CoII to CoI and a reverse peak at a negative current value when the voltage is applied in the positive direction. TDTO

At the start of the scan (Figure 5), the CoII molecules in the layer surrounding the electrode are reduced to CoI. When acid is added, the CoI reacts with the protons via the pathways described previously, generating H2 and returning to the original CoII state. Therefore, more CoII regenerates within the diffusion layer, ready to accept electrons from the electrode, resulting in a higher peak current. The reverse peak, or the oxidation of CoI back to CoII, is absent when protons are present because every molecule of the reduced species has already been oxidized in the process of forming H2. Hence we conclude that the catalyst produces hydrogen at a CoII/Ireduction potential of -0.37 V versus SCE. The catalyst operates at a low overpotential and is the first known dinuclear complex of this kind to be synthesized.

FUTURE DIRECTIONS

To determine if this dinuclear cobalt complex is indeed faster than the monocobalt derivatives (Figure 2), we will use cyclic voltammetry and other electrochemical techniques to obtain a rate of hydrogen evolution, k. To carry out this sensitive calculation, we need to ensure that no other molecules are interacting in the pathway, and so we will repeat our electrochemistry in an aerobic and dry environment, free of oxygen and water. To optimize the hydrogen evolution, other catalysts will be synthesized by altering the linker backbone; replacing the methylene chain with a ring system such as dibenzofuran. We hope to study this catalyst and use the knowledge we obtain to pursue the best candidate for the overall solar fuel cell.

Measurement-based Quantum Computing Using Polarization-Path Qubits

Author / Gabriel J. Mendoza
Mentor / Jeremy O'Brien / *University of Bristol*

Introduction

The holy grail of quantum information science may be the construction of a scalable quantum computer, a computer that utilizes quantum mechanical phenomena to solve problems. In principle, quantum computers can efficiently solve certain problems that would currently take the fastest PCs the age of the universe to solve. However, quantum computers are notoriously difficult to build; they operate using tiny quantum particles, qubits, which are very fragile. Unwanted disturbances from the environment, or noise, easily destroy these qubits, making it difficult to stitch many of them together.

In this research, we explored how special properties of photons can be used to increase the number of qubits in a quantum computer without increasing the noise level. By utilizing this strategy, we demonstrated simple quantum computations with high efficiency.

Funny Photons

Unlike desktop computers, which store information in the state of electrical signals called bits, quantum computers store information in the state of quantum particles called qubits. While a bit can take the binary values of either 0 or 1, a qubit can exist as both a 0 and 1 at the same time. Only when a measurement is made does the qubit "collapse" to one of the two states. This fact is comparable to flipping a coin in the dark. Until the lights are turned on and the coin is measured, the coin exists in a state of both heads and tails (Fig. 1).

Single particles of light—photons—are promising physical implementations of qubits. Unlike most other quantum particles, photons have low noise properties and enable encoding in several degrees of freedom. Photons can store information in the orientation of their oscillations, called polarization (Figure 2A) and based on their physical locations, called paths (Figure 2B).

However, photons do not interact easily with each other, presenting a problem when trying to execute quantum algorithms that are based on qubit interactions. Although this problem was once considered a dead-end for photonic quantum computing, breakthrough work in 2001 by Knill, Laflamme, and Milburn revealed a clever scheme to "trick" photons into interacting with one another. This scheme was further improved using a measurement-based approach to quantum computing.

In measurement-based quantum computing, a quantum cluster state is prepared before the computation takes place (Fig. 3). In this cluster state, qubits are linked together in a lattice using entangling operations called CPHASE gates. A series of strategic measurements on the states of the qubits guide the output to certain register qubits at the end of the process.

Figure 1: Qubit Measurement.
In the quantum world, particles behave like strange coin flips. The coins exist as a ghostly superposition of two outcomes until a measurement is made.

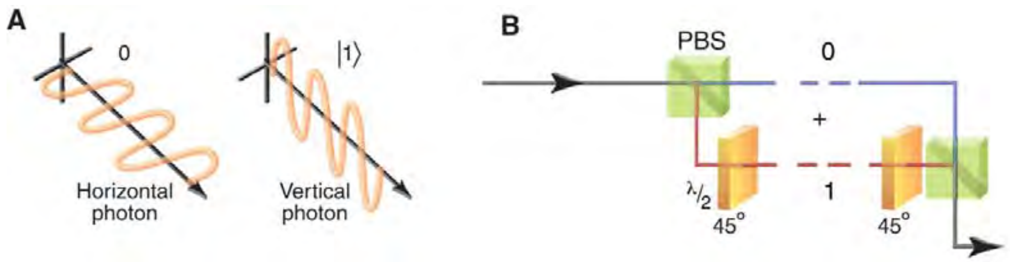


Figure 2: Different ways that a photon can act as a qubit.
A. Information is encoded in the polarization of a photon—horizontal (H) or vertical (V).
B. A photon can exist in a superposition of two different physical paths. In this experiment, we used a 4-way "super"- superposition that combined both the path and polarization degrees of freedom.

"Single particles of light—photons—are promising physical implementations of qubits"

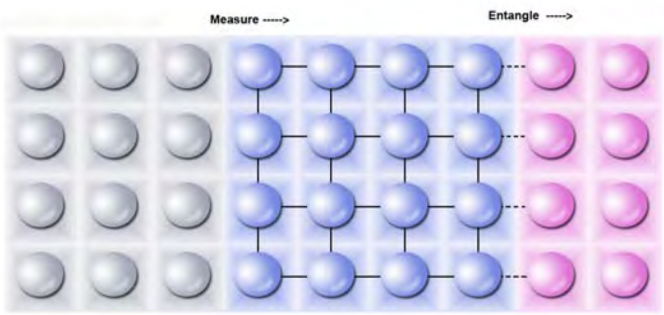


Figure 3: Measurement-based quantum computing.
In a quantum cluster state, individual qubits are linked together in a lattice using special entangling operations. The computation proceeds via a series of measurements which guide the output to certain register qubits. These register qubits are then read and the output is found.

