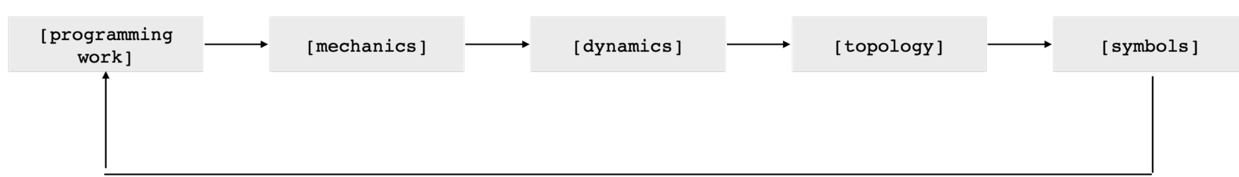
Kod*fest: What Is Robotics?

May 22, 2022

Koditschek
Festschrift




Change

Kod*fest: What is Robotics?

Editors: Aja Carter, Noah J. Cowan, Aaron Johnson,
Diedra Krieger, Matthew Kvalheim, and Abriana Stewart-Height

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The entire Kodfest Youtube Playlist can be found here:

`https://www.youtube.com/watch?v=UJGEStR5lpM&list=PLPk-tMiZO-V6GzSFvrS1w2sffhur3UGxV&ab_channel=kodlab`

Part I

Early Years

Watts per kilogram per centimeter cubed is the scarce resource in robotics.

Professor Daniel E. Koditschek

Dan Koditschek – Some Early Influences and Interactions

Theodore Koditschek, University of Missouri
Brother

Dan and I grew up in a household in which the values of political progressivism were closely joined with a commitment to scientific advancement. Our mother was a PhD microbiologist, who taught at the local state college, while our father was a trained mathematician who worked to establish an early computer-based inventory control system for a cosmetics firm. Although he was three years my junior, Dan slipped more comfortably into the technical side of this equation between science and progress than was the case for myself. Nevertheless, we were both strongly marked by our family traditions, and we took to discussing fundamental questions of truth, knowledge, and meaning as we moved into adolescence. For example, I remember several conversations about Norbert Wiener's *Cybernetics* (which we had found on our father's bookshelf) when I was still in high school, which means that Dan must have been no older than 13 or 14 at the time. Dan did not share all his interests with me, and I only found out later how much he had been influenced by Isaac Asimov's *Foundation* series. However, some of his other early enthusiasms, such as for D'Arcy Thompson and Ludwig von Bertalanffy, did become the focus of joint conversation. We would talk about how nature was structured, and about how far organismic behavior might be explained by algorithmic means. Eventually, Dan and I went in different directions, and it became clear that our primary intellectual orientations would not dovetail, but only loosely overlap. As I dove deeply into Marx, Mill and Bertrand Russell, it was primarily when discussing the latter that our interests continued to intersect.

Nevertheless, over the years, we have occasionally resumed our conversations about 'the big questions' in an episodic way. I recall Dan's freshman year at Yale, when he went very rapidly through a series of prospective majors, first in English Literature, then in Anthropology, and then in Math, before finding a permanent academic home under the mentorship of K.S. Narendra in Electrical Engineering and the then fledgling field of robotics. Dan was intrepid. I recall visiting him one summer when he was a counsellor at a music camp. We were both early risers, but when I woke up at 5:00 in the morning, I was surprised to find him already in full steam, solving math problems at a table he had set up on the beach. Still, the choice between understanding the world and changing it continued to exercise a certain polarizing pull, and Dan took some time before making an irrevocable commitment to the academic life. There was the gap year he spent in Chicago (I believe it was 1974–5), and the subsequent year, after his B.A. graduation, when he tried his hand at labor organizing. Nevertheless, by the end of the 1970s, Dan had fully settled into the profession in which you have known him. Because I was now ensconced along a different professional trajectory, and because we have lived in different parts of the country, our interactions have become less frequent over the years. Yet, I am very interested in learning more of the details about what the Kod*lab has accomplished, and I look forward with great interest to your own recollections about the more recent stages of Dan's career.

Part II

Kod*lab Alumni – Yale Years

The great thing about the English language is that it has infinite depth—you can always add another comma, parenthesis, etc.

Professor Daniel E. Koditschek

Robot Navigation Functions

Elon Rimon, Technion – Israel Institute of Technology
Kod*lab PhD student, 1987-1991

Dear Dan

You took me into your group as your second student, back then at Yale.

With great patience and hard work, you made sure I'll get traction as a robotics researcher.

Training included many skills that have to be carefully learned and practiced, like the meaning

of innovative research, the process of writing research papers, lab research work and building contacts.

I stated at the beginning of my UPenn Grasp Seminar a couple of years ago:

It was an amazing experience to morph under your guidance from a practical engineer to a robotics researcher.

This made me grateful for life.

Our Yale group expanded rapidly, Martin, Louis, Al and myself. I recall we convinced you to give a special

advanced topics course just for us. We felt privileged to have the best teacher just for us.

A funny memory from these classes is that while absorbed and excited lecturing, you climbed on a desk to

add some facts on top of the board, then climbed down without even noticing this excursion. . . .

I am sure all younger students have benefited from this energy. It was a huge motivator for all of us.

Please do not slow down. Please consider training new students, making new research breakthroughs

and summarizing some of your key contributions as books!

Kod*Lab: The Early Years at Yale

Louis L. Whitcomb, Johns Hopkins University
Kod*lab Undegratuate 1983–1984, PhD student, 1986–1992, Friend and Colleague 1992–Present

Kod*Lab: The First Year: 1983–1984

The first time Daniel Koditschek changed the course of my life and career was in September 1983 when he posted signs around the campus engineering buildings at Yale University declaiming that Yale had a new program in robotics, that he was offering to advise and sponsor student projects in robotics, and would soon offer a new course entitled "Robotics". I was a Mechanical Engineering undergraduate student looking for a mission for life. I drank the Cool-Aid. Dan had recently completed his Ph.D. with K. S. Narandra at Yale in May 1983, and was then a newly minted Assistant Professor of Electrical Engineering at Yale. Dan had a faculty office, no lab, and no graduate students. Dan's new robotics course was the most difficult and most rewarding course of my undergraduate career because of the mathematical rigor and extraordinary depth and breadth of the subject matter. Each lecture left us breathless; it was like "drinking from a firehose". We were mesmerized by the clarity of Dan's vision connecting the beauty of mathematical modeling and analysis to the practical problems of enabling robotic systems to do useful work in the real world. Dan also very kindly agreed to supervise my "Senior Essay", a wonderful Yale thing that enables seniors to study almost anything, under the guidance of a faculty advisor. My project was to develop the mechanical and electrical hardware, and associated software to provide closed-loop feedback control of the steering angle of the front steering wheel of a "Heathkit Hero" wheeled mobile robot.

The second time Dan Koditschek changed the course of my life and career was in May 1984 after I graduated with the B.S. M.E. As I was being spectacularly unsuccessful in my job-search in the (then minuscule) robotics industry, Dan very kindly hired me to work in his lab in the summer of 1984, during which I implemented a closed-loop control system for a DC motor with power op-amps, optical encoders, and a PDP-11 Digital computer (the computer was the size of a full-size refrigerator!). As I recall, Dan hired three summer interns that summer, each of which he mentored assiduously, and none of us produced a publishable result. It was a lab shared with K. S. Narendra and his students, including Anuradha Annaswamy, with whom he was completing their seminal text "Stable Adaptive Systems". Dan got me my first real job in robotics by introducing me to Dr. Chia Day, R&D Manager at GM-Fanuc Robotics in Detroit. I interviewed, got the job, and spent two exhausting and exhilarating years at GM-Fanuc, during the first crazy boom-market-years in the infant robotics industry, developing three-dimensional (3-D) computer vision systems for robotic automotive manufacturing, and installing them in customer factories (e.g. Ford, GM, and Chrysler).

Kod*Lab: The Early Years

The third time Dan Koditschek changed the course of my life and career was in 1986 when I applied to Ph.D. programs in robotics, and Dan admitted me into the Ph.D. program in Electrical Engineering at Yale, taking a significant gamble on me given my less-than-stellar undergraduate academic record. In the two years that I was at GM-Fanuc, Dan recruited two incredibly talented Ph.D. students, with whom he developed a robotics laboratory in a basement room of Becton Center. Dan's Ph.D. student Martin Buehler was both talented analytically and was a first-class "lab warrior". Martin was developing, with Dan and the electronic design genius Professor Peter Kindlmann, a two-dimensional planar "juggling" robot to test their theories of stable dynamic control in intermittent dynamical environments [1, 2]. Dan's Ph.D. student Elon Rimon, who was off-the-charts talented analytically, was developing, with Dan, gradient-field potential functions for for the holy-grail problem of provably correct simultaneous planning and control of robotic tasks [4, 6]. Martin Buehler and Dan's part time electrical engineer Forrest Levin developed the first of a family of custom computer boards for real-time control employing the INMOS Transputer, a novel 32-bit CPU equipped with an on-board floating-point processor, four high-bandwidth serial DMA communication links and, initially, only programmable in a well-intended but awful programming language known as OCCAM [5]. Alfred Rizzi, who joined Dan's lab about a year or so after me, focused his polymath theoretical, design, and experimental abilities on the problem of three-dimensional spatial "juggling" robot, an extraordinary accomplishment expanding upon Buehler's pioneering exploratory research [7–9].

My Ph.D. research focused on the far more prosaic problem of model-based adaptive control of robot manipulators [10, 11]. After finishing my thesis, I had the immense good fortune to spend a short period of time working with Dan on the problem of encoding simple assembly task planning as gradient vector fields, with the goal of obtaining provable stability results. Although we made progress, I failed to complete our desired stability proof. Happily, Işil Bozma, a friend from our graduate student days at Yale, subsequently picked up this problem and, together with Dan and her students, solved it [3].

Paradise must be very much like the Koditschek lab of my graduate student years – a small but intensely vibrant research community, where my colleagues were enthusiastically willing to share their knowledge with each other, in active pursuit of the nascent synthetic science of programming work. In the mix of this lab were a great variety of undergraduate and graduate students, staff, and faculty (like the aforementioned genius Peter Kindlmann who, with his spouse Marcia, took us under their wing) in hot pursuit of a panoply of exploratory theoretical, numerical simulation, and experimental investigations toward developing a science of robotics.

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Part III

Kod*lab Alumni – Michigan Years

> Synthesis is the final arbiter of understanding.
>
> — Professor Daniel E. Koditschek

A Natural Sequence

Rob Burridge, TRACLabs, Inc.
Kod*lab PhD student, 1993-1996

I was very fortunate to have met Dan when I was an undergraduate Math major at Yale in the mid-80's. My interest in electronics led me to take EE classes, which led me to Control Theory and Dan and Robotics at Yale. Dynamical Systems Theory was a good fit for me, and I loved how robotics was at the intersection of math, computer science, and electronics. Learning about and studying the stability of Raibert's hopping robots was an eye-opening experience. I think it's fair to say that I was rather more impressed by Dan and his work than the other way around. Somehow, I ended up with a dual degree in Math and EE. After some time off to collect my wits, during which I was a professional programmer, I headed to Michigan for a PhD in Computer Science. I was disappointed to find that nobody there seemed to be engaged in Dan's style of study of intelligent mechanisms. After a couple of years of doing symbolic AI research (my CS Master's degree was in Natural Language Processing), I was losing hope when, incredibly, Dan moved to Michigan – into the very building (The Advanced Technologies Lab) where I had my office! When he agreed to take me on as a student (it took some convincing), I felt like I was back on track. The 2D and 3D juggling machines were set up, Al Rizzi joined the lab, and Kod*lab was off to the races once more! Because we were working in the realm where symbols and signals meet, the members of Kod*lab fit in well in the larger Intelligent Systems and AI community in the ATL, and many interesting discussions took place at all hours. We could even field our own "AI Lab" line on the University's Ultimate team! The work I did for my dissertation on "Sequential composition of dynamically dexterous robot behaviors" (a.k.a., "Funnels, and how to use them") [1] remains one of the most fulfilling projects I've worked on, because it felt like we were opening the door on a new way of understanding the world. A couple of snapshots from my thesis video are shown in Figures 1 and 2. Over a dozen different controllers were available. At any given time, one was selected entirely based on the state of the ball. Left to its own evolution, the system will capture the thrown ball and maneuver it along a sequence of juggling set points until it gets near the obstacle. Once stabilized there, it will launch the ball over the obstacle, corral it on the other side, and eventually catch it on the paddle. All of these behaviors was shown to be locally stable, and they were sequenced by placing the set points of lower-priority controllers inside the domains of attraction of higher-priority controllers.

At NASA, we employed the same funneling/backchaining idea to compose a sequence of behaviors for a robot to acquire a sample box from a rover. The "Centaur" robot uses a long-distance perception algorithm to recognize the outline of the rover. When it finds it, it drives toward it. When it gets within a certain distance, it switches to locating the box and approaching it. When close enough to the box, it picks it up. If holding the box, it rotates and puts the box on the back of the Centaur. If in possession of the box, it drives home. All these behavioral transitions were driven by the state of the robot and its environment, rather than a traditional symbolic planner [2]. In Figure 3, the robot is in the middle of the sequence, having acquired the box.

Since leaving Michigan, my career has taken me in directions I did not expect. I've mostly worked on intelligent robot control from the symbolic side...designing interfaces with sliding autonomy, controlling space rovers across time delay, abstracting grasping tasks, and more. Somehow, the "fun stuff" – the underlying dynamical system – has always been just out of view. But fundamentally, I'm always trying to find ways to harness the natural tendencies of the system and steer them toward useful ends. All stable systems are funnels! Being a member of Kod*lab was a great experience, and it fundamentally shaped the way I try to

Figure 1: Tossing a ball to the juggler. The ability to handle ball tosses was a new behavior.

approach new lab groups that I join. I will be forever grateful to Dan for giving me that opportunity.

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Figure 2: Maneuvering a ball over an obstacle. A sequence of different types of juggling behaviors was created, including one that propelled the ball from one side to the other of an obstacle, and one that successfully caught it on the other side.

Figure 3: A sequence of behaviors is chained together by considering the domains of attraction within the state space of the system, and where the goal state of each behavior will be.