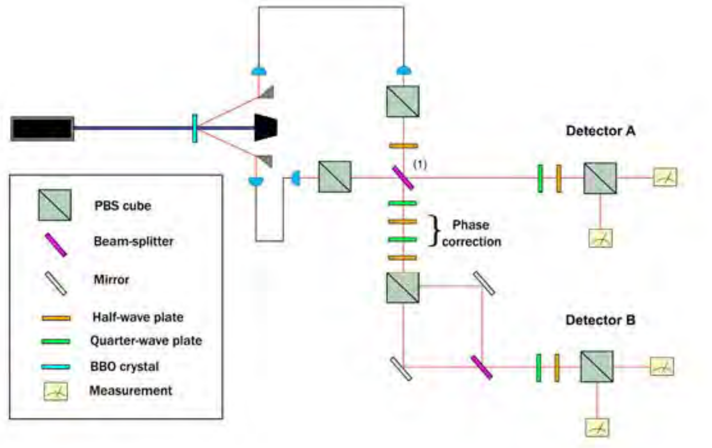


Figure 4: Circuit for generating and manipulating the quantum cluster state.
A laser is pumped into a crystal, generating identical photons that are coupled into optical fibers. The beam-splitter (1) produces the polarization entanglement between the two photons, and several wave plates and beam-splitters create the additional path qubit. The path qubit can be manipulated into any state by strategically measuring the polarization qubits at Detectors A and B.

Experiment Design

While photons are extremely robust, increasing the size of a quantum cluster state is still not an easy task. The entangling CPHASE gates required to append additional qubits are very noisy and increase the instability of the quantum computer. Fortunately, special properties of photons can be used to circumvent CPHASE gates in some instances, essentially adding qubits to the cluster state "for free". By utilizing path and polarization degrees of freedom simultaneously, a photon can be placed into a 4-way "super"-superposition relatively easily. This doubles the storage capacity of a single photon, and the extra degree of freedom can be used as an additional qubit.

In this experiment, our goal was to take advantage of this polarization-path property of photons in order to demonstrate high-efficiency, measurement-based quantum operations. The first step was to build an optical circuit to generate and manipulate a two-photon, three-qubit cluster state (Fig. 4).

Measuring Quantum Weirdness

We confirmed the stability of the circuit and cluster state by measuring a Hong-Ou-Mandel dip and quantum entanglement. The celebrated Hong-Ou-Mandel dip is a direct result of non-classical interference. If two identical photons impinge on a beam-splitter, classical probability theory predicts that there are four possibilities (Fig. 5A). However, quantum interference produces a counterintuitive result: the photons only have two options, either both are reflected or both are transmitted (Fig. 5B). Experimentally, this phenomenon can be confirmed by measuring both outputs of the beam-splitter and monitoring for simultaneous photon detection at certain outputs, known as coincidence counts.

In our experiment, a well-defined Hong-Ou-Mandel dip confirmed the presence of non-classical interference (Fig. 6).

The next step was to confirm the presence of entanglement correlations. If two non-identical particles (Photon A and Photon B) impinge on a beam-splitter, a strong correlation between their polarizations is produced after they exit. Amazingly, it seems as though that these particles can instantaneously communicate, even over huge distances. For instance, if Photon A is found to possess a horizontal polarization, Photon B will automatically assume a vertical polarization. This polarization, however, can only be determined once measurements are made (recall the penny example, Fig. 1).

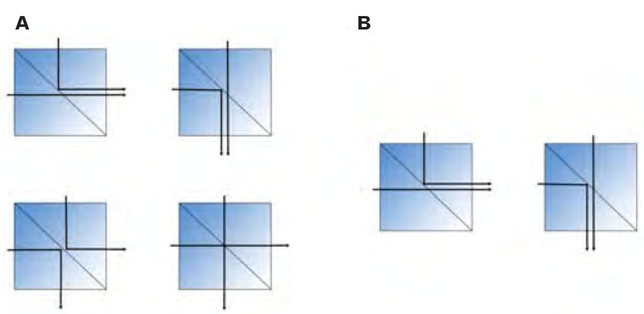


Figure 5: Classical and quantum outcomes.
A. When two photons impinge on a beam-splitter, probability theory predicts that there are four possible outcomes: one photon is reflected while the other is transmitted, or both photons are reflected or both.
B. However, quantum mechanics predicts that only two outcomes are possible: the cases in which both photons are reflected or transmitted. Non-classical interference "cancels" the other two outcomes out.

These photon count correlations were observed by measuring polarizations at the circuit detectors (Table 1).

Qubit 1 / Qubit 2	V	H
V	-	+
H	+	-

Table 1: Observed photon count correlations at detectors A and B.
When qubit 1 is found to have a vertical polarization, qubit 2 is found to have a horizontal correlation, and vice versa. This confirmed the presence of quantum entanglement.

Finally, measurement-based quantum operations were performed in order to manipulate the path qubit into any arbitrary superposition (state). We measured the three qubits at certain angles, and quantum entanglement forced the path qubit onto a certain path with a known probability. This control over the path qubit is evident in the interference pattern that resulted (Fig. 7). When coincidence counts reach a maximum, this indicates that the path qubit is on the same path as the detector. When coincidence counts reach a minimum, this indicates that the path qubit has been forced onto a different path. Observations of these fringes confirmed the correct one-qubit rotations were realized via measurements of the two-photon, three-qubit cluster state.

When Will I Have A Quantum Laptop?

In this research, we experimentally demonstrated simple quantum operations using a two-photon, three-qubit cluster state. Like all implementations of measurement-based quantum computing to date, our scheme is not scalable to larger systems. However, we have shown how qubits can be added to a quantum cluster state "for free" by encoding photons in a polarization-path state. This allowed us to conduct simple measurement-based operations with high efficiency.

It may be worthwhile to consider other photon degrees of freedom, such as momentum or time bin, to create more advanced "hyperentangled" states. Further research into photons encoded in multiple degrees of freedom may yield practical applications for future quantum technologies, as well as important insights into the workings of quantum information theory and quantum mechanics. Although the prospects for quantum information science are exciting, quite a bit of research remains before large-scale quantum computers can become a reality.

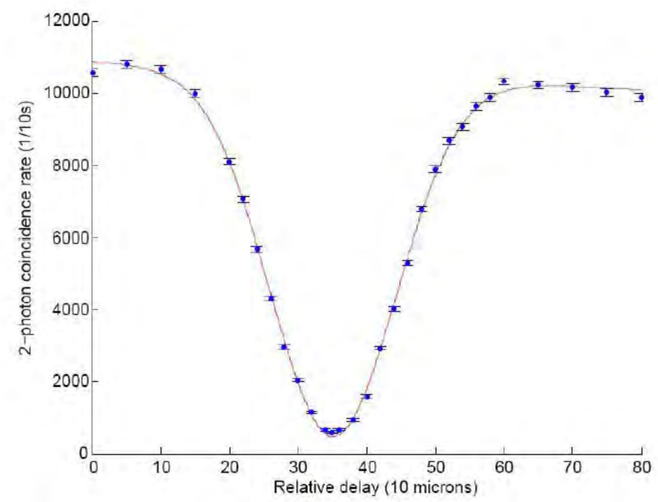


Figure 6: Hong-Ou-Mandel Dip.
Photons are measured at certain outputs as they exit the beam-splitter. Coincidence counts clearly disappear in the middle of the dip, indicating non-classical interference.

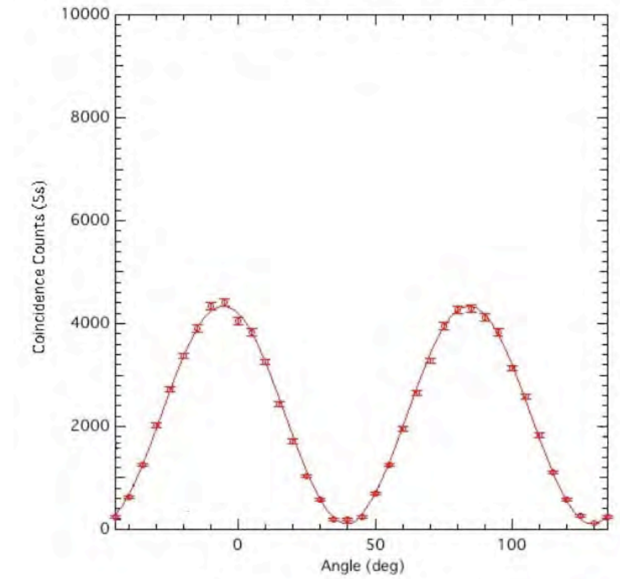


Figure 7: Detail of the manipulation of the state of the path qubit via polarization qubit measurements.
Coincidence counts are a function of the measurement angle of the path qubit. By varying the measurement angles, the path qubit can be manipulated into any state.

Further Reading

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Direction-Dependent Communication System

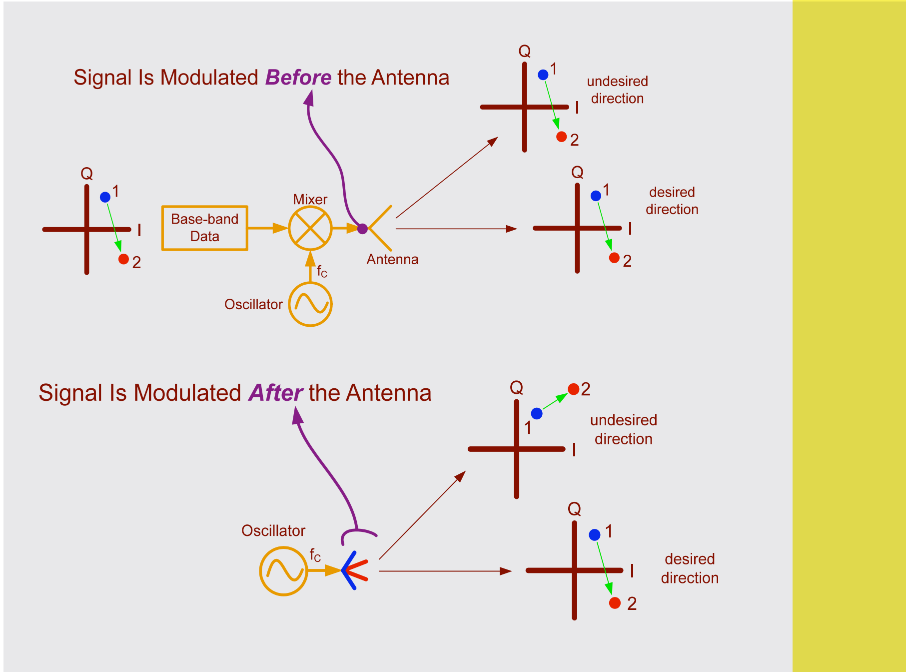
Author: Arthur Chang
Mentor: Professor Ali Hajimiri, Dr. Aydin Babakhani

Introduction

With the rapid advance of wireless technology, radio frequency (RF) circuits used for transmitting and receiving signals have become ubiquitous. However, one inherent flaw in the popular direct and two-step up signal conversion designs is data security. In these direct or two-step up-conversion transmitter architectures, the components of the signal are encoded, or modulated, at base-band, then up-converted to a radio frequency. The resulting modulated signal at the carrier frequency is then amplified and finally transmitted through an antenna. Antenna patterns in these systems remain unchanged at the transmission of each symbol, i.e. unit of data consisting of one or several binary bits. Hence receivers located in different spatial directions capture the same modulated signal, with only differences in power level and time delay.

In directional transmitters designed for greater control over signal direction, a large portion of the radiated power is coupled to the main signal beam, but a small part is leaked to the side lobes of the antenna. This means that even in such systems, a sensitive receiver can eavesdrop on the information by picking up the signal from the side lobes. To prevent undesired receivers from capturing the same information, an alternative system with the capability of transmitting information in a truly direction-dependent fashion is necessary.