Juggling (robots)

Noah J. Cowan, Johns Hopkins University
Kod*lab PhD Student, 1995-2001. Kod*lab collaborator: 2017–present

Some people ask, "Noah, are you a scientist? Or are you an engineer?" Neither. I am a juggler, and since I can remember, I've been fascinated by how things move. Dan—and the ecosystem of visionary scientists and engineers he has trained and influenced—has nurtured my passions for understanding movement and its control beyond my wildest dreams. Indeed the great majority of *my* influencers are card-carrying members of the Dan Koditschek Universe... or maybe "*Danoverse*" for short.[1]

In the days and weeks leading up to Kod*fest, I have had the opportunity to read the myriad insightful anecdotes of this Festschrift, have deep interactions with many amazing people in the *Danoverse* that span generations of Kod*lab interactions, and peruse the beautiful photographs that have been assembled. This process has been so much more than "nostalgic": it has reawakened my appreciation for the *tremendous* fortune I have had to learn from, collaborate with, and—I hope in some small way—influence Dan Koditschek over so many years.

When I interviewed at Michigan, and learned about the Buehgler [21, 27] (Fig. 1), I had found my match. Little did I know at the time how well the intuitive insights that I gained as a young juggler would be fully manifest as a deep and broad intellectual universe created by Dan. I set off in 1995 to build the world's best juggling robot, with delusions of passing clubs with the robot on the Tonight Show. I failed miserably—but got so much more. Using a few examples, I hope to provide a glimpse at how deeply indebted I am to Dan and his *Danoverse*.

Hammer flips (mechanics). In juggling, one must first and foremost master how individual objects move. In middle school, I was enthralled with the annoying "twist" that a hammer or tennis racket would execute when flipped around a special axis that I only later learned was called the 'intermediate axis'. I did not know why, but if you gave me any object I could "guess" which was the "twisty" (intermediate) axis. What broke the symmetry? I.e. how did the hammer choose to go this way or that way? Was it the small asymmetries in the hammer? NO! I could give the object a slight hint when I flipped it and it would twist that way or this way on command.

Fast forward some 12-15 years later, and I take, at Dan's recommendation, Prof. Tony Bloch's course on nonholonomic mechanics [2]. Right on the cover of his secondary course textbook [15] was an image that unlocked the key to finally understanding my middle school fascination. And, the math is *hard*—I know of nobody who can explain in lay terms why this works, or teach it to undergraduates in anything but a superficial way, but in the language of energy and momentum, the solution is clear and beautiful. Indeed the "twisty" nature of an intermediate-axis flip is like the instability of an inverted pendulum: the pendulum doesn't tend to stay upright, and "falling" is a consequence of an unstable fixed point in TS^1, much like "twisting" is the result of an unstable orbit in $T\mathrm{SO}(3)$ of the flipping hammer. But, just like the pendulum does not "prefer" to fall this way or that way, neither does the hammer "prefer" to twist this way or that.

From Prof. Bloch, I also learned the beautiful and complex relationships between feedback control and nonholonomic systems, ideas that were ultimately married by my lab mate Gabriel Lopes', whose beautiful

[1] But I'm not sure if I should call it "*Danoverse*" so I'm going to define a Macro, and add it to my `kodhdr.tex` file right now:

```
\newcommand{\dank}{\emph{Danoverse}}
```

and then make a large footnote, explaining this critical but fairly circuitous thought process, surely to ensnare the Kod*lab aficionado in this glorious treasure hunt!

Figure 4: (left) Cover of Prof. Bloch's course text [15]: hammer flip explained! (right) Cover illustration for our article, featuring my graduate school juggling partner Josh Casey [1]. (lower) Parallel composition by Noah Cowan and Rick Chaffin in the Hayes High School football field.

dissertation work with Dan on the perceptual control of nonholonomic systems [14] connected my own dissertation [6, 7] with nonholonomic control. It truly is a universe of ideas!

Pair jugging (parallel composition and phase) As a high school junior, I competed in the International Juggler's Association (IJA) annual competition, in the "pairs" division (spoiler: we didn't make the cut). Pair juggling involves coordinating the independent actions of two dynamical systems (at the time, Rick Chaffin and Noah Cowan). The ability to assemble the coordinated actions of my hands or among groups of jugglers in parallel ties deeply to the *Danoverse*, with inspiring work by lab mates Eric Klavins and Al Rizzi [11, 20]. Issues of parallel composition require phase; phase can be enforced by a robotic programmer (or it can emerge [12]), using an internal clock, but for the biological experimentalist, one needs a data-driven approach to infer the state of the biological clock. Two more members of the *Danoverse*, Shai Revzen and John Guckenheimer, stepped in to fill that gap [19] developing ideas that we hope to marry with our approach to system identification of rhythmic systems using harmonic transfer functions [25, 26]. It should be noted that ideas of timing and phase have brought my career full circle,[2] as we have been investigating the roles of the neural control of timing of *juggling*, my first love [1, 18].

Strings of tricks (sequential composition) Paramount to a juggler's repertoire is the ability to string together tricks in sequence, and every good juggler understands that the order of such tricks is crucial: some tricks naturally "prepare" other tricks. For example, a high throw out of your left facilitates a behind-the-back toss with the right:

$$\text{high toss with left hand} \succeq \text{back cross with right hand}$$

and so on. A robust theoretical framework of "pulling off sequences of tricks" was put forth in the thesis work of my lab mate Rob Burridge [3]; Rob also expanded my motor repertoire, introducing me to disc golf, the ultimate venue for experiencing frustration in such compositional endeavors!

Since 2017, thanks to the extraordinary and visionary leadership of Dan (not to mention the thankless task of managing DOD grants and contracts to maintain our team) we have been collaborating through the Kod SLICE MURI grant, giving me the opportunity to bring Jim Knierim into the *Danoverse*. He and our students are now aimed at understanding how rats perform sequences of behaviors when jumping and ditching across a gap.

So much more... In addition to the many influences described above, the *Danoverse* has influenced me in countless other ways. I saw the value of building rigorous approximations of analytical models from Bill Schwind [23] and data from Rick Groff [9, 10]. I watched Uluc Saranli developing the now famous RHex robot [22]—who can forget when he was checking his email on RHex? It was also the time that Dan was working with my eventual Postdoc advisor Bob Full on their seminal paper on templates and anchors [8]; it was indeed the addition of Bob to the *Danoverse* that started us toward understanding and embracing the marvels of how "good mechanics" can simplify and improve control, a framework that has transformed my own work [4, 24]. It was through this connection with Bob as part of the *Danoverse* that I was able to move my career into brand new directions for my postdoc and beyond [5, 13, 16, 17]. This bridge, created by Dan and his many trainees and influencers, shaped my transition to neuroscience, where I have gotten to work with the very best neuroscientists in their fields (Fortune, Bastian, and Knierim to name a few). It is 100% because of Dan and his *Danoverse* that I have been able to move so fearlessly into these exciting directions that are now my life's passion. There are so many more ways that the *Danoverse* has shaped my career, and I can in no way cover them all in these short words. I apologize to all my *Danoverse* colleagues if I failed to mention you by name. Likewise, the words above did not convey the deep and sincere gratitude I have for my own students who are the product—and shapers—of the *Danoverse*, especially insofar as my contributions to it.

Thank you Dan! Your passion, creativity, imagination, and the incredible people you have assembled in the *Danoverse* have been the blessing of my intellectual life.

Now, let me finalize that macro and submit this paper.

[2]That's an S^1 joke.

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My Precious Time with Kod*lab at UMich

JUN NAKANISHI, MEIJO UNIVERSITY
KOD*LAB EXCHANGE MS STUDENT, 1995–1996, SUMMER VISITING PHD STUDENT, 1997–1999

It is a great honor to be a part of Kodlab and also to be invited to Kod*Fest. I spent time with Kodlab back in the mid to late 1990's, which is about 25 years ago. From 1995 to 1996, I studied in the master's program (EE: Systems) at the University of Michigan based on the exchange program between Nagoya University, Japan and the University of Michigan. Kodlab was located in the ATL building in the North Campus of U of M, and the lab was quite small at the time, consisting of 5-6 people. At U of M, in addition to taking classes, I had an opportunity to do research at Kodlab as a part of my master's thesis. I worked on robot brachiation from a nonlinear control point of view. I remember that this started when I had lunch with Prof. Koditschek for the first time. He drew a picture of a double pendulum on a paper napkin, and asked me if I was interested in working on this problem and suggested deriving equations of motion of such a system. Every week, I had a meeting with him and had discussions on how we tackle the problem. I was very fortunate to have such a series of valuable weekly meetings with him. These meetings were always with full of passion and enthusiasm. I was able to learn so much from him on how to formulate problems mathematically and think in a critical fashion. In addition, I have learned much about scientific writing. Prof. Koditschek guided me on how to write a paper on a paragraph by paragraph (actually, word by word) basis. He was patient enough to spend a whole month in summer to help me finish writing the initial technical report, which finally led to a journal publication a few years later [1]. During my PhD study at Nagoya University in Japan, I spent summer at Kodlab in the following next few years. Without his support, advice and a number of illuminating discussions, my thesis could have never been accomplished. My few years of invaluable experience at Kodlab has formed a solid foundation for my career. I greatly appreciate the support from Prof. Koditschek and all the people who I met at Kodlab back then. I wish you all the best and hope to have a chance to visit the University of Pennsylvania in the near future.

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Figure 5: ATL building at U of M (1995)


Figure 6: Lunch at Dan's home (circa 1998 or 1999)

Tenacity

Eric Klavins, University of Washington
Kod*lab PhD student, 1998-2001

Somewhere around 1999 I had only been working with Dan for a few months. He had given me a paper he and Rob Ghrist had written on configuration spaces for beads on networks of wires. I didn't understand a bit of it, but I wanted to mainly because the pictures in the paper looked neat. I was also somewhat jealous that Uluc already had a working simulation of his project and all I had was a bunch of vague ideas about groups of robots. I came to Dan's office almost every day for a few weeks asking him about identification topologies and potential functions. He was super busy but always made time at the end of the day when I know he was trying get get out of the office and go home! At one point he said "I appreciate your tenacity!". How many of you has he said that to? Just wondering. The statement was simultaneously inspiring, an acknowledgement I was making progress, but also an indication that although I still clearly didn't get it, that my hard work was a valuable asset. To this day I tell motivated but otherwise clueless students in the same situation that I "appreciate their tenacity". Works wonders!

Eventually I figured how the paper worked and was able to generalize it a bit. Then Dan told me I was going to Stanford to give a talk on that paper that he was supposed to give because he was busy. Woah. I was terrified. What if they asked me a question I couldn't answer? But it was a great opportunity and a great example of how Dan would treat his students like junior colleagues knowing they would step up to the challenge. So I went to the conference and people were like: "Wow, you're Dan's student. That's so cool." Suddenly I realized I was in this amazing lab with this big shot advisor! That one trip opened up a lot of doors. And there were more to follow. One time we took Rhex to a ski resort in Colorado (or somewhere like that) and built an obstacle course for it. That was fun! It was such a great experience to meet Dan's extended community and it definitely gave me the taste for research and also an aesthetic for mentorship that I use to this day with my own reports.

Thank you Dan for getting me off to a great start, kindly introducing me to people all over the world, and trusting me! All these years later I'm still trying to be as tenacious as possible!

God Cannot be That Cruel

Haldun Komsuoğlu, Robolit LLC, Hotel Drita Corp
Kod*lab Engineer (1998), PhD student (1999–2004), Postdoc (2004–2008)

Spanning a decade, from my very first job as an engineer in 1998 until my departure as a postdoc in 2008, I lived a sizable portion of my adult life in Kod*Lab working with Prof. Dan Koditschek[1]. Looking back I see it clearly that throughout this time Dan was not only a technical mentor guiding me through my professional growth but in fact a *guru* of sorts who helped me find my way not only intellectually but also emotionally. I know this sounds rather corny but nevertheless it really is true.

My first encounter with Kod*Lab was a talk by Bill Schwind on SLIP as a mathematical model for bipedal running [9]. I was a big mecha anime nerd at that time so this beautifully intuitive approach to study legged locomotion looked fascinating. Following a tour through the basement of the Advanced Research Lab, where Dan's group worked, I literally fell in love there and then. It was hard not to be impressed by the breadth of work. During my visit I was shown the 2D juggler [2] (unfortunately broken in pieces) and the visually guided 3D juggler [7] (mind you this is mid 1990s) capable of juggling multiple balls [6]. I remember listening to Dan describing the back chaining technique [3] which sounded very elegant to my young ears. I do not know what it says about me but I vividly remember that the whole lab looked like a candy shop to me.

Though, looking back, I think what really struck me at Kod*Lab was not the cool robots being built but the *feng shui* of the place if you will—collective quality of the people and the way they worked together—the

[1]In my home country it is a taboo to omit the "Prof." salutation. It took me a good year and half to get used to calling Dan by his name.

Figure 7: Entrance to the Advanced Research Lab at University of Michigan where Kod*Lab was situated. Led by Dan this is the birth place for seminal projects DARPA-RHex [8] and DARPA-RiSE [1] that I was fortunate to be part of.

Figure 8: (top) Feeling good after two successful oral Ph.D. qualification exams. (bottom) After being crushed by Dan's simple questions and the realization that I did not know anything.

lab culture. In later years, I remember many occasions where I enjoyed spending days on end at the lab sleeping on the floor, or not sleeping at all, rather than going home. When we went on site visits and stayed at road side cheap motels it somehow felt like a luxurious vacation. It was like a mission or an adventure being there with the whole team working on cool problems. It was pure joy even though it also meant multiple sleepless nights and frustrating failures. One can only endure and even desire to be in such situations if there is strong culture, a vibrant community. If I were to list Dan's super powers I would say the ability to establish, maintain and grow such a team and such a culture is at the top of the list.

When I got accepted by University of Michigan my original plan was to get my M.S. degree and return right back to Turkey. However, after I saw Kod*Lab and worked with Dan for a year as an engineer, I decided to pursue the Ph.D. program. To qualify for the Ph.D. program at UofM one needs to pass three oral exams. Following the educational model I was accustomed to back in my home country, which emphasizes the ability to solve problems rather than deep understanding, I reviewed all my text books front to back for three weeks. My first two exams went pretty well and I was feeling invincible (Figure 8(top)). My third exam was with Dan. As we started I suppose I looked rather cocky. His first question right off the bat was "what is a system?" I could have solved any text book problem but this seemingly simple but fundamental question floored me. It painfully showed me that I did not have a full grasp of the subject nor was I a good communicator. The rest of the exam felt pretty lousy and I was sure I failed the qualifiers when I left Dan's office (Figure 8(bottom)). Fortunately, by the grace of robot gods, I passed but this experience stayed with me as an embarrassing reminder always pushing me to question the fundamentals of any problem I am working on. Dan taught me a lot throughout our time together. Yet, I would say this fundamental *mannerism to seek the basics* he instilled in me is the most valuable teaching I had gotten from him.

Anybody who ever worked with Dan knows that he is a very diligent communicator, even to the point of obsession one might even say. This personality trait shows up most explicitly when writing papers. Many students of him could share a memory or two where they came close to eating the paper their draft is printed on. I was by no means an exception. Worse yet when I first started working with Dan I was probably in the lower quartile when it comes to communication as my earlier education did not emphasize communication as strongly as it should have.

An event during our first paper together [5] illustrates his devotion to good writing the best, which also left an enduring mark on me. Like any paper we were going through iteration after iteration and I was getting pages covered in red marks. A fast approaching deadline was making me anxious so I suggested at some point that the draft was may be ready for submission. His response was immediate and succinct: "if you like to submit it as is you can take my name off of it." His comment may sound harsh but it definitely worked in my case and instilled a strong interest in writing better, propelled by a combination of sense of embarrassment and challenge. Naturally, I did not get good at writing overnight, and arguably not even by the end of my time with him. Yet, seeing his approach and devotion to writing was the starting point for me when it comes to written communication. Many years later I organized a seminar class on communication [4] at a local university where several learnings from Dan were the center piece of the material. Interestingly though, while Dan is impressive in written communication his presentation preparation approach often leads to rather heavy slides that are hard to decipher—an interesting contradiction.

Research requires a very particular personality—one needs to be unafraid of the unknown and have an innate belief that a solution is attainable. It can be argued that most people with an interest in academia would naturally have these qualities to some degree. Though, like most super hero characters, at the onset of an academic career such personality traits are typically under-developed and rough. More than any specific engineering accomplishment, the goal of graduate studies, and therefore, the research advisors, is to help students polish and sharpen these key personality characteristics. This however is easier said than done. Unlike teaching calculus or nonlinear control, guiding somebody in the course of his/her personal growth is a black art. I observed Dan excels in this art. I am uncertain if his approach can be codified but it seems to consist of two components: 1) establishment of a vibrant lab community serving as a melting pot—an unsupervised learning arena; and 2) identifying and applying *just enough* technical/psychological hand holding.

Dan's unique success in the former was mentioned in earlier paragraphs. To illustrate the latter I can share one memory of mine. In early 2000 I was stuck in the proof section in [5]. We could see the characteristics in simulations but the algebraic explanation was eluding me. As I was really getting discouraged looking at the equations on the blackboard and all of a sudden Dan said "God cannot be that cruel." It is very hard to explain and probably would be different for different people but that was weirdly what I needed to hear. Not long after a very elegant solution emerged in our discussion. But that one statement really stuck with me telling me if sufficient amount of honest energy is put in a task one would attain a result. This is just one of those things you cannot learn in a classical education system, which I observe Dan to be excellent at.

While I spent a significant amount of time in academic research I always wanted to be in the commercial sector. I know Dan was not very keen on this path. Finally, in 2006 I embarked on a (ill fated) start-up venture. Despite his strong reservations Dan offered me all the help he could. I knew that this was not an area he was familiar with nor felt comfortable, yet he was there from the very beginning doing everything he could. I owe Dan a dept of gratitude for his support and would like this document to serve as a public acknowledgement of his positive role. That start-up adventure ultimately failed spectacularly in 2008, primarily due to my shortcomings in running a business at the time. Afterwards, I went into a year long deep depression. Throughout, both in good and bad, Dan never stopped his support. While painful this experience was extremely valuable for me and I could not have it if it was not for Dan.

For the past decade I have been engaged in a number of business ventures (more successful ones) and I keep finding myself employing learnings from my time at Kod*Lab and with Dan. I consider myself extremely lucky to have the opportunity to know and work with the Kod*Lab community. I am well aware that who I am now is strongly shaped by my time at Kod*Lab and working with Dan. I can only hope that in my life time I can carry the Kod*Lab culture providing opportunities for others to grow both technically and emotionally just as Kod*Lab and Dan has done for me.

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Part IV

Kod*lab Alumni – Penn Years

Attracting, invariant,
submanifold.

Professor Daniel E. Koditschek

Reflections on a Dozen Years with Kod*lab

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Kod*lab Undergrad, 2000–2002,
Kod*lab Collaborator, 2002–2008,
Kod*lab Postdoc 2008–2011,
Kod*lab Collaborator 2011-2012

I was in the Kod*lab orbit for the first 12 years of my career, starting as an undergraduate intern, collaborating afar during graduate school on various multi-university robotics projects, rejoining Kod*lab for a postdoctoral fellowship, and working together on a research project for the first year after my postdoc. As such, I have many fond memories of the work we did, the relationships and friendships developed, and the growth experienced during those years. This document is a personal reflection on many of those experiences.

Most of my research collaborations with Al Rizzi (my Ph.D. advisor during graduate school and Dan's former student) and Dan (during my postdoc) focused on understanding the topological implications of controlling legged robot gaits. This work was a natural extension of Eric Klavins' earlier research on coordination control [10], but it brought to bear learnings gained from numerous robot experiments. We built parsimonious representations of gaits and gait "obstacles", and developed planning and control methods that could navigate the gait space whilst avoiding regions that might cause a robot to become unstable or fall down. We utilized homotopic equivalences amongst gaits to inform control laws that could naturally stabilize robot gaits as well as perform effective transitions in time, particularly useful when performing challenging tasks such as negotiating stairs or climbing vertical walls [4–6]. Our research was exciting, and I felt great personal growth in my ability to conduct advanced R&D, learning to create hypotheses, design structured tests, and using a wide set of tools to analyze results.

But I also feel like I should mention the vast systems engineering work we did as part of Kod*lab. As a group, we never shied away from robot experiments, as studies conducted only on paper or in simulation could not sufficiently prove the utility of a given approach to real-world systems. As such, we spent countless hours building robots, maintaining systems, and figuring out how to be more efficient at these tasks. A handful of notable accomplishments I was personally involved with:

- Through a large collaboration led by Dan, we built the RiSE robot [13] and conducted numerous field tests at the Southwest Research Institute (SwRI). Through amazing grippy feet (built by Mark Cutkosky's group at Stanford), novel robot mechanisms (by Boston Dynamics), and robot behaviors (by Dan's group at U-Penn and Al's group at CMU), our robot was able to scale the vertical stucco wall of the library on the SwRI campus (circa 2006). A subsequent version climbed telephone poles rapidly [2] (circa 2008).
- When I rejoined the lab as a postdoc, we had a desire to conduct an even more varied set of experimental research, and we felt the need to improve our ability to design and build our own robotic platforms. Dan (perhaps begrudgingly) agreed, and thus the X-RHex robots were born [1] (circa 2009). We

built several generations of new robotic systems (via our Laboratory on Legs [3] concept: X-RHex, XRL, and Canid), focused on utilizing off the shelf parts for easy serviceability of our robots, and built a payload architecture that allowed researchers to easily swap parts, such that the same robot could perform dramatically different research experiments minutes apart. Through the use of new exteroceptive sensors, this work led to some of our first truly autonomous mobility experiments [8], for instance navigating a stairwell fully autonomously. Furthermore, we continued our tradition of field experiments, this time bringing multiple generations of RHex robots to the mountainous desert landscapes of Twentynine Palms over several years.

- As part of our systems engineering, I personally pushed for a more flexible software architecture to make us more efficient at performing robot experiments, developing the *Dynamism* software library [3]. With a focus on ease of use, our software allowed interns to program and test robot behaviors on day 1 of their internships, and the system was so easy to use that we delivered functional robots to collaborators across the pond, with folks like Andrew Spence conducting research comparing robot gaits to those of terrestrial animals [16]

Through our systems engineering, it truly felt that there was a resurgence in our ability to build unique robotic systems, a resulting increase in the group's research output, and numerous students who came through the lab and got their own starts at careers in robotics from our laboratory work.

One thing that felt unique in our work was how we involved everyone in the research process. When I started as an undergraduate intern, I remember Noah Cowan taking the time to carefully explain everything about his research to me. While I was mainly focused on developing interface software for our robot arm (a UMI-RTX robot that felt ancient even then, over two decades ago), Noah felt it was important for me to understand the greater picture of the work we were conducting, and the mathematical equations I was translating to code. Later, as a graduate student on the RiSE project, our multidisciplinary research team of biologists, mechanical engineers, controls experts, and software developers all shared in the responsibility of building a unique set of climbing robots, constantly strived to educate one another on progress, and we published many useful papers from these collaborations. As a postdoc, personally moving into more of a lab manager role, I had a wonderful learning experience onboarding new students and summer interns, taking robots to the desert or to the Royal Vet College along with our undergraduate students, and involving as many as possible in our research.

In hindsight, there are some aspects I feel like we could have improved. The first and foremost was that we held a slight prejudice against the use of machine learning in those early days, a bias I personally carried until this most recent decade when, like so many other fields, ML completely revolutionized robotics. This prejudice was perhaps born out of a desire to always understand our concepts via first principles, something that is sometimes difficult with ML systems. The most advanced learning method we used on our robots was Nelder-Mead [15], a rather simple, gradient-free optimization algorithm. I now reflect that today's ML systems are capable of producing parsimonious representations all the same, but optimizing both the intrinsic parameters within a representation as well as choosing the manifolds on which the representations live.

A second area we could have focused more effort on was the diversity of our research team. As a white male engineer, starting out in a lab largely full of white male engineers, we could have performed more outreach to get people with different backgrounds involved in our work. As an undergrad, I had never considered pursuing a Ph.D. and I partially attribute my decision to apply to Noah Cowan making the suggestion. But I also wonder, how many other intelligent, young engineers could have benefited from suggestions like those, and could we have worked harder to reach out to them. The world has changed in the last 20 years, and I certainly hope it has moved toward the better in this regard.

In my career since leaving Kod*lab, I feel like I have reaped the benefits of our time spent together during those 12 years.

- As I moved into industrial R&D, my time in the lab working on "signals and symbols", developing an understanding of systems via first principles, was extremely useful as I worked on self-driving vehicles. As the team lead for our "prediction" system at Uber, I led a group of engineers and ML researchers developing methods to predict actor-actor interactions between an autonomous vehicle and other road users and road infrastructure, probing into a truly unique set of homotopies in an *interaction space* [9, 11, 12, 18]. This separation of symbols from signals largely informed the design of our software architectures.

- Kod*lab's extensive experience developing large robotic systems informed my efforts leading the software development of the CHIMP robot [7, 14], CMU's humanoid robot that was an entrant to the 2015 DARPA Robotics Challenge, one of the only robots to complete the challenge, and 3rd place winner, and was extremely useful as I moved into large system architecture roles designing significant portions of an autonomous vehicle's autonomy system at Uber.

- And last, our multifaceted and dynamic relationships working together in the lab helped me immensely as I moved into mentorship roles in the years since, interviewing hundreds of engineers, and directly mentoring dozens. Of those relationships I've formed since, one of my greatest honors was mentoring someone over many years and strongly advocating for *her* to replace me when I moved on toward new pursuits.

In no particular order, here are a few other random memories of Kod*lab and related activities:

- Sneaking off for games of foosball with the gang in the basement of the ATL at U-M (circa 2000)
- Taking RHex for hikes in the Arb at U-M (circa 2001)
- Installing (and subsequently drawing blood from) razor sharp claws during RiSE robot testing (and sharing that experience with a friend who incorporated it into a tongue-in-cheek book about the future robot uprising [17]) (circa 2004)
- Enjoying the Spaten Optimator after RiSE climbed the SwRI library wall, the wager that Bill McBride had put up to entice us to try the climb (circa 2006)
- Desert testing trips with Aaron Johnson, Greg Moore, Gill Pratt, and others, surviving the desert heat but sometimes burning out robot motors (circa 2009)
- Having an X-RHex celebration party at my apartment, on the day that we finished putting the robot together but also the day we instantly fried the battery control board when first powering the system (The robot did not walk for another month or so, and the joke was that the party was more of a funeral than a celebration) (circa 2009)
- Numerous group lunches at White Dog Cafe and other local establishments near Penn's campus (circa 2011)

It has truly been an honor and an inspiration to have been a part of such a dynamic, unique research group over many years, and I have much gratitude for all of the experiences we have shared.

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On Wisdom, Scholarship, and Mentorship

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Kod*lab undergraduate researcher, 2007–2011

Wisdom

I first walked into Dan Koditschek's office at Penn as a nervous-but-excited seventeen year old in my first few weeks as an undergraduate student. I remember being struck (and somewhat intimidated) by the two "layers" of outer offices and corresponding administrative assistants that guarded the inner sanctum of the Chair's office. My interest in Dan's group had stemmed initially from a brief essay that Penn required applicants to submit on whom they would like to work with if admitted; after reading about the different groups at the GRASP lab, I had written about my interest in Dan's research on bioinspired legged locomotion. In my first meeting with Dan, I conveyed this interest in working with his group (having little-to-no understanding of the actual mechanics of what this would entail or whether I had any background whatsoever to do so). Dan seemed quite intrigued by the fact that I had found his research group before I had arrived at Penn, and agreed to allow me to work in his group. However, he did add the following caveat: "Since you're a freshman, you still have a lot to learn. But, we'll find you something to work on, even if it is cleaning our doorknobs!". As is his wont, Dan said this with a beaming smile and a wise twinkle in his eye. And so began my relationship with someone whose wisdom, scholarship, and mentorship have had an immeasurably large impact on my life.

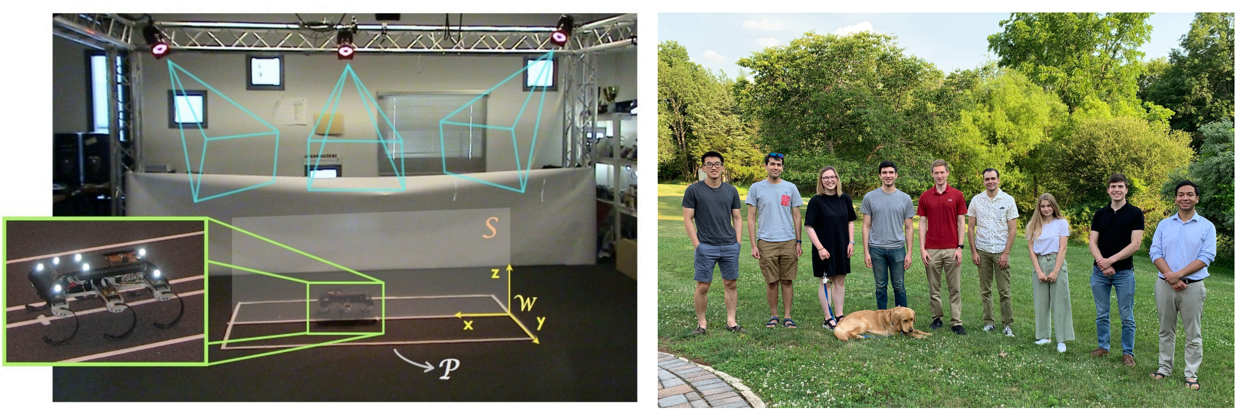

Figure 9: Left: the experimental setup in [4]. Right: the Intelligent Robot Motion (IRoM) Lab at Princeton (2021).