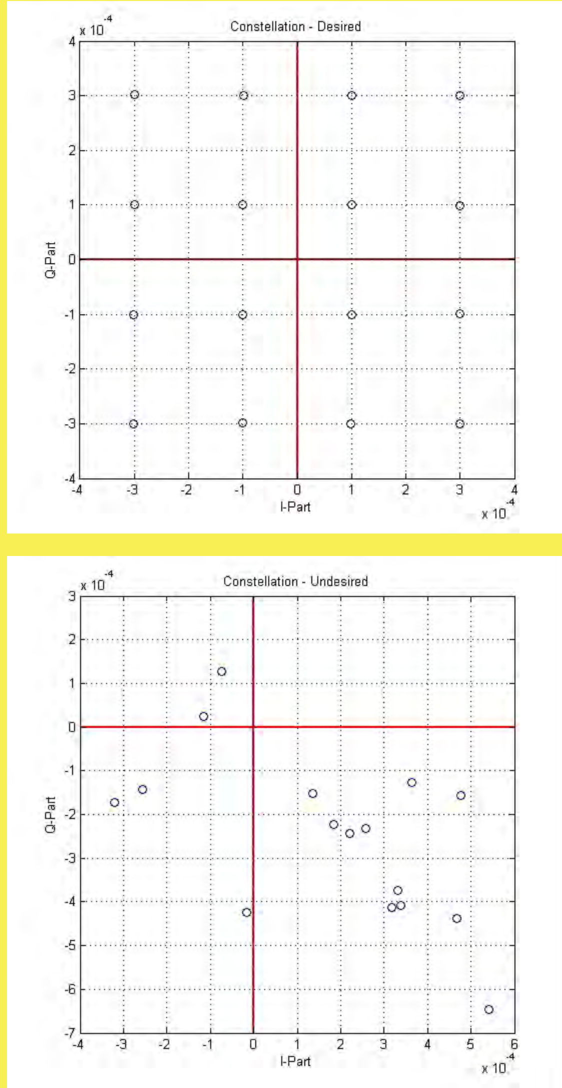
Solution: near-field direct antenna modulation



> Figure 1 : Comparison between modulation at base-band (top) and modulation after the antenna (bottom).

The Near-Field Direct Antenna Modulation (NFDAM) technique, which scrambles the transmitted signal in all directions except the desired one, can be used to overcome the security challenge. NFDAM uses switches or varactors (voltage-controlled capacitors) to constantly change the scattering properties of antenna reflectors, thus changing the boundary conditions of the antenna. Such variation permits modulation of the signal after the antenna broadcast (Fig. 1). Because the signal is modulated post-antenna and the scattering properties of the reflectors vary with angle, receivers located in different directions observe different signals. Visually, symbols can be represented as points on the complex plane (Fig. 2). By graphing in the in-phase component (I-part, modulation of cosine carrier signal) on the real axis and the quadrature component (Q-part, modulation of sine carrier signal) on the imaginary axis, the signal can be represented as constellation points with I- and Q-coordinates in a constellation diagram. In short, NFDAM generates directional-dependent constellation points—the correct signal constellation is generated only in a certain direction, and scrambled in all other directions.

In NFDAM systems, as the signal is only modulated in the near field after antenna radiation, the signal passed through the power amplifier is not modulated, permitting the use of narrow-band high-efficiency power amplifiers without disturbing the constellation points. In addition, NFDAM can utilize many degrees of freedom through the implementation of many switches (2^N degrees of freedom with N switches), allowing a broad range of modulation schemes and extra security. It is worth mentioning that any arbitrary digital modulation scheme, including both constant envelope and non-constant envelope ones, can be adopted by this system.



> Figure 2: Simulation of 16QAM in desired direction (top) and undesired direction (bottom). Blue circles represent symbols.

Theory of Operation

A simplified model of NFDAM implementing one switch can give some insight into the concept behind the system (Fig. 3). The reflector is composed of two metal strips connected with a switch. When the switch is open and the main dipole antenna radiates a signal of the generic waveform $A_0 \cdot \cos(\omega \cdot t + \varphi_0)$ in the z-direction, part of the signal's power is coupled to the reflector in the near field of the antenna, causing it to radiate a reflected wave with the waveform $A_1 \cdot \cos(\omega \cdot t + \varphi_1)$ in the z-direction. If the switch between the two metal strips is closed, the reflector's effective length can be changed. This will affect the scattering characteristics, causing a shift in amplitude and phase to produce a new reflected wave with the waveform $A_2 \cdot \cos(\omega \cdot t + \varphi_2)$ in the z-direction. Thus, the far-field signal produced in the z-direction with either open or closed switches can be calculated.

From these equations, it is evident that toggling the switch on the reflector can modulate the amplitude and phase of the received signal. However, it is important to remember that the example is overly simplified. Since the reflectors are placed in the near field of the antenna, the simplified model does not account for the complete electromagnetic analysis necessary for such a system to function, while the complete analysis is considered in actual implementation. To take this analysis a step further, we see that changes in the reflector boundary condition cause changes in the antenna parasitic (undriven elements in the near-field that can be used to alter the radiation parameters such as antenna pattern and beam width) without necessarily changing the path delay. Thus by changing the antenna parasitic in the near-field, the far-field signal can effectively be modulated.

Open Switch: $A_0 \cdot \cos(\omega \cdot t + \varphi_0) + A_1 \cdot \cos(\omega \cdot t + \varphi_1) = A' \cdot \cos(\omega \cdot t + \varphi')$

Closed Switch: $A_0 \cdot \cos(\omega \cdot t + \varphi_0) + A_2 \cdot \cos(\omega \cdot t + \varphi_2) = A'' \cdot \cos(\omega \cdot t + \varphi'')$