Scholarship

I spent all four years at Penn working in Dan's group and was mentored by a number of Dan's PhD students and postdocs (including Kevin Galloway, Hal Komsuoglu, Shai Revzen, and Clark Haynes). Initially, I worked with Kevin Galloway on re-designing the legs for the RHex (and related) robots with the goal of preventing them from breaking frequently. I also helped out with Kevin's gait tuning experiments for his work on variable compliance legs. This exposed me to blackbox (i.e., derivative-free) optimization and the Nelder-Mead algorithm in particular. Seeing the algorithm automatically tune the gait of the robot through multiple hardware trials allowed me to obtain invaluable experience working with physical robotic platforms and understanding their vagaries (in addition to exposing me to the basics of Linux, ssh, scp, etc.). The hours of watching the robot tune its gait also sparked some (vague) ideas on the relationship between the frequency characteristics of the robot's center of mass (COM) motion and the energy efficiency of the gait. I remember shooting off an excited email to Dan about these ideas, without necessarily expecting this to lead anywhere. To my surprise, he responded rapidly to express his enthusiasm and asked me to setup a meeting with him to discuss the ideas once the semester had wrapped up. Dan mentioned that Hal Komsuoglu had been thinking about related directions and asked me to chat with him.

This project with Hal, Dan, and Yasemin Ozkan-Aydin was a tremendous learning experience for me. Dan took the time to meet with us weekly throughout the summer. Being involved with these discussions allowed me to see first-hand what research looks like, all the way from conception to execution. The thoroughness, attention to detail, and care that Dan, Hal, and Yasemin approached the research with have had a lasting impact on the way I try to approach my own work. I learned about how one goes about formulating a clear and mathematically precise hypothesis to carefully constructing and conducting hardware experiments. Perhaps the biggest learning experience was being involved with the paper writing process. Hal tasked me with writing some of the sections of the paper and then took the time to provide a meticulous set of edits on both high-level and sentence-level structure. After several iterations of this, we sent Dan a draft of the paper for feedback. Dan's response has stuck with me through the years: "This is a very good draft... it is only about 5-7 iterations away from being done!". The paper that ultimately resulted from this work (on the relationship between the energy efficiency of the EduBot (Fig. 9 left) robot's gait and the closeness of its COM motion to that of a spring-loaded inverted pendulum) was my first publication as a co-author [4]. The care that both Hal and Dan took with the research and writing process is something I strive to convey to my own students now.

Looking back at these formative experiences, I am struck by the impact that they have had on how I approach research. Leading my own research group at Princeton (Fig. 9 right), I try to convey many of the lessons and themes that I learned at the Kod*lab to the PhD and undergraduate students with whom I work. In my mind, the Kod*lab's research is characterized by deep formal reasoning combined with a commitment to validating and demonstrating the power of this formal machinery on physical robotic machinery. This "feedback loop" between theoretical/algorithmic work and hardware experimentation is now central to our group's research on controlling agile robotic systems with formal guarantees on safety and performance. In addition, the Kod*lab's focus on leveraging powerful mathematical techniques (from algebraic topology in particular) inspired my various forays over the years into learning about topology, measure theory, abstract algebra, and category theory. Indeed, my decision to pursue a double major in mathematics (with mechanical engineering) was largely inspired by Dan's deep belief in the power of formal reasoning. This openness to leveraging powerful mathematical machinery to solve practical problems is a theme in my own group's research, and one that I try to convey to my students. Beyond thematic influence, Dan's research (with R. R. Burridge and A. A. Rizzi) on sequential composition of "funnels" [1] served as inspiration for much of the work I did during my PhD with Russ Tedrake [6]. In addition, a recent line of work in my group has been inspired by many conversations I have had with Dan over the years on his ideas on "programming work" [3]. In particular, my group has been thinking about (i) how one can formally compare the "complexity" of different robotic tasks via *reductions* [2] , and (ii) information-theoretic techniques for establishing fundamental limits on performance imposed by a robot's sensors [5].

Mentorship

Dan has played an immensely important role in shaping my research career. Perhaps most importantly, Dan helped me find my own path as a researcher (as he has done with countless others). Early on in my undergraduate career, Dan took the time to have one-on-one conversations to provide feedback on various less-than-half baked ideas I went to him with. One particularly memorable conversation stands out in my mind. Towards the end of my first semester at Penn, I went to Dan with some ideas on neural networks and learning for robots. I was somewhat hesitant to describe these to Dan, but he encouraged me by saying that his whiteboard was meant for half-baked ideas. Dan listened carefully to my thoughts and encouraged me to continue thinking about them with three pieces of advice that have remained with me through the years. First, he asked me to think of the simplest non-trivial example that would elucidate what I had in mind. Second, he gave me a book on discrete mathematics (which ended up sparking a long-term interest in information theory). Finally, he told me that to be a successful researcher, one must maintain a fine balance between ignorance and knowledge. Too much ignorance results in not having the requisite background to work at the cutting edge. But too much knowledge biases one towards paths already trodden. With these wise words, he helped me realize that I had a lot of learning yet to do while still encouraging me to continue trying to find my own research path.

Later in my undergraduate years, Dan helped me start planning for life after Penn. In my junior year, he asked me if I was interested in pursuing a PhD. When I answered in the affirmative, he gave me some homework: curate a list of 20-25 papers that I found interesting. When I went back to him with this list, he pored over it carefully and created a list of potential PhD advisors from the list of authors on the papers (in addition to some names he suggested himself). At the top of this list was Russ Tedrake at MIT. Dan then helped me connect with Russ and recommended me for a summer internship in his group. This eventually led to my pursuing a PhD with Russ a year later. This ability to help students find their own way (and to help them move forward when the time comes) is something that I find myself striving for as a mentor. I have borrowed the technique of asking undergraduate students interested in a PhD to find their interests by curating a list of papers on their own. I can only hope that I am able to have even a fraction of the impact that Dan has had on my research path and on those of countless others.

I am immensely grateful to Dan for his mentorship, kindness, and support. Dan and the Kod*lab have contributed immeasurably to my growth as a researcher. I look forward to many more years of seeking his sage advice, reading his group's papers, and admiring his impact on the robotics community.

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Wandering Through the Desert: How Kod*lab Launched My Career

Aaron M. Johnson, Carnegie Mellon University
Kod*lab PhD student, 2008–2014, Postdoc 2014

I feel incredibly fortunate to have had the opportunity to complete my PhD under Dan – it was, with no exaggeration, life changing. My time with Dan has set me up for a lifetime of exciting research and a career that I love. It is impossible to capture in a short document all the ways that Dan has influenced my work and my life, but I will attempt to capture some relevant anecdotes and reflections along with a summary of the research I did in Kod*lab and since.

My start in Kod*lab

I feel especially lucky to have ended up in Dan's lab since I wrote my graduate school application essay about multi-robot systems and computer vision (which is not at all what Dan works on or what I ended up doing, with small exceptions [22]). Dan was wise enough to ignore what I wrote and extend me an offer. Dan often talks about having a "nose for talent," and this ability to look past the surface (in my case, an undergrad claiming to be interested in unrelated topics) and find good talent is one that I hope to develop further over time.

I think many of us remember our first meeting with Dan. For both the initial phone call and when I came to visit in person, I remember discussing deep philosophical ideas about robotics and coming out of the meeting with a long list of things to look up. Once I was in the lab, we would always try to catch perspective students right after their meeting with Dan. They often came out dazed and overwhelmed, but with an excitement about the grand ideas that they covered, and needed some time to debrief and recover.

Mix of theoretical and empirical

One thing that is incredible about Kod*lab is that it has always been strong in both theoretical and empirical engineering. Dan is, clearly, the driving force on the theoretical side. What is surprising once you get to know Dan is that the lab has also been so strong in the design and experimental side of robotics, most notably with the RHex, RiSE, and Minitaur robots as well as alumni (and designs) going on to key roles in Boston Dynamics, Ghost Robotics, and other companies. I don't know how conscious a effort this has been, but my suspicion is that Dan intentionally recruits students who are strong empirically to maintain the success in that area.

A good example of this mix from my thesis work is my ICRA 2013 paper [17], which both introduced a way to describe the different contact conditions that a legged robot will experience as an abstract simplicial complex, and also demonstrated that different paths through this complex led to different leaping behaviors that could jump onto ledges and across gaps.

Continuing on this theme, the main focus of my research then as now has been contact. Changing contact conditions is a fundamental challenge to both legged locomotion and object manipulation. On the more theoretical side, in addition to [17], another major part of my thesis was a new formulation of hybrid dynamical systems where we were able to prove several consistency properties [11]. On the more empirical side, my first paper in Kod*lab was a proprioceptive contact detection and reactive controller [13], which we then used for stair climbing [9, 12, 39] and terrain identification [27].

In my lab this focus on contact and hybrid systems has continued, with both theoretical and empirical results. A lot of work has focused on the saltation matrix, which captures first order variations through impacts, which we can use to analyze stability [40], perform Kalman filtering [21, 31], and generate new trajectories with iLQR [20]. We have also developed new methods of contact localization [36], improved the accuracy of contact-implicit optimization [28, 34], and built robot hands that can more transparently react to contact [2, 3].

Students need to wander in the desert

Dan would often say that a young graduate student needed to "wander in the desert" for a while to figure out what the most important thesis topic is. I found this phrase incredibly confusing, seeing as how I went on a total of four trips to actual deserts (Mojave, Jornada, and White Sands) [12, 32]. In truth, that time literally wandering in the desert was incredibly valuable to my development.

The initial trips to the Mojave desert with Clark Haynes and an original RHex (plus some small robustness upgrades) exposed many limitations with the design and required a lot of in-field repairs. This motivated the need to build the next generation X-RHex and XRL robots [6, 7], exposed to me the importance of thermal modeling for motors [5, 6], and led me to derive the self-manipulation modeling framework (capturing the kinematics of legged locomotion in the same way as an object manipulation) [14, 16], which was required in order to prove the validity of a controller that reactively stands on rocky terrain without burning up the motors. These trips also provided a test case for hill climbing autonomy [8, 12, 15, 19] and motivated the need for jumping [17] and tails [4, 18, 23, 26] to traverse extremely rocky terrain. Pictures and videos from these trips would be a mainstay of every talk I gave for about a decade after the first trip.

I have tried to apply this philosophy in my own lab as well, giving students the space to explore different ideas and change topics along the way. As for the literal wandering in the desert, I have managed to get one student to a desert, the Atacama, where we tested an approach for digging trenches in sand using the wheels of a rover [29, 30]. (My lab has also taken environmental monitoring robots out to west Texas, though not technically in the desert.)

The legacy of RHex as a "model organism" for robotics

It is incredible how deep and wide an impact RHex has had. Over a span of about two decades (I believe starting in 1999, with first papers in 2001 [33]), RHex has provided generations of researchers with a dynamically-interesting but relatively stable platform to conduct research. It has been used for graduate research, undergraduate classes, and K12 outreach. At times it held records for efficiency, speed, leaping ability [17], autonomous stair climbing [9, 12, 39], and more on legged robots. In some ways its simplicity as a legged robot gives it an advantage in terms of longevity – if a new idea can be demonstrated on a simple, well understood robot like RHex, isn't that more valuable than showing it on a more complicated robot with multiple confounding factors?

I think that RHex should be considered a "model organism" for robotics. Some criteria for this designation: Versions of RHex have been used in more than a dozen labs at McGill, Michigan, Berkeley, CMU, Boston Dynamics, Georgia Tech, NTU, ARL, RVC, FSU, JHU, OSU, and more. I estimate that in total there have been at least 30 copies made and at least 50 papers featuring RHex, though the real numbers could be twice this. Its dynamics and control are incredibly well understood. Any new results produced on RHex are more valuable than a random new robot because there is a rich history and context that the new work falls into. (Some other robots that should probably be considered "model organisms" include: PR2, Turtlebot, quadrotors, and, increasingly, the class of quadrupeds that include Spot, Vision 60, Cheetah, A1, and ANYmal).

When we were building the X-RHex and XRL robots about 10 years after the original RHex [6, 7], Dan would ask us "are we just building YARR – Yet Another RHex Robot". But there were a number of important innovations that came with that generation of robot. They were the first to feature BLDC motors with low gear ratios (quasi-direct drive) that enable transparency and proprioception – an architecture that is now standard in legged robots. They were the first legged robots with a GPU, and were capable of greatly improved perception and autonomy. They had improved peak power output. Though designing X-RHex and XRL was a major undertaking, they enabled a new generation of students to work on RHex during its second decade of relevance.

I am sad to say that while I have an XRL in my lab now, it has not been used in a few years and we recently disposed of the aging batteries. I don't know if it will walk again. However, my lab has produced two new robots on the RHex family: MiniRHex [1] is a small, open-source, $200 RHex robot that we developed for outreach events (though it has also been used for research in my lab and elsewhere). T-RHex [24] is a slightly bigger version that includes microspine toes that is capable of hanging from vertical surfaces and climbing slopes up to 60°. Interestingly, my lab has also recently developed a new legged robot design featuring just "one actuator per leg," one of the defining features of RHex, but in this case as a passive dynamic walking-inspired bipedal robot [10].

Misc thoughts on Dan

Dan did not like to use the word "planning" (or "learning"); instead in the lab we would call everything "control" (or at most "planning and control"). I think Omur Arslan and Vasileios Vasilopoulos have cured Dan's aversion to the word. This is one area that I have worked to expand beyond the scope of Kod*lab's research, working on both planning [15, 25, 35] and learning [37, 38], though bringing in many ideas from control into these domains.

Dan would always treat his postdocs like faculty, his grad students like postdocs, and his undergrads like grad students. As a grad student, I spent a lot of time managing the RCTA project, even working out the budget for the DMUM section with Al Rizzi on the phone and calling in as Penn's rep to the PI meetings at times. I think this was incredibly valuable in preparing me for a faculty position, and has also led to at least 16 other PhD/Postdocs and at least 5 BS/MS students from Kod*lab that went on to faculty positions.

Dan taught me a greater degree of restraint and patience – sometimes it is better to hold back and get a better paper/video/job/etc a few months later. As a student I found this frustrating as I was too eager to get things moving, but I have come to appreciate the value of patience.

Dan also taught me how to write and, by negative examples, how not to write. Dan once told me that what he liked about the English language was that it had "infinite depth" – you can always add another comma, parenthetical phrase, etc. What results is that text from Dan would involve incredibly long sentences that I would then go back through and break up into multiple sentences. One example that made it into a paper [17] are these two sentences that have between them five commas, four parenthetical phrases, two dashes, and span 15 lines in the original document:

> Next, in Section II, we review some preliminary formal ideas concerning the central object of study, a two legged sagittal plane hopper, and exhibit the topological space – the "ground reaction complex" (in this case a simplicial tetrathedron) – over whose variously dimensioned cells the Hamiltonian flows of its holonomically constrained body evolve as directed by the ground reaction forces. This cellular construction indexes in a computationally effective ("grammatical") manner the realizable sequences of continuous dynamics that are physically available, providing crucial intuition for hand-designed behaviors (as suggested by the new capabilities we document) as well as parameterizing the various sequences of constraints that would be required for any automated method of behavior generation (i.e. a learning or optimization based approach).

While Dan's sentences are always formally correct, they taught me to appreciate the importance of readability in technical communication.

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The Shape of Robotics

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Without a doubt, Dan Koditschek has been one of the most important mentors and collaborators of my academic career. Starting in 2006, Dan became a *de-facto* PhD co-adviser to me. We would have weekly hour long calls during which we would guide my studies of relevant topics of control theory, and inculcate me with his perspective on robotics and the ideas of templates and anchors that guided my work during the first 10 years of my career. Dan and his intellectual progeny continue to exert a major influence on my work and that of my former and current students (see Fig. 10).

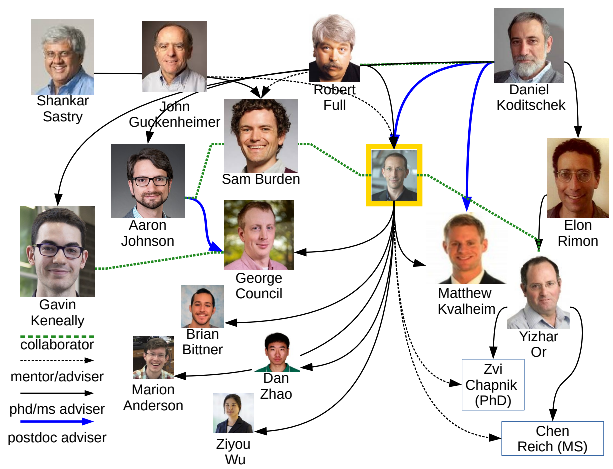


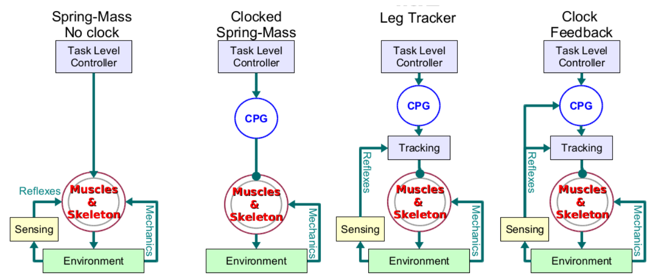
Figure 10: Koditschek's extended network of mentorship and collaboration that surrounds my research activities.

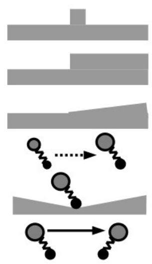
The Shape of Robotics

One of Dan's lasting legacies is the creation of a culture of intellectual curiosity and daring. The Kod*Lab is a group that asks big questions, and is not afraid of using difficult and non-trivial cutting edge mathematics to answer those questions. The questions all surround the notion, coined by Dan, that ROBOTICS IS THE ABILITY TO PROGRAM MECHANICAL WORK.

In my years of working with Dan, his students, and now my own students, this touched upon several key areas, as expressed in our work either with Dan or directly inspired by my collaboration with him:

- The structure of knowledge and modeling, as expressed by the "Templates & Anchors" hypothesis. This led to multiple publications by myself and my student Matthew Kvalheim (who went on to do a post-doc with Dan) on the arxiv [13] and leading to a book chapter on the topic [12], and ultimately one of the most important math papers Matthew and I co-authored [10].
- The idea of exponentially stable oscillators as the fundamental templates of all locomotion gaits, and through that the use of perturbations and phase to identify the controllers generating these gaits [19]





	NCA0 *Spring Mass No Clock*	NCA1 *Clocked Spring-Mass*	NCA2 *Leg Tracker*	NCA3 *Clock Feedback*
Bump	P	D	=	P
Step	P	D	=	P
Incline	O(F)→N	D,P→N	P→N	P,F
Mass	P	P	P	P,F
Substrate	O(F)	O	=	P,F
Impulse	P	D	=	P

= no asymptotic changes
P continuous phase resetting
D discrete phase resetting
F frequency change
O change of orbit
N no stable solutions

Figure 11: Different Neuromechanical Control Architectures can be identified using phase response alone. Reproduced from

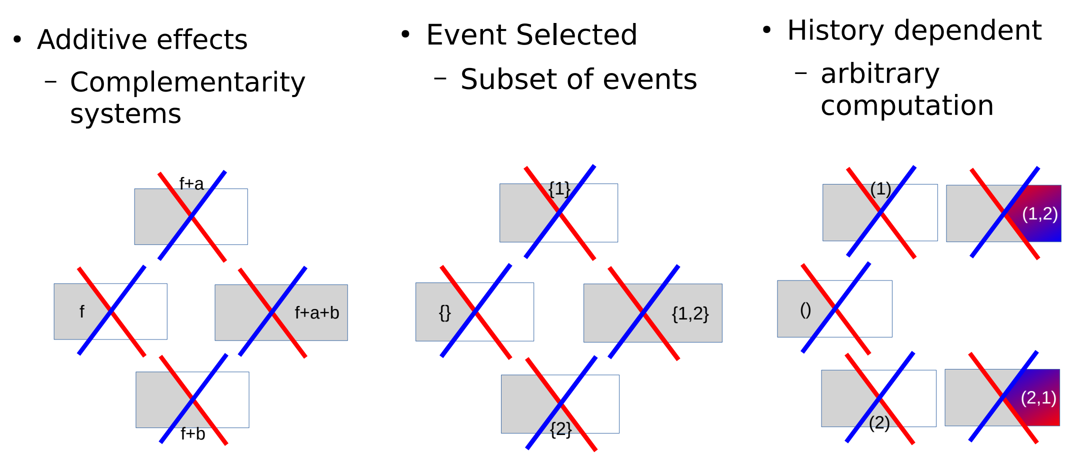


Figure 12: Event selected systems are hybrid systems that may have intersecting guards (red, blue), whose flows irreversibly cross the guards. Those flows depend only on the set of guards that was crossed and not the order of crossings.

and Fig. 11. This became the most important and influential idea in my PhD thesis [15], and the estimation of phase and its uses [16] continues to shape my career to this day [21, 22], finding broad application in creating data driven models of locomotion of various types [14, 20] and in particular a fruitful collaboration on data driven models using ideas of geometric mechanics [1–6, 11].

- The idea of "programming" second order dynamical systems with first order "reference generator" dynamical systems [17]

- Some insights into the fundamental limits of robotics as a (robust) computational process [18]
- The formulation and analysis of event-selected systems (ESS) [7], which provide the theoretical backing and tooling for analysis of multi-contact mechanical collisions (see Fig. 12). These formed a significant part of George Council's thesis [8] (he went on to do a postdoc with Dan's former student Aaron Johnson) and lead to substantial computational and theoretical improvements [9](now in print).

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Robotics: Programming Work or Programming Motion?

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Kod*lab PhD student, 2009–2016, Postdoc 2016-2017

Happy Birthday, Dan!

Becoming a member of the Kod*lab family was a unique experience and privilege for me to grow as a robotics scientist with the Kod*lab culture that produces high quality innovative ideas with high scientific integrity and social impact. I would like to thank Dan once again for giving me this opportunity, and many thanks to all Kod*lab members for their inspiring work and support. Below I briefly reflect on my personal experience working at the Kod*lab and then provide a brief critical review on Dan's vision on robotics and programming work [12].

Kod*lab Culture & Influence

In my opinion, one of the greatest achievements of Dan is that he created a safe, open, and diverse research environment, Kod*lab, for his students and collaborators to conduct curiosity driven multidisciplinary fundamental research in robotics. The diversity and openness of its atmosphere significantly contribute to the Kod*lab research quality, which is also ensured by high research integrity and ethics standards accepted by Dan and the lab members. I think Kod*lab is one of the few research labs where the research culture prioritizes quality over quantity.

Innovation at the Kod*lab often starts by bringing and combining different disciplines together. This is mostly because of Dan's broad interests in biology, psychology, math, computer science, and engineering, to name a few. Many times I observed that Dan encouraged his students to take a risky step into an unexplored territory at the intersection of different research fields. I think all Kod*lab members strongly embrace the fact that the road to innovation is through commitment and many failures, which is at the heart of the Kod*lab research culture. For example, Dan and I explored the use of hierarchical clustering for symbolic abstraction and coordination of multirobot systems [1], which is at the intersection of machine learning, robotics, discrete mathematics, and topology. I am very proud of this work because it is the first time that one can have explicit symbolic dynamics [2] to compose local robot behaviours to solve a complex planning task instead of constructing search-based symbolic dynamics offline [7]. An open research question we still don't have an answer to is what other explicit symbolic dynamics are relevant to autonomous robot motion design. I was first introduced to symbolic dynamics and sequential composition of local control policies [7] while doing my MSc research on legged locomotion [6] with another former Kod*lab member and my MSc supervisor, Uluc Saranli [14]. In my opinion, the idea of sequential composition is very strong and promising for closing the gap between low-level motion control and high-level motion planning, which is still a fundamental challenge of robotics (Problem 3 in [12]).

What about my failures and mistakes during my time at Kod*lab? It was a difficult experience publishing our early research results with many rejections. I believe that my biggest mistake was that I ignored the profile of my target audience: the robotics community. As a young PhD student, I had thought that Dan was my only target audience and his approval of a high quality innovative research was enough, which was a mistake. After a number of rejections, Dan reminded me that science is a social construct, and scientists generally do not like (and do not have time) to study and learn completely new ideas introduced by others.

Hence, these rejections were completely normal because we chose swimming against the current by daring to introduce completely new perspectives that others need to study and learn. After these unpleasant experiences, I decided to take a step back to better understand and relate to the robotics community. In my opinion, the exceptional scientific impact of some influential Kod*lab work [7, 8, 13, 14] is due to their simplicity. Since then, I set my goal as to achieve simplicity in my research because, as said by Leonardo da Vinci, "simplicity is the ultimate sophistication". Accordingly, before completing my PhD research, we demonstrated a simple application of partition clustering for identifying a local convex safe region around a robot to continuously move towards its closest point to a given goal position [5]. This simple strategy offers a provably correct sensor-based reactive navigation algorithm for spherical worlds, which before required a properly tuned navigation function using global world knowledge [13]. I think this result was very surprising to Dan since we solve a nontrivial navigation problem without using a navigation potential, but exploiting the local geometry of the environment. I was also very happy to see that this work was well received by the robotics community and nominated for the best paper award at the 12th International Workshop on Algorithmic Foundations of Robotics in 2016. I consider reactive robot navigation with local safe zones [5] as a continuous sequential composition [7] of infinitely many local controllers that are abstracted by robot position. This interpretation motivated us to design new feedback motion planners by extending path planners to second-order robot dynamics in complex environments using reference governors and total energy [4], thanks to Dan's prior efforts on using total energy for controlling mechanical systems [10, 11]. Although, this is a promising research result that supports Dan's vision on robotics and programming work, I have some practical concerns after observing its conservatism due to the invariance of Lyapunov/energy level sets. I am currently questioning if robotics is about programming work or programming motion as I discuss below.

A Brief Review of Dan's Vision on "What is Robotics?"

In a recent review paper [12], by drawing parallel lines with computer science, Dan suggests that "robotics is an emerging synthetic science concerned with programming work — the exchange of energy and information between a machine and its environment toward some specified set of goals". In this description, I see two potential issues with the notion of "exchange of energy". First, a literal understanding of "exchange of energy" makes this description not specific enough to only cover robotics; for example, the Internet-of-Things (IoT) can be simply included in this category, but IoT devices are often stationary with no motion, where motion is essential for robotics. Second, a more informed guess based on Dan's specific approach to robot programming by composing several local controllers that minimize a sort of total energy makes this definition too conservative since robot motion can be generated using many different ways. Of course, one can argue "the existence of an intrinsic scalar-valued Lyapunov function down which flows must decrease along the way to their steady-state attracting sets" [12], but this is a simple consequence of inverse Lyapunov theorems and the existence argument is often based on the executed robot motion (e.g., travel distance) towards the steady-state attracting set. As a result, there is a chicken-egg problem: is the robot motion due to the robot energy or is the robot energy (i.e., cost-to-go) due to the robot motion? In general, the notion of "work" is not clearly defined in [12], and so in the rest of the discussion, I will simply use the word "task" instead of "work".

According to Dan [12], performing a given task (i.e., "work") by a robot in its environment requires addressing three main challenges: robot hardware design (Problem 1), low-level robot control (Problem 2), and high-level robot intelligence (Problem 3).[1] Leaving Problem 1 aside, I see that Dan suggests addressing Problem 2 using energy-based dynamical primitives [10, 11] so that Problem 3 can be addressed using composition of these motion primitives [7]. My primary concern is about why we should restrict ourselves to the invariance properties of dynamical motion primitives while composing them. Lyapunov functions and invariant sets are essential in the stability analysis of low-level control policies, but they are very conservative in practice (and not invented) for high-level robot motion design. Invariant sets are limited in describing actual robot motion since they are not specifically associated with a given initial robot state, but any set of robot states that share the same "energy" level correspond to the same invariant set. For example, if a robot moves along a narrow corridor, the invariance of Lyapunov level sets often results in a cautious robot motion that avoids collision with corridor walls although the robot might be properly oriented along the corridor, because the information about the direction of motion is completely ignored once we just look at

[1] These are my intuitive interpretation of these problems. Please refer to [12] for the original problem statements.

the Lyapunov function value (i.e., "energy"). My current research focuses on developing new dynamical system theory for accurate motion prediction with stronger dependency on initial robot state to enable agile and dexterous robot motion design [3, 9]. As a robotics scientist, I completely agree with Dan regarding the urgent need for new dynamical system theory specifically developed for robotics, but I consider robotics as the science of programming mechanical motion instead of programming mechanical work/energy.