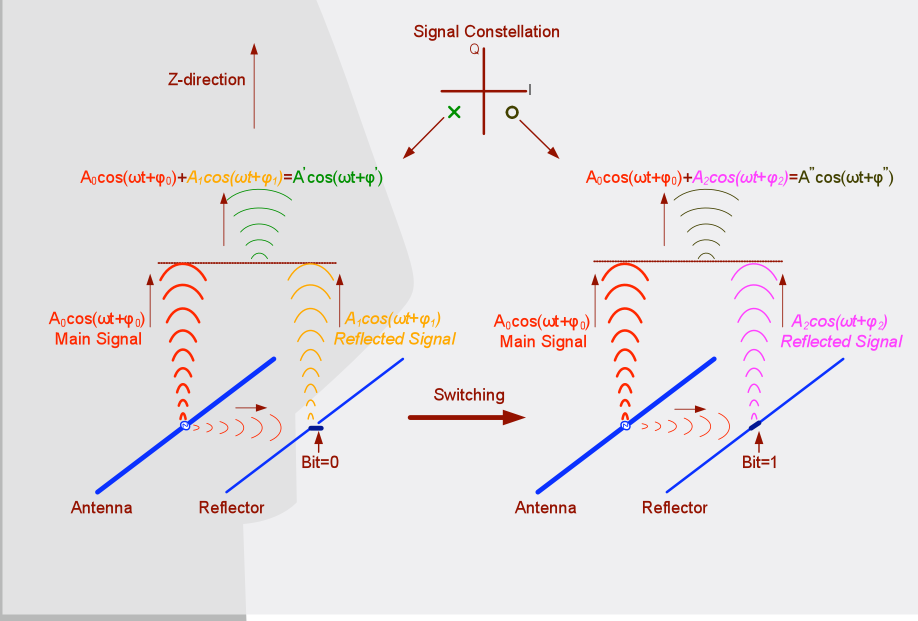
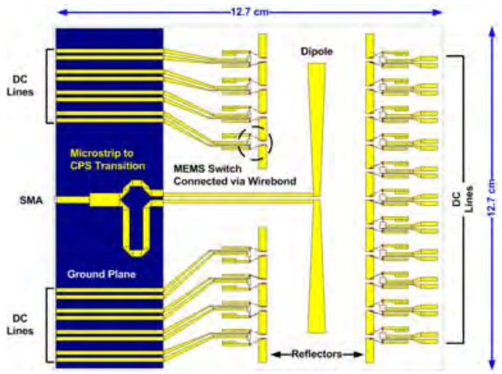
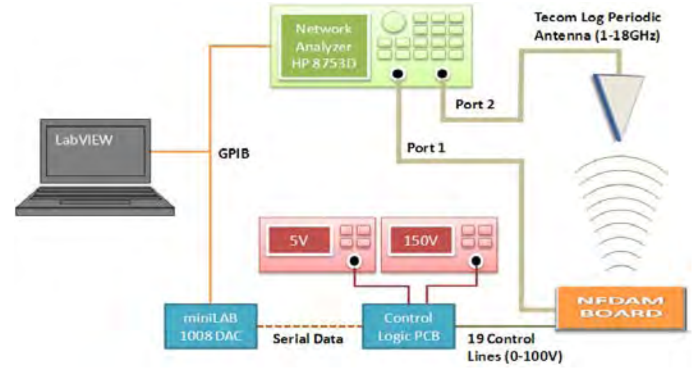


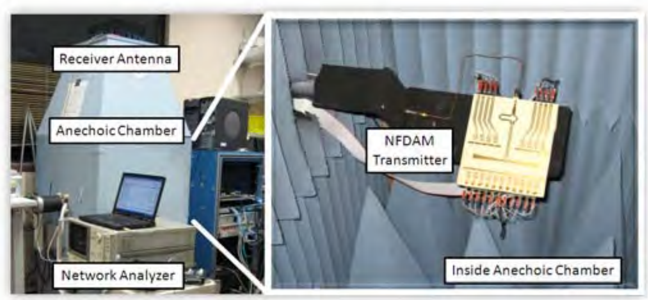
Figure 3: Signal modulation using switches on the reflectors.



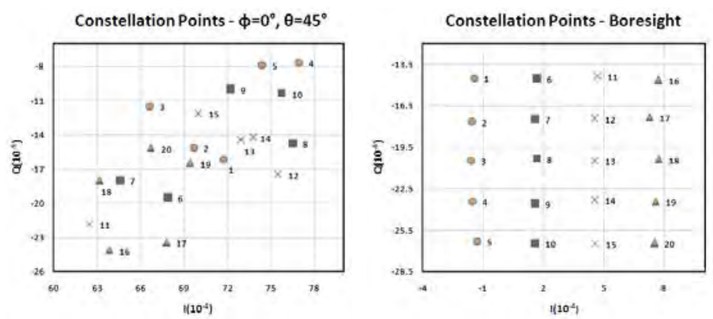
> Figure 4: Layout of the fabricated 2.4GHz NFDAM transmitter on microstrip.



> Figure 5: Measurement Setup Block Diagram



> Figure 6: Picture of the Measurement Setup



> Figure 7: Measured constellation points of the NDFAM Transmitter microstrip.

Preliminary Simulation of NFDAM System

A simulation with 2^{19} switching combinations was conducted to see the effects of the induced voltage on dipole receivers in the far field (Fig. 2). At the transmitting end, one reflector with either 8 or 11 switches is placed on each side of the antenna. The asymmetry in the number of switches arises from the signal feedline present on one side of the dipole antenna (Fig. 4). At the receiving end, dipole receivers are placed in two different spatial directions relative to the antenna, with one direction being the desired direction, and one being the undesired direction. Based on the data gathered by the dipole receivers, the shape of the constellation diagram coverage looks fundamentally different at different locations (Fig. 2). As predicted, when a 16 QAM test signal is generated in the desired direction, the receiver at another direction picks up a scrambled signal—a different constellation diagram.

Note switching combinations that result in excessive signal return loss (signal return loss, S_{11}, worse than -10dB) are removed when considering the constellation coverage. From simulation, these only consist of about 3% of the total switching combination.

Designing the setup

The dipole antenna, as described previously, is used with a wideband microstrip to co-planar waveguide transition (Fig. 4), and integrated with several instruments for measurement (Fig. 5 and 6). In the first measurement, the radiated far-field signal from the NFDAM transmitter is characterized using an HP 8753D network analyzer. A LabVIEW program controls the state of the Micro-Electro-Mechanical Systems (MEMS) switches through a data acquisition unit and a control logic Printed Circuit Board (PCB) with low-charge injection high-voltage analog switches. The data acquisition unit sends serial data stream to the control logic PCB and the PCB then generates the voltage swings needed to set the state of the MEMS switches.

After setting the desired state for the switches, the LabVIEW program communicates with the network analyzer through a General Purpose Interface Bus (GPIB) card. One of the ports of the network analyzer sends a 2.4GHz signal to the NFDAM transmitter while the other port uses a Tecom Log Periodic antenna at the receiving side to accurately measure the phase and amplitude of the S_{21}, or transmitted signal.