Finally, I would like to say that I am greatly impressed and always inspired by Dan's dedication and efforts for establishing robotics as a field of science [12]. In addition to research questions and social impact, I really like the emphasis on education and people as the foundational elements of robotics science. I think it would have been nice to include a discussion about the current profile of the robotics community and robotic scientists: Are we, the robotics community, ready to call ourselves a scientific community? If not, what is missing? If so, why is robotics not science yet?

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The Lasting Influence of Koditschek on Contemporary Robotics

Avik De, Ghost Robotics Co-Founder and CTO
Kod*lab PhD student, 2010–2017, Postdoc 2018

I am co-founder and CTO of Ghost Robotics, a startup company commercializing legged robotics in Philadelphia. Previously, I completed a postdoc at Harvard SEAS advised by Rob Wood, where I researched design of micro-scale flapping robots, as well as strategies for their control. I received my Ph.D. in 2017 under Dan Koditschek. The main thread tying all of my work together has been bio-inspired design and control strongly anchored in empirical robotics. I entered Kod*lab with what could be considered tailored preparation for a Ph.D. there: mentoring by Dr. Noah Cowan (a Koditschek graduate), research experience, a publication, and some amount of experience with hands-on hardware work. Nonetheless, it became clear that there was much to learn as I began my time at Penn working with Dan, about myself as well as the academic enterprise.

My first introduction to the contemporary Kod*lab was a meeting I sought out (Dan was not nominally accepting students that year) during visit weekend, with then-doctoral-student Goran Lynch. I still don't quite know why he volunteered himself for this meeting–not just donating some of his time that day, but also potentially diluting his advisor's future time–but I suspect it had to do with the strong culture of mentorship in the lab. I benefited from this firsthand, when Goran and Aaron Johnson helped me hit the ground running with a small self-contained research project my very first semester. The resulting first-authored publication [5], while not earth shattering in impact, helped me tremendously with building confidence, and has taught me a lasting lesson about the impact of mentorship on younger peers.

Another characteristic of Kod*lab, that ended up influencing my career in unexpected ways, was the active culture of building and using robotic hardware. I have found it quite uncommon in robotics to come across a lab full of people simultaneously capable of abstract thought, mechatronic design, and the mettle to do experimental work. The surprising part of all this was that Dan himself was completely at sea in the lab, and the persistent "trade" knowledge for hardware work has been passed down through graduate students over the years. (I have more to say on Dan's role in this aspect of the work below). During my time in the lab, I went from learning the "infrastructure du jour" to contributing and maintaining my own creations and tools, and have since my departure come to understand that the current students have built up their own set of components and robots. At times, I have wondered if this process is inefficient; I witnessed at the same time the growth of Dr. Sangbae Kim's lab at MIT, where students get far less choice in the platform they work on and the lab has been described to me as "run like a company." It took me a long time to understand that Dan's priority was less the attention-grabbing demonstration or publication for Kod*lab, but instead to boost the chances that, in time, his graduate student would have the tools necessary to grab their own limelight for their own lab or company. It is not difficult to find examples of graduates of some of the superstar "hardware" labs struggle to step outside the shadow cast by their alma mater. I do not think that Ghost Robotics (my current occupation, and a company I co-founded while in Kod*lab) could have come into being without this unique lab culture we emerged out of.

Turning my attention now to Dan himself, I believe there are five distinct ways in which he has had a large impact on me during and beyond the time we worked together. The first, no doubt, is his intellectual influence. In a similar manner to his cultivation of hardware fundamentals, he expects a strong foundation of mathematical principles in all his students. While this had some downsides (namely, in how much groundwork it took to get to the main topic in his course syllabi or papers), I found that it gave me an intuitive understanding of topics that are absolutely critical in this field. These include a deep understanding of the relation of linear algebra to geometry (and how one can reach to either set of tools to solve problems in the other), as well as of what effect nonlinearities have in a dynamical system and what tools are available to navigate them. I don't doubt that textbooks can help with either of these topics, but I do believe that the ease with which I can access these fundamentals when tackling a problem has had a large bearing on the success I have had bringing robotic systems to life in the real world. In particular, [3, 14] strike me as pertinent examples of the applicability of these fundamentals to empirical progress, but in truth I anticipate that they will continue to bear fruit long into the future. I mentioned above the seeming juxtaposition of Dan's lack of prowess in hands-on lab work with the capability of his students. In time, I have come to realize that it is not as much of an accident as it may seem at first–some of his earliest work [10, 11] demonstrate a preference for methods that (a) are robust to modeling errors, (b) work well with a limited understanding of the environment due to sensory limitations, and (c) are efficient due to their reliance on analytical rather than numerical methods. As it turns out, these very characteristics are extremely beneficial to deployment on robot platforms. It is truly a testament to Dan that 35 years later, in my capacity as CTO of Ghost Robotics, I talk about these very points as the levers we have been able to pull on to differentiate from our competition.

Second, after some initially difficult research endeavors in my first two years, Dan allowed me the invaluable freedom to explore and essentially choose what I wanted to work on. This extreme is somewhat unusual, but my understanding from watching the theses from the lab is that he is willing to be quite flexible in addressing the demands of various funding sources to the benefit of his students. I can only imagine that this is a delicate trade-off to strike in order to continually propitiate said funding agencies, and my exposure to other labs since has suggested that it is also not common. While the (relative) carte blanche can also be daunting as a graduate student (Aaron Johnson referred to it as "wandering in the desert"), I believe that this process is also an important avenue of growth. After somehow earning this right, I turned to the work of Raibert [13] (and the related past Kod*lab work [12]) for inspiration. In combination with growing time spent in the lab learning mechatronics, and working with labmate Gavin Kenneally, I had the opportunity to create the first new robot in the lab for many years, Jerboa [4], and Minitaur [9]. These robots, in turn, paved the way for the founding of Ghost Robotics and my current endeavors.

The third salient feature of working with Dan was his close mentorship. I was fortunate to have at least an hour, and sometimes up to two or three, of one-on-one time working through research problems with him for most of my Ph.D. My exposure outside Kod*lab has shown me that this is not something that can be taken for granted, and also how much effort it takes from the mentor. The benefits of this dedicated active mentoring go beyond the intellectual training, and include the careful behind-the-scenes management of the collaboration within the lab. Not once have I gotten the sense of students stepping on each others' toes, or indeed feelings of any potential conflict, despite the various cross-cutting projects that make the productivity of the whole lab greater than the sum of its parts.

Fourth, and the most unusual aspect I have mentioned yet, is Dan's extremely strong sense of idealism in the methods and research directions he will push his students towards. Most readers will have had the experience of him speak about the "15 minutes of fame" earned by entire sub-fields that seem hegemonic in the limited field-of-view of a doctoral student. Indeed, I have the distinct memory of a sense of frustration when going out to look for an external postdoctoral position, with a Ph.D. full of methods that were completely non-contemporary. In particular, my thesis [2] was more closely related to old ideas of hierarchical control structures [8] and composition [1, 13] than any robotics work of the 21st century. I would get the feeling that researchers in other labs thought I was obtuse to not use "standard" methods, and I assume the effect was quite similar when the same people were reviewing my papers. I utilized my postdoc to immerse myself in more contemporary methods (for instance, [6]), but as historical records will show, I doubled down in the latest paper I authored with Dan [7] to advocate for the usage of dynamical templates in control synthesis. These ideas remain pivotal in our development at Ghost Robotics, and I suspect that there is quite a bit of wisdom in persevering on methods that are *not* the fashion of the day. I believe that the added cognitive effort of keeping both the contemporary style and your own work in context simultaneously affords a broader and more nimble world-view than following the tide (and ending up stuck with its limitations).

Fifth, and last, I feel compelled to share a few anecdotes that exemplify Dan's character and its effect on me personally. I have mentioned a few times in this essay the company Ghost Robotics: as of this writing, the company has grown to over 35 employees and shows every promise of being successful. It has been the only job I have had, and it is no exaggeration to say that it has been my life's work so far. Dan was of course instrumental in facilitating the company's founding, and its early existence. The intellectual property relation and a (potentially large) Penn ownership in the company could have devolved into a quagmire that sunk the company, but even while keeping the lines impeccably clean and above board, Dan gave us all the boosts that we needed to stand on our own feet. The company had a rather meteoric phase of growth after 2018, and toward the latter half of 2021 there was a sequence of events that were quite difficult for our company, and the founders in particular. Despite certain actions by the company's then-CEO having a largely negative fallout on Dan, he extended his support to us personally in a way that was extraordinarily meaningful. One would assume from what I have said so far that Dan is an advisor and/or shareholder, but early on he divested himself of any stake in the company in order to avoid even any hint of impropriety as he supported us by buying our robots for his lab. This is unheard of in other similar university spin-offs, but is just another manifestation of the uniqueness of Dan's character among his peers. The company owes a lot to him, and in lieu of the equity stake that he forfeit, I will leave this testament for now, and hope to be able to pay it back in kind to Kod*lab in some way in the future.

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Remarks on my time with Daniel E. Koditschek

Jeffrey Duperret
Kod*lab PhD student, 2011–2019

I had the opportunity to do my doctorate under Dan, and two things stand out to me as things that made him uniquely impactful in his field: his insistence on formalism grounded in the requirement of empirical results, and the unique composition of his group.

Many research labs develop formal results, and many others attempt experiments "in the wild" with robots. Doing both well is a rare thing – especially when you build your own legged robots – and Dan's success at both is a testament to the efficacy of his ideas. During my time in Kodlab I was a part of testing our in-house RHex robots [3, 5] in places ranging from the Tengger desert in China to the dunes of the White Sands National Monument to winter trips in outdoor sponsor locations in rural Pennsylvania. We even imposed weekly "robot walks" for our new students and undergraduate lab members to get out of the lab and see the performance of the robot in the real world. In addition, I had the opportunity to build my own platform and associated software architecture: the spined Inu robot created from the lessons of the Canid project (these opportunities to "burn one's fingers" as Dan puts it prolong a Ph.D. but also when else in one's life does one have the opportunity to experience the "full stack" of robotic development without distraction).

All of this I believe kept us honest during our paper writing, and let Dan and his students avoid the common pitfall of becoming "armchair researchers" whose work might get highly cited but is nevertheless with those cold and timid results that will never see the light of day outside of the lab. I believe it was Louis Whitcomb who coined the phrase "simulation is doomed to succeed," something Dan would often repeat to his students. Rather, what let us succeed outside of Matlab and the mo-cap arena was Dan's philosophical adherence to formal guarantees grounded in dynamical systems theory that provided a sufficient degree of structural stability. This often came in encoding an anchoring to strongly attracting template dynamics [2] but more generally utilizing the system's natural dynamics to achieve some asymptotic behavior [4]. Such results are fundamentally hard to come by due to both the generic lack of closed-form flows of such systems and the hybrid nature of legged dynamics, and motivate a compositional approach to deal with the associated complexity. To his credit, as dense as some of our papers on this matter were (in addition to the ever-present "Danglish") they were accompanied at Dan's insistence with strong experimental results. This marriage of the formal and the empirical greatly benefited our Ph.D. work and has served me well in my current role as the lead of the controls team for a legged robotics company where we have developed a reputation for successful operation in harsh conditions. Dan's compositional project is not yet complete, and it is incumbent on us as his students to further the work. Towards the end of my Ph.D. I became quite fascinated by the idea of using the hybrid transitions inherent to legged locomotion as an affordance in itself for compositional-style control [1]. Being lucky enough to have access to the state-of-the-art in robotic hardware, I am at a position where the rubber meets the road to put these ideas into practice. Stay tuned!

Finally it is worth noting that the Kodlab group that Dan assembled during my time in it from 2011 to 2019 was truly remarkable. Instrumental to its success was a core of high-quality post-docs and senior graduate students who maintained the culture and helped in mentoring and the transfer of knowledge. Aaron Johnson, Deniz Illhan, Shai Revzen, and Paul Reverdy were some of my seniors that I particularly benefited from interacting with. Dan's policy of keeping students around for an extended tenure – much to the department's chagrin – certainly helped maintain our core group and keep people together long enough to foster a robust intellectual and social community, and in retrospect I found a longer Ph.D. was invaluable to achieve a deeper level of intellectual maturity. Dan's group wasn't just limited to his current students; he brought together biologists (Robert Full, Lucia Jacobs, Andrew Spence, Noah Cowan), mathematicians (Yuliy Baryshnikov), and philosophers (Lisa Miracchi), among others, that I was fortunate enough to interact with and learn from. But one of the things I benefited most from was that for the entirety of my Ph.D. Dan had a resident post-doc mathematician on hand – most unusual for a robotics lab doing hardware – in the form of Dan Guralnik and Matthew Kvalheim, both of whom were extremely passionate about their field and always willing to spend hours at a time in discussion. The sheer intellectual collective force and diversity of the Kodlab circle was more than any student could ask for to be a part of. Dan's group was much more than the sum of its parts and the community he helped build will continue to blossom throughout his student's careers.

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Energetic costs of running on sand and energetic gains from a supportive lab

SONIA ROBERTS, NORTHEASTERN UNIVERSITY
KOD*LAB PHD STUDENT, 2012-2021

Energetic costs of running on sand

For my dissertation with Dan, I modeled the energetic cost of transport for a direct-drive legged robot running on sand. I began with a Raibert-style compression-extension controller. This controller commands the leg to behave like a soft virtual spring during the first half of stance, as the body falls towards the foot. When the robot leg is fully compressed and begins to extend again, the controller injects energy into the virtual leg spring – in my case, by drastically increasing the leg's spring stiffness. On solid ground, this pushes the robot body up quickly, causing the robot to jump. However, on sand, this also causes the foot to push quickly down into the sand. This is a problem for two reasons: First, sand dissipates energy at a rate that is cubic in proportion to the foot's intrusion velocity, meaning that the quick intrusion into the ground dumps a lot of energy into it; and second, the robot has to jump at least to the height of the ground surface before it is even possible for it to take a step. I found a reactive way to reduce that energy cost – adding damping to the leg's virtual spring as it pushes off of the ground reduces the foot's intrusion speed and therefore the energy transferred from the foot to the ground [3, 4, 6].

This project represents a congruence of several ideas that were kicking around in the lab at the time. Granular media is "simple" enough that it can be modeled analytically in an idealized setting, making it possible to conduct simulation experiments, but complex enough that sand with heterogeneous compaction, grain size, and so on still eludes on-board modeling efforts. Because of this unpredictability, any controller meant to handle a variety of natural desert environments should not require a complex and highly accurate model. A reactive controller, which we can mathematically interrogate to reveal the conditions under which it should be expected to succeed, is ideal. Students of Dan's will find this a familiar argument.

The intended application of these robots running around on sand was to assist geological field scientists studying erosion and dune migration in deserts [2]. Another side of the project was led by Drs. Feifei Qian and Cristina Wilson, who were then postdoctoral researchers. The goal was to study the geologists and model how they make research decisions [8]. Here, the goal was to improve the spatial and temporal resolution of the data sets available to geoscientists by automating data collection, but also to learn expert data collection practices from seasoned field scientists and to provide feedback and support for scientists in the field to improve their decision making.

The last piece of the puzzle comes from a combination of my own interest and background in cognitive science, and Dan's frequent conversations with Dr. Lisa Miracchi Titus, who was then a junior professor in philosophy at Penn. The three of us collaborated to describe a method for designing robot behaviors as exploitations of affordances, which are opportunities for purposeful action for an agent in an environment [7]. We argued that robots do not need to model affordances in order to be programmed to use them effectively. Rather, the key is to build controllers that drive the robot-environment system to a desired state using information that is directly perceived from the environment – that is, controllers that are as close to reactive as possible. Using the language from cognitive science and philosophy to describe this process reveals the intelligence displayed by a machine achieving these goals, although "machine intelligence" is unfortunately rarely used to describe these kinds of control methods.

I am now in a postdoc position at Northeastern University working with Dr. Kris Dorsey on soft sensing. I am currently working primarily with origami sensors and 3D-printed textiles [1, 5], but also developing knitted sensors that I plan to integrate into seamless knitted robots. Knitting is a 3D manufacturing process that can be performed both autonomously by a knitting machine and by hand with a pair of sticks. Knitted robots that could sense and move through their environments could be sent to disaster sites and other planets, used to teach robotics to students even in schools with very few resources, and used as wearable health tech. As soft, deformable robots in an unpredictable world, they will also benefit greatly from reactive control.

Energetic gains from a supportive lab

I don't know how many times I said "I want to strategize my life" as I sat down across from Dan for our weekly meetings when I was a PhD student, but I am sure it was a lot. We started having those kinds of meetings when I was a first-year PhD student, and the content would range from what classes I should take to best prepare me for my qualifiers; what classes or research tasks I should *prioritize* when the semester inevitably made it impossible for me to finish everything; what resources I would need from Dan, or would need Dan to request from other people on my behalf; and so on. Dan always made sure that I had the tools I needed to succeed in the program and perform my research. Perhaps the single most extreme example was when I asked him to come on the first desert field trip I organized, which was to be over a week in China. He booked flights with almost no follow-up questions. I later learned that he had been forgoing attending conferences because he was too busy to travel.

This attitude extended to the rest of the lab as well. Kod*Lab has always been generous about sharing equipment, tools, and expertise. When I needed to learn more about dynamical systems theory, Dr. Dan Guralnik, then a postdoc with the group, tutored me. When I mentioned that I was shopping for a string potentiometer, Dr. Gavin Kenneally, then a PhD student in the group, handed me one. We have shared controller boards, motors, cables, expertise, and ideas. I could go on. A lab with a strong culture of generosity and mutual support is incredibly important, and it is much easier to establish if each student is well supported by their advisor.

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Dan Assisted Dynamic Self Righting

A. Brill, General Motors
Kod*lab Undergrad, 2013–2015, Master's student 2016-2018

I joined Kod*lab at the end of my freshman year at the University of Pennsylvania. I started with "menial" tasks like taking the robots out on hikes and fabricating the composite C-legs and RHex shells. Even as a young undergraduate Dan made time to talk with me not just about what I could do in the lab, but about what I was thinking in regards to my future. The older students in the lab were welcoming and always open to discussing what they were working on. The environment of the basement lab space at the time, although dingy and overcrowded, contributed to this camaraderie. Helping graduate students run experiments or fix the variety of robots let me see firsthand what pushing the boundaries of human knowledge was really like. Conversations with Dan were engaging and usually left me with more questions than I arrived with. He encouraged me to think beyond the things that felt most pressing at the time, like homework deadlines and midterms, and consider my future. Dan also always looked for ways for me to incorporate my creativity and was immensely supportive of my art projects with the robots, such as the video "Rainy Day" [1].

As my confidence and skills grew, I was able to collaborate closely with Avik De on the Jerboa robot. I ran experiments with him and we worked together to build and debug the second version of the robot. While running experiments for Avik's hopping controller, we tried some non-steady-state behaviors culminating in some cool new leaps. The robot bounded up ledges and across gaps in an impressive fashion, and we worked together with Dan towards a conference paper showcasing both the theoretical and conceptual implications of these dynamic behaviors. The support of Avik and Dan helped me push through even when I had to repeat experiments multiple times. I worked closely with them and Aaron Johnson to help write parts of a conference paper, and I had the opportunity to present it at IROS 2015 [3], Fig. 13. Although it was nerve-wracking to present, the compelling story was exciting to share. I am proud of the hard work I put in to synthesize what I had learned and translate that into a presentation, and it would not have happened without Dan.

Currently I am part of a brand new engineering team at General Motors. We are finding our footing as engineers in a design-focused space, but I see our potential. My experiences in Kod*lab and with Dan have given me the tools to make a positive impact here, and to facilitate a culture modeled after Kod*lab. During the interview process for this position my current manager found and watched the video interview produced by Diedra Krieger following my experience as a Robot Technician for the Robot Revolution museum exhibit [2], Fig. 13, and he later mentioned to me that this was one of the main reasons he hired me. This video showcased my time as a Robot Technician for the Museum of Science and Industry (MSI), and my return to Penn to finish my undergraduate and Master's degrees.

My decision to take a gap year to work for the traveling museum exhibit was the result of one of Dan's outreach collaborations. He had worked to include RHex and the lab as part of MSI's "Robot Block Party" in the past, and when the museum was developing a new exhibit, he collaborated on the portion featuring RHex and included me in the process. When I had the opportunity to work as a Robot Technician for the exhibit, Dan was the one I talked to about how to go about making the decision to take a gap year and pursue this opportunity. He asked insightful questions which made me deeply consider the impact of taking time off from my studies, and was incredibly supportive when I reached the decision to take the position. Even though I was far away from Kod*lab during my time working for MSI, I knew I still had the support of Dan.

Figure 13: (Left) Anna Brill presenting at IROS 2015. (Right) RHex in the museum exhibit.

Figure 14: (Left) Last Kod*lab meeting, featuring RHex cake. (Right) Mitch Fogelson and Jeff Duperret with RHex on a hike.

One of the things I have learned over and over from Dan, and especially during my gap year, was how important it is to take a step back and evaluate. Taking this opportunity to reflect on my time in Kod*lab, I know that without Dan's guidance and support I would not be where I am today.

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Motivation Dynamics

Paul Reverdy, University of Arizona
Kod*lab Postdoc 2014–2017

The first time I met Dan, I launched straight into explaining my PhD research. We talked for a few minutes until, at some pause in the conversation, he mentioned that this was not how he had anticipated the conversation going. Somewhat concerned, I asked him how he had anticipated the conversation going and he responded with a classic Dan-ism: "I expected to convince you that you should become a professor, and that in order to do that you should come do a postdoc with me." I ended up doing both of those things, and it's been an interesting ride ever since.

I went to grad school expecting to work on geometric control, only to find that I had more or less missed the boat on that particular field; I ended up writing a thesis on statistical decision theory with applications to foraging and human-machine systems. When I joined Kod*lab I saw the opportunity to connect the tools I had developed for high-level decision making with the kinds of tools the group was working on, e.g., for motion planning.

As for a topic, Dan suggested seeing "how far we could push dynamical systems," i.e., seeing how much symbolic decision-making logic we could encode into a vector field. I connected this idea up with some others I had seen back at Princeton [1] quite quickly and saw that I had a way to encode a limit cycle that corresponded to a two-point recurrent patrol behavior[1]. Getting the theoretical analysis to Dan's desired level of rigor took quite a bit longer, but resulted in a nice paper in SIADS [6], as well as a follow-on empirical paper [3] that showed how we could use this new "motivation dynamics" to integrate elements of statistical decision theory (so the robot would conditionally branch its behavior based on noisy external stimuli) as well as to sequentially compose given low-level navigation tasks.

Motivation dynamics was the core of the work that I did in my early days as an assistant professor [2, 4, 5, 7], and kept a couple of my students intellectually "fed" through their graduate degrees. The papers are starting to get some following in the wider community as well. I am now working on navigation problems in industry (that is a whole topic for another day), and the training I received in Kod*lab proves valuable every day.

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[1] The mechanism is neat: encode the decision about which task to perform should be encoded in a scalar variable, and endow that variable with dynamics embedding the unfolding of a pitchfork bifurcation; using feedback from the agent's location on the unfolding parameters, I constructed a system that would switch tasks once its current task was completed

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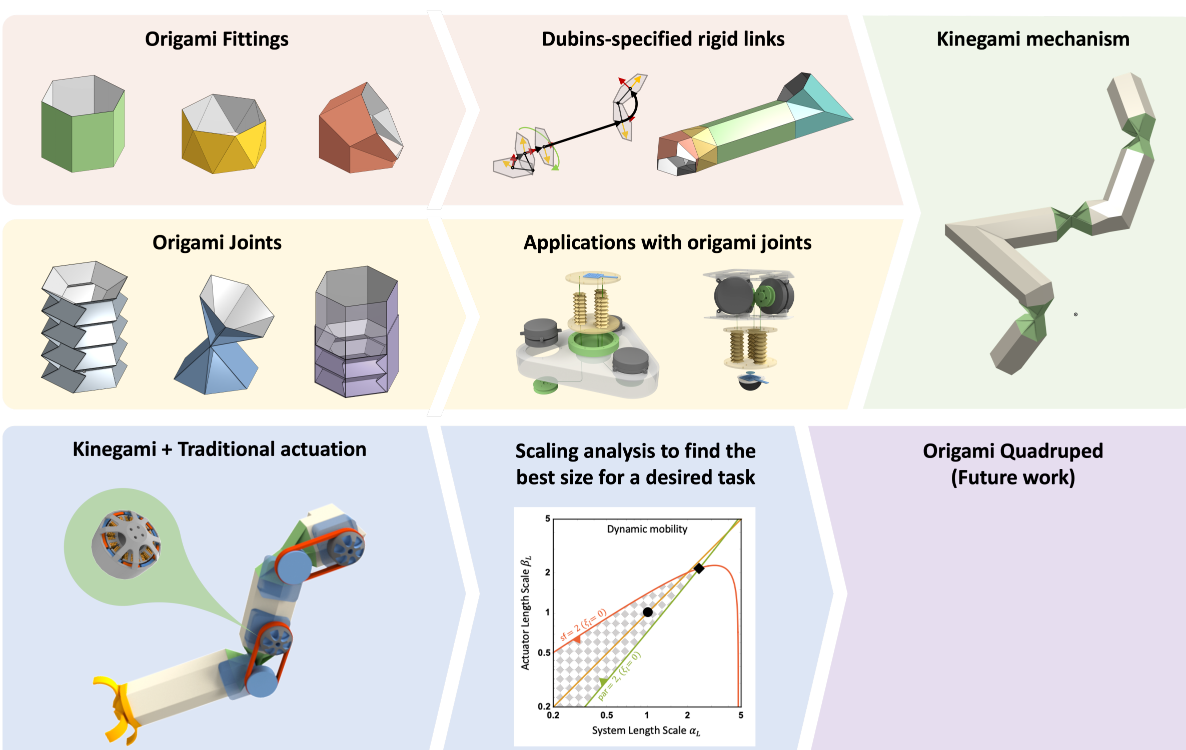
Kodlaboration

Wei-Hsi Chen, University of Pennsylvania
Kod*lab Ph.D. student, 2015–2022

It was high noon, and I was having lunch with Dan trying to figure out what my research thesis would be after a year "wandering in the desert." Dan expressed his academic philosophy that he wanted his students to do what they are told not to because he is always looking for collaborators that could teach him something he does not know, proving him wrong. I was fortunate enough to find a research topic that interested me in the SLICE project soon after that crucial lunch, but Dan's philosophy became the foundation of my research strategy, now denoted as the "Kodlaboration."

It was an epiphany for me to realize that I do not need to know everything to do research; research is all about all the resources you can get to understand something you do not know. Fortunately, Dan is a resourceful man, and he loves sharing his resources with his students. During the SLICE project, I collaborated with interdisciplinary researchers, including material scientists, mechanical engineers, and biologists. Dan's way of asking hard questions pushes me to develop an in-depth understanding of our joint projects. The result was a new method of utilizing a compliant origami mechanism as a power cascading device [3] to achieve dynamical behavior, including juggling [2] and hopping [1]. If I were to take away one thing in my Ph.D. life, it is the Kodlaboration philosophy!



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To My Favorite Science Fiction Writer

Abriana Stewart-Height, University of Pennsylvania
Kod*lab PhD student, 2018–present

When I first joined Kod*lab, I was so nervous. Even though I had visited the group twice prior to committing to the university, I was still very anxious. I was worried that I would not fit into the lab culture or live up to the high expectations that I assumed Dan had of me. It's no secret that past and present associates of the lab have gone on to accomplish great things in the field of robotics and beyond. I was fearful that I would not be good enough to add to that legacy. However, Dan never made me feel that I was not good enough or that I did not belong. Back then, I had no clue what he was thinking I'd accomplish while working under him but I'm thankful that he had so much confidence in my abilities. Although, I don't think either of us had expected me to be working on the set of a science fiction movie (*Lapsis*), where RHex was one of the main characters! It's crazy how life works. In May of 2018, I was worried that I was not prepared enough to do robotics research and in less than a year later, I was second author on a journal paper that was published by IEEE Robotics and Automation Letters and accepted to the International Conference of Robotics and Automation [1].

I appreciate Dan for allowing his students to bring to him research project ideas that we are truly excited about, even if they are sometimes a bit bizarre or out of his realm of expertise. When I first proposed wanting my research project to incorporate rehabilitation and legged robots, neither Dan nor I was really sure what that would look like. Four years later, I have been awarded two fellowships (National Science Foundation Graduate Research and Institute of International Education Graduate International Research Experiences) and published a journal paper [2] for the work that has come from this "bizarre" idea. Being a part of Kod*lab has been nothing short of an adventure, and I am eternally grateful for Dan giving me this opportunity to do amazing work with some wonderfully intelligent people. I look forward to becoming a Kod*Lab alum in the near future. I am confident that being a part of this group and working under such a great advisor/mentor has given me the skills I need to be an influential scholar in the robotics community and beyond.