Testing Results

With the antennas in an anechoic chamber to suppress reflected electromagnetic waves, the amplitude and phase of S_{21} can be accurately measured for each switching combination. The measured real and imaginary parts of the signal can then be plotted on the signal constellation diagram as before (Fig. 7). The variation of S_{21} in two different directions (along bore-sight—no x or y displacement—and along ϕ=0°, θ=45° off-center) with an angular separation of approximately 45 degrees is measured for the same set of switching combinations. A total of 10,000 randomly chosen switching combinations were measured and the ones which result in 20 equally spaced constellation points in the desired bore-sight direction were selected. The signal constellation points are completely scrambled in the undesired direction (Fig. 7), proving the increased and feasible security of the NFDAM system.

It is important to verify the repeatability of the measurements of S-parameters. To do so, the same switching combination was assessed over the course of 3 hours to gain an estimate of error in the measurement. This error is extremely small when compared to the spacing between any two points in the 20 points shown above, indicating the repeatability of the near-field direct antenna modulation at 2.4GHz using MEMS switches, and that the effects of temperature change, supply voltage noise, and other interferences are low.

Lastly, measurements of the return loss, S_{11}, of the radiating antenna with different switching combinations are required to ensure that the impedance variation at the input of the antenna is minimal for maximizing the power transfer. With the 10,000 randomly chosen switching combinations, we have measured the S_{11} to have a mean of −9.98dB, a maximum of −9.60dB, and a minimum of −10.34dB, which are favorably low. This verifies that the antenna input impedance does not change excessively.

Conclusion

The proposed NFDAM system is capable of transmitting information in a direction-dependent fashion by sending the correct signal constellation in only the desired direction while leaving the signal constellation points scrambled in undesired directions. This direction-dependent constellation scrambling nature of the NFDAM systems prevents undesired receivers from correctly demodulating the signal intended for a receiver at a desired direction, increasing the security of data transmission.

Acknowledgmenets

The author would like to thank the Summer Undergraduate Research Fellowship program and Professor Ali Hajimiri for providing the opportunity to work in this field. The author also appreciates Dr. Aydin Babakhani for his mentorship. The timely advice and support of Hamdi Mani and the facility at the Caltech Millimeter-Wave Laboratory are also appreciated. The author also extends gratitude to the Aerospace Corporation for funding a considerable portion of the project.

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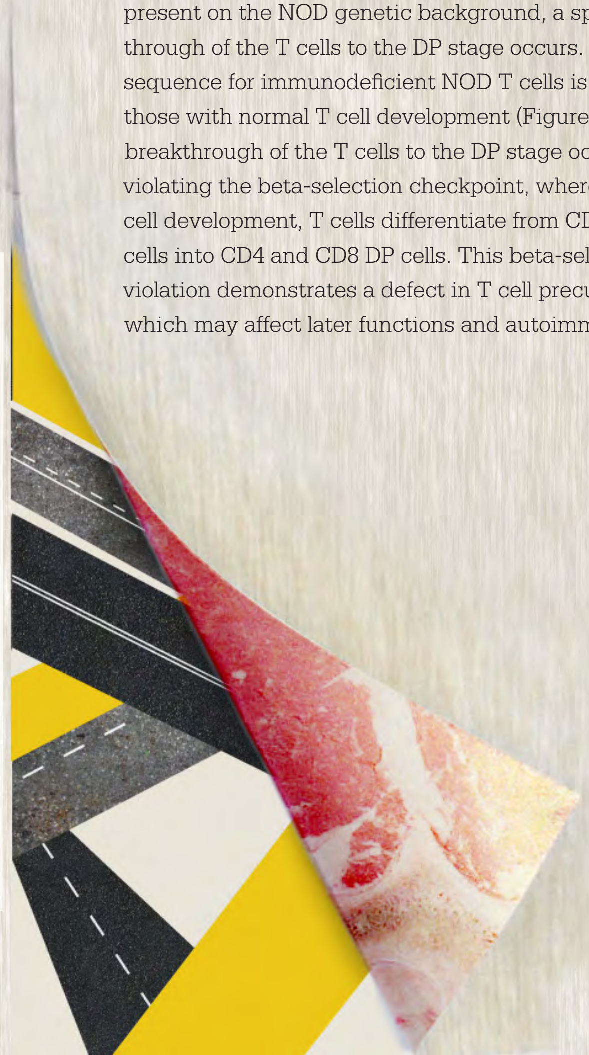
GENETIC MAPPING OF THE T CELL BETA-SELECTION CHECKPOINT VIOLATION IN NON-OBESE DIABETIC (NOD) MICE

Authors Justine X. Chia | Dr. Mary A. Yui | Dr. Ellen Rothenberg

Currently, as many as three million Americans have Type 1 diabetes (T1D), which has caused an increase in efforts to understand the disease. T1D is an autoimmune disease where the body is unable to produce insulin to convert sugar and starches to energy that the body can use. The origin of T1D can be traced back to early thymic T cell development, where possible candidate cells pass through many checkpoints, before being allowed to differentiate into the different types of T cells. If the candidates do not meet the requirements presented at each checkpoint, then cell death should be induced. Normally, T cells differentiate from CD4 and CD8 double negative (DN) cells into CD4 and CD8 double positive (DP) cells, and eventually into CD4+ and CD8+ single positive T cells (CD4 and CD8 are glycoproteins that are found on the surface of T cells). Ideally, if the genes that make mice susceptible to autoimmune disease could be found, parallels could be drawn to human autoimmune disease. Thus, the focus of this research is to identify the genes within a subset of diabetes susceptibility loci that make the mice susceptible to autoimmune disease by mapping the T cell checkpoint violation in certain crosses of mice.

"IF THE GENES THAT MAKE MICE SUSCEPTIBLE TO AUTOIMMUNE DISEASE COULD BE FOUND, PARALLELS COULD BE DRAWN TO HUMAN AUTOIMMUNE DISEASE."



Background

In theory, early T cells from non-obese diabetic (NOD) mice which are crossed to either mice lacking Rag recombinase (Rag-/-) or mice with a mutant DNA repair gene (scid), should not be able to pass through the first checkpoint and differentiate from DN to DP. These cells should not be able to undergo differentiation from DN to DP because they are unable to create a rearranged T cell receptor (TCR). However, studies have shown that when the Rag-deficiency and the scid mutation are present on the NOD genetic background, a spontaneous breakthrough of the T cells to the DP stage occurs. The developmental sequence for immunodeficient NOD T cells is different from those with normal T cell development (Figure 1). A spontaneous breakthrough of the T cells to the DP stage occurs in NOD mice, violating the beta-selection checkpoint, whereas in normal T cell development, T cells differentiate from CD4 and CD8 DN cells into CD4 and CD8 DP cells. This beta-selection checkpoint violation demonstrates a defect in T cell precursors in NOD mice, which may affect later functions and autoimmunity.

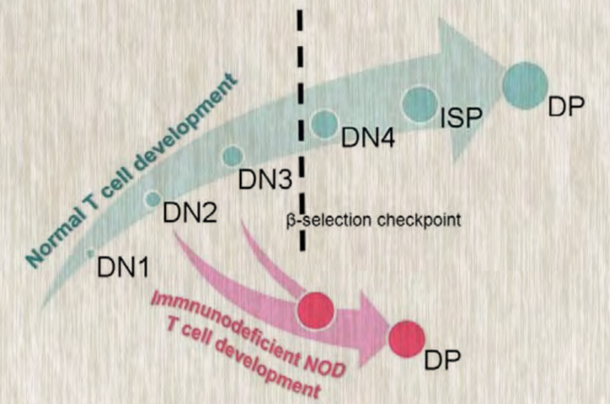


Figure 1 Stages in Normal and Immunodeficient NOD T cell development.

Many genes are known to be associated with higher incidence of disease in the NOD mouse model. Previous research has been done to map more than 20 loci containing genes that contribute to diabetes in this mouse model, although few of those genes have actually been identified. Preliminary results from a pilot genetic analysis done in the Rothenberg lab suggested that the violation of the developmental checkpoint may map to 2 or more of these diabetes susceptibility loci, although that study did not use a sufficiently large pool of animals to give robust results. Mapping of this T cell checkpoint violation in the NOD.Rag-/- mouse could be done to identify the genes within this subset of diabetes susceptibility loci that make the mice susceptible to autoimmune disease.

NOD mouse beta-selection checkpoint violation was mapped, as well as other early T cell traits that differ between NOD and B6 cells, by phenotyping and genotyping a genetic intercross between NOD.Rag -/- and B6.Rag -/- mice and a backcross between (NOD.RagxB6.Rag) F1 and NOD.Rag. An F2 intercross between NOD.Rag -/- and B6.Rag -/ mice was initiated in the lab for the analysis of the beta-selection breakthrough trait found in NOD.Rag -/- but not B6.Rag -/- mice. This was to determine the association between the NOD beta selection checkpoint violation and diabetes susceptibility, Idd, loci on various chromosomes. Additional phenotypes are also mapped using these crosses. Because the rate of breakthrough is very low in the F2 cross, a backcross was also carried out to increase the incidence of checkpoint breakthrough.

Construction of the genetic map

The mice were first phenotyped using flow cytometry, a technique for examining the physical characteristics of cells. This is done by suspending them in a stream of fluid and passing them by an electronic apparatus to detect surface markers. They were then characterized by the detection of different surface markers. The backcross mice were then analyzed in the two parameter histograms (Figure 2). In the figure, notice that the graphs on the left have a majority of their points under both thresholds, meaning that they are double negative (DN). Also, notice that the top four graphs on the right have the highest concentration of points above both thresholds meaning that they have high CD4 and CD8 saying that they are the "breakthrough" phenotypes. For intermediate breakthrough phenotypes, other stains including cKit were considered, using the parental stains as controls. From the flow cytometry data collected by Ni Feng in the Rothenberg lab for phenotyping, some of the samples were clearly CD4+CD8+ double positive (DP) and some were clearly not DP, while others appeared to be in the transition to DP, as determined by CD4+, CD2+, and/or cKit+ cells. Based on the phenotypic analysis, all the samples were scored by Dr. Yui, based on percentage DP and levels of cKit, and these categories were later used in the statistical analyses.

PCR-based genotyping

After phenotyping with flow cytometry, genotyping was done on the DNA extracted from the tails of F2 progeny and backcross mice by augmenting the desired gene using PCR and gel electrophoresis. During PCR, we used Mappair primers (Invitrogen), which are single sequence repeat polymorphisms between NOD and B6 mice, and have known map locations near the genes of interest. Single sequence repeat polymorphisms are very helpful in the genetic mapping, because they tend to be highly polymorphic, occur frequently throughout mammalian genomes, and can be easily assayed by polymerase chain reaction (PCR). The samples of DNA were then run on a gel with map pair primers D4MIT233, the primers for chromosome 4 (Figure 3). A single upper band means that the genotype for the F2 mouse is NOD/NOD (N), a single lower band means the F2 mouse is B6/B6 (B), and two bands means that the F2 mouse is NOD/B6 heterozygous (H) for that locus on chromosome 4. The genotyping results from these assays were combined and tabulated, as shown in Tables 1 and 2.

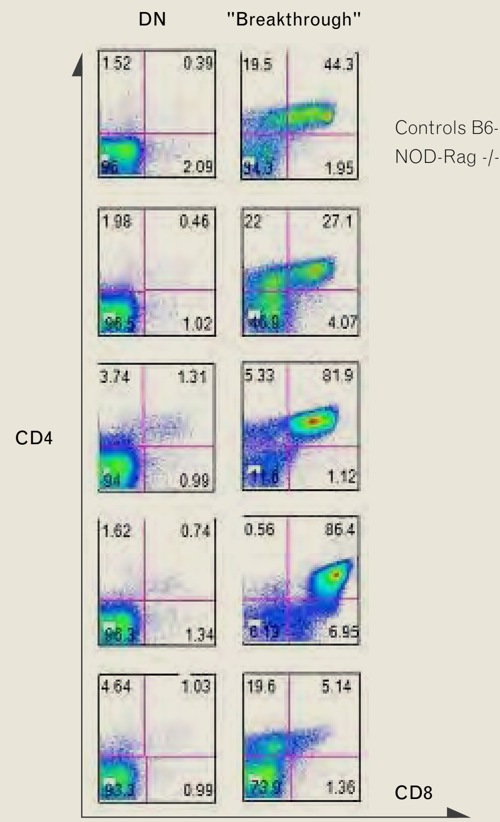


Figure 2 Genetic Analysis using (NOD - Rag X B6 - Rag) F1 X NOD.Rag Backcross Mice