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Figure 15: Kod*Lab on the set of *Lapsis*

Professor Daniel E. Koditschek's influence on me

Matthew D. Kvalheim, University of Pennsylvania
Kod*lab Postdoc 2019–2022

I joined Kod*Lab in August 2019. Almost immediately, I began working with Dr. Paul Gustafson and Professor Daniel E. Koditschek on a now-published [12] generalization of Conley's "fundamental theorem of dynamical systems" [4, 15] to a class of "hybrid" dynamical systems relevant for modeling things such as robots. I learned much from both Gustafson and Koditschek during this time. Later, I found that Koditschek and I shared an interest in Professor Roger W. Brockett's necessary condition for asymptotic stabilization of control systems [2]. Prompted in part by this and by stimulating conversations with members of Kod*Lab, in particular Mr. J. Diego Caporale, I started wondering whether Brockett's necessary condition could be extended to handle stabilization of subsets more general than a single point. I found that it could, and Koditschek made the valuable observation that similar reasoning yields necessary conditions for the somewhat-dual situation of control systems operating "safely". This led to our paper [13] under review.

Questions arising from my work with Koditschek on [13] led to my current project [9]. I am grateful for the intellectual independence and leeway Koditschek has granted me during this time, and in fact also while working on several other projects: [1, 3, 5, 7, 8, 11, 16] were all initiated and completed during my time in Kod*Lab, and some significant fraction of my work on [10, 14, 17] was also performed during this time.

In addition to intellectual independence, I am particularly grateful for the respect with which Koditschek has always treated me, and for his numerous generous gifts of time, advice, ideas (including those explicated in [6]), insights, vision, wisdom, and more. I treasure these gifts and believe they will prove useful for many years to come.

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Updates on the Penn Jerboa

Shane Rozen-Levy, University of Pennsylvania
Kod*lab PhD student, 2019–present

As a current PhD student in kod*lab I'm working on studying how to design control strategies for the Penn Jerboa which allow all of the actuators to contribute to energizing the system. Many modern walking robots feature high degree of freedom limbs allowing easy control of ground reaction forces. Unfortunately the high degree of freedom limbs means that during most behaviors the robots will not be using their full power density. I suspect that due to Jerboa's low number of actuators we will be able to develop gaits that leverage its full power density in the output space.

Additionally I'm working on creating the Kod*Lab Mjbots SDK [1]. This SDK is a spiritual successor to koduino in that it is an open source set of code designed for the creating of legged robots. In this case the SDK works with motor controllers developed by Mjbots to control BLDC motors at 1 kHz. My hope is that the SDK will become widely used, but only time will tell.

The culture of the lab is still one based on collaboration, though each PhD student has their own project. As opportunities arise various students will collaborate. Recently the lab has been shrinking as many PhD students that have been here for 7+ years have graduated resulting in the lab forming a tighter community where everyone is familiar with everyone else's projects. COVID has damaged the output of our lab, but as we turn the corner we have a number of exciting projects and robots that will hopefully be finally shared with the world at ICRA 2023.

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My Night-light

Cristina G. Wilson, University of Pennsylvania
Kod*lab Postdoc 2020–present

I started working with Dan in 2018, initially as a postdoc in cognitive psychology at Temple University, on problems of human-robot teaming for field science data collection [2]. I moved to Penn and joined Kod*lab in 2020 to continue this line of work and build-out my research program that emphasizes the human mind in human-robot teaming. This summer I am starting a research faculty track position in robotics at Oregon State University, but I will continue collaborating with Dan on new work (funded by NASA) to improve collaboration between human scientists and autonomous legged robots for scientific exploration of soil dynamics on Earth and other planets.

I am honored to be one of the many eclectic scholars that comprise Dan's past, present, and (likely) future postdocs. What do a cognitive scientist (me), paleontologist (Aja Carter), and mathematician (Matt Kvalheim) have in common? We all currently enjoy a position as postdoc in Kod*lab under Dan's mentorship.

I know from conversations with my fellow postdocs that the type of mentorship we receive from Dan, how we spend our time with him, varies widely – perhaps not too surprising given our very different intellectual traditions and research interests. For me, Dan has been a figurative "Night-light" [1], illuminating the dark and unknown places within academia. He has helped reveal the unspoken rules and expectations of the ivory tower, served as translator in situations clouded by double meaning, and used his privilege and social/cultural capital to provide me with opportunities that would not otherwise have been possible without his explicit support. One memorable example of the latter is when Dan helped me to secure an exception to a Penn policy that only allows postdocs to serve as PI on a grant if a Penn faculty member is co-PI; without his intervention on this issue it would not have been possible to pursue the independent collaborations that I have worked hard to build in my time as a postdoc.

In his role as Night-light, Dan is often in the unfortunate position of telling me something that I do not want to hear – usually something about the status-quo in academia that conflicts with my intuitions or ideals – unfortunate because I do not have the most gracious reaction to the discovery of such conflicts. However, one of the things I appreciate most about Dan is that he never forces a particular resolution of conflict. Instead he encourages me to make my own judgment while ensuring I have all the relevant information to do so. Dan and I do not always agree, but he has always acknowledged and respected my reasoning, and I will always appreciate his guidance and support.

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Daniel Koditschek's Paleontological Reach: three-hundred million years in the making

Aja Mia Carter, University of Pennsylvania
Kod*lab Postdoc 2020–Present

I met Dan before I knew who Dan was. Before giving an invited lab talk, I sat at a desk that once belonged to the ever-illustrious Feifei Qian and explained the function of vertebral elements using fossils and 3D prints of ancient vertebrae. I suggested that some forms were evolutionarily selected because they were better suited for specific functions than others. Dan (whom I did not know was Dan at the moment) suggested the counter-hypothesis that forms evolve randomly (which is sometimes true!). Later in the GRASP conference room, when I began my formal talk, I figured out this roaming professor with interests in other models of evolution was Dan. A year later, I was awarded the Vice Provost Fellowship in Academic Diversity and joined the lab as a Postdoctoral fellow. In my time thus far, I have come to enjoy Dan's broad and inviting way of thinking. As a paleontologist, my formal training, and academic responsibility, includes the geologic history of the Earth spanning five billion years and the evolution of life for the last four billion years. I tend to believe that I am a broad thinker, but in the two years I have spent conducting postdoctoral work with Dan, my definition of broad thinking has only grown. There are currently many projects pushing the boundaries of what I thought were capable of robots in the lab, from origami robots, robots with spines, to robots with damaged limbs. By watching students imbue robots with what can be, I have been challenged to think more deeply about what could have been in extinct animals. While I have always thought of my vertebrae and, in turn, the animals themselves colloquially as dynamic (i.e., exciting) animals, I have only recently begun questioning our amphibious ancestors' dynamic capabilities.

This growth is partly due to Dan's willingness and patience when introducing tools. I have always felt invited to join intellectually in a room of mathematical giants (the Matthew Kvalheims of the world). Dan once told me that the tools I was learning (like Linear Algebra) were made for people like me, asking the questions I was asking. In addition to several meetings walking through basic concepts, that statement helped me get over my math phobia. Furthermore, through that ever-going journey, I am open to new spaces and ways of thinking, and the richness of five billion years is made only richer.

Part V

Collaborators and Other Influencers

If you bang your head against the
wall hard enough, the wall will
always break—but not always
where you're banging your head.

Professor Daniel E. Koditschek

FGHK: The Mathematician's Perspective

John Guckenheimer, Cornell University
KOD Tutor 1990, DARPA and FIBR Collaborator

Happy Birthday Dan! This is a wonderful opportunity for me to reflect on our long collaboration with Bob Full and Phil Holmes that began 44 years ago at the Institute for Mathematics and its Applications in Minneapolis. That workshop (my initial exposure to biomechanics) and the collaboration which grew from it had an enduring effect on my career.

I grew up immersed in the culture of mathematics with its emphasis upon rigor and proof, but yearning to connect its austere realm to the real world. In graduate school, my decision to study dynamical systems theory was based partly on its promise to have broad impact across the sciences. That promise was more than fulfilled, as "chaos theory" discovered common phenomena and principles across a staggering array of subjects. Indeed, we first met when you approached me to explain the theory of bifurcations in families of one dimensional maps so you could apply it to your work with Martin Buehler on juggling robots. A decade earlier, the same theory drew public attention with its characterization of the period doubling route to chaos in fluids – with no analysis of fluid equations. Dynamical systems theory became a poster child for Wigner's famous aphorism about "the unreasonable effectiveness of mathematics."

Stimulated by Thom's catastrophe theory, I was intrigued by whether the phenomena of dynamical systems theory were deeply embedded in biological organisms. Catastrophe theory and dynamical systems theory both emphasize the principle that observed phenomena should be *generic* within an appropriate universe of systems; i.e., robust to perturbation within that universe. They then proceed to characterize and classify generic phenomena in different universes. As an example, this strategy gave rise to systematic study of bifurcations in dynamical systems with different symmetry groups.

I came to regard locomotion as one of the grand challenges of science through our FGHK collaboration. The *anchors and templates hypothesis* that was a starting point for FGHK resonates with the mathematical perspectives I described above. Organisms are so complex that detailed, first principles models seem out of the question. The anchors and templates hypothesis that animals have *evolved* to behave like simple low dimensional dynamical systems proposes a resolution to this conundrum: we can hope to discover the templates through observation, experiment and analysis of models. Locomotion has a rich repertoire of behaviors we observe with motion capture and probe with stimuli and perturbations. Our FGHK collaboration was an exciting attempt to understand neural control of locomotion from the outside in. Inevitably, we failed. Still, we can look back at what we learned and keep trying. Here are a few of the lessons I (think I) learned:

- 3D SLIP, the pogo stick that was our template, requires augmentation to achieve adequate lateral stability as a model of bipedal running.
- Natural selection preserves behaviors that continue working in the face of evolution. Dynamical systems theory provides a framework for viewing organisms as a composition of irreducible processes.
- Classical paradigms of control theory and optimal control theory are hardly optimal for animal locomotion, in part because feedbacks are bidirectional. Multiple time scales and discrete event switches give an alternative way of decomposing the complex dynamics of organisms.

- Stochasticity is important in enabling organisms to tune their controllers. The probability distributions of these processes is an important factor in how readily organisms can estimate their state and feedback gains.
- Collaboration seldom induces a major change in the primary focus of senior investigators, but it provides a great opportunity for junior investigators to take a lead role in innovative research that bridges the interests of their mentors.
- DARPA cares more about robots than cockroaches.
- Real data is almost always messy. I'm still waiting for detailed, verified mechanical models of robots.
- Modifying commercial software to extend its capabilities is likely to be an exercise in frustration. We usually underestimate the effort required to produce high quality software despite enormous advances in programming languages, tools and libraries.
- Similar comments apply to machines and devices. Dan, I never got my promised RHEX.

On that note, let me end by returning the robot I never got as a virtual birthday present. I'm happily retired and will only need a robot as a caretaker to look after me when my health declines.

Mechanical Systems with Impacts

Anthony M. Bloch, University of Michigan

Work Inspired by Dan

I have had numerous inspiring conversations and interactions with Dan at Michigan and beyond and I have always enjoyed my interactions. Much of his thinking has permeated parts of my work on control and robotics. Two items in particular stand out: pogo sticks as simple models of robotic walking with an integrable aspect to the flight dynamics, and potentials (or navigation functions) for steering. The former has inspired work with my students Hamed Razavi and William Clark and with Jessy Grizzle on legged locomotion. The second has inspired work with with Islam Hussein, Peter Crouch, and Leo Colombo and others on controls with obstacle avoidance on Riemannian manifolds (see e.g. [1]).

Much of my work that relates to robotics has involved smooth nonholonomic systems such as the Chaplygin sleigh (see [2]). Nonholonomic systems are systems with nonintegrable velocity constraints and naturally apply to the motion of wheeled vehicles for example. They can exhibit fascinating behavior such as energy conservation but asymptotic stability. The sleigh (rather like a supermarket cart) illustrates this nicely.

Dan of course is famous for his work on legged locomotion. One can extend the idea of a system interacting smoothly with its environment to a nonsmooth interaction – impacts due to locomotion say. With Hamed Razavi and Jessy Grizzle we looked at symmetric gaits for two-legged systems, see [4] – here the original inspiration goes back to Dan's pogo stick among other places – which also have a nice discrete symmetry for locomotion. In this setting we were able to produce stable gaits.

In work with Will Clark we consider a wheel impacting a closed surface. This models the classic mathematics of billiard dynamics but in this case with a wheel impacting the surface and producing beautiful symmetric dynamics. Here it is illustrated in the case of a circle, see [3]. This is a nice illustration of the beauty and utility of mechanical systems with impacts.

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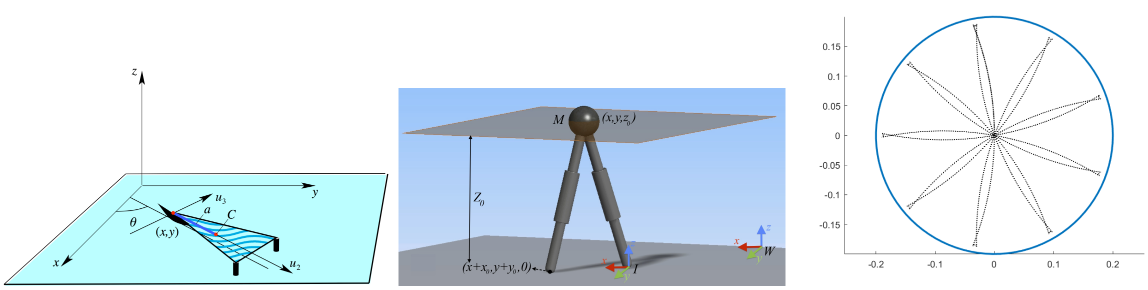

Figure 16: (left) Chapylgin Sleigh. (middle) Symmetric gait. (right) Penny impacting a circle

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To Dan: a great mentor, collaborator, cultivator, and synthesizer Also there was gait math

Andrew Spence, Temple University
Kod*lab Postdoc/Collaborator via Full lab 2004–2009, Collaborator 2009–2017

The Full Lab, FIBR grant days

"Synthesis is the final arbiter of understanding" we would shout as we ran down the hallways of the Valley Life Sciences building at Berkeley in 2004–2006, inspired by the FIBR grant that was melding Kod*lab and Full Labs. That was when I first met Dan as a postdoc in Bob Full's lab. My mind was being blown