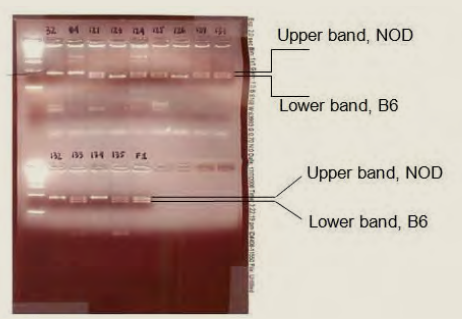


Figure 3 (A) Gel for Genotyping
(B) Tabulated results for the gel

SAMPLE	32	84	121	123	124	125	126	127	131	132	133	145	135	F1
GENOTYPE	B	B	H	N	H	H	N	H	H	B	H	B	H	H

Shown in Table 1 is an association of the double positive breakthrough trait to microsatellite markers in F2 progeny in chromosomes 1, 2, 3, and 4. For the F2 progeny, chi square tests were performed to determine the p values for statistical significance. Only taking into consideration the double positive samples, none were found to be statistically significant. When all the F2 progeny with intermediate phenotypes were included in analysis, nothing was found to be significant from the results of the chi square tests.

The p values from chi-square tests are listed. In the first part of the analysis, the intermediates with high cKit were excluded, and only the samples with a high DP count (high CD4 and CD8) were considered. Results and p values taking into consideration intermediate breakthrough phenotypes are shown in the shaded region of the table.

TABLE 1

*Association of the DP breakthrough trait to microsatellite markers in F2 progeny in chromosomes 1, 2, 3, and 4.

*Genotypes: nn, NOD homozygote; nb, heterozygote; bb, B6 homozygote

MARKER	GENOTYPE	NOD-LIKE	B6-LIKE	*p* VALUE
	nn	2	21	
D1 Mit156	bb	3	32	0.7523
n=120	nb	8	54	
	nn	4	10	
D2 Mit47	bb	2	9	0.6642
n=46	nb	7	14	
	nn	6	13	
D3 Mit95	bb	3	14	0.0586
n=76	nb	3	37	
	nn	8	32	
D4 Mit233	bb	2	26	0.0526
n=125	nb	3	54	
	nn	8	21	
D1 Mit156	bb	7	32	0.5814
n=125	nb	13	54	
	nn	7	10	
D2 Mit47	bb	7	9	0.8302
n=61	nb	14	14	
	nn	6	13	
D3 Mit95	bb	7	14	0.5988
n=88	nb	11	37	
	nn	14	32	
D4 Mit233	bb	3	26	0.0741
n=140	nb	11	54	

As shown in Table 2, for the backcross mice, the data were analyzed in two ways. The first way was just looking at the DP population of cells and comparing it to the negative controls. Using this criterion for analysis, only the data from chromosome 4 was moderately significant (p=0.0126). The other method for analysis was to look at the percent DP and percent CD4 positive, from the phenotyping. This second method has broader criteria for being scored as having a breakthrough phenotype. Again, only chromosome 4 was significant but much more strongly with the additional data (p<0.0001).

TABLE 2

*Association of the DP breakthrough trait to microsatellite markers in (NOD-Rag X B6-Rag) F1 X NOD.Rag Backcross Mice, in chromosomes 1, 2, 3, and 4

*Genotypes: nn, NOD homozygote; nb, heterozygote; bb, B6 homozygote

MARKER	GENOTYPE	NOD-LIKE	B6-LIKE	*p* VALUE
D2 Mit47	nn	3	13	
n=33	nb	4	13	1.0000
D3 Mit95	nn	3	17	
n=34	nb	5	9	0.2278
D4 Mit233	**nn**	**7**	**12**	
n=33	**nb**	**0**	**14**	**0.0126**
D17 Mit200	nn	4	10	
n=34	nb	4	16	0.6892
D2 Mit47	nn	6	10	
n=33	nb	5	12	0.7207
D3 Mit95	nn	5	15	
n=34	nb	7	7	0.1633
D4 Mit233	nn	14	8	
n=36	nb	0	14	<0.0001
D17 Mit200	nn	5	9	
n=34	nb	7	13	1.0000

Discussion

The marker D4Mit233, which is close to the susceptibility locus, Idd9 on chromosome 4, was the only marker showing significance in the statistical analysis for the backcross. Thus, the DP trait appears to map in part close to the D4MIT233 locus. While all mice with the breakthrough were homozygous “nn”, not all of the “nn” mice were DP phenotype, implying that either the mapping location is not exactly on the gene and/or there are other genes involved. Chromosome 4 was found to be significant in a preliminary genetic cross using NOD.scid rather than NOD.Rag mice, so this confirmed the previous finding. It is not clear why this locus was not found to be significant in the F2 cross. Again, this locus may be some distance from the gene and/or other genes maybe involved. The low frequency of breakthrough among the F2 mice makes it very likely that the breakthrough trait is multigenic, meaning several genes would be required for the trait. In a backcross, one chromosome is always of the “n” genotype so the trait appears with greater frequency.

Using Chi square tests and Fisher’s Exact test to analyze the data from chromosomes 1, 3, and 17, the DP trait does not appear to map close to the D1MIT156, D3Mit95, and D17Mit200 loci, respectively, because the results were not very statistically significant. In agreement with the preliminary study using NOD.scid mice, these aforementioned chromosomes did not seem to be closely correlated with the DP trait.

Unexpectedly, the results from Chi square tests and Fisher’s Exact test indicated that the DP trait does not appear to map close to the D2Mit47 locus. In the preliminary pilot study with NOD.scid mice, the DP trait had appeared to map close to the D2Mit 47 locus. The genetics of NOD.Rag mice differ slightly from the genetics of NOD.scid mice, and a possible explanation for the DP not showing up may be that the Rag gene interfered, since it is also on chromosome 2.

In the future, a genome-wide analysis will be carried out using these DNA samples. After this more complete genetic mapping has been completed, a quantitative trait loci (QTL) analysis will be performed using the quantitative data (percentages of breakthrough cells, etc.). Also, using this analysis method, potential interactions between genes can be determined.

Acknowledgements

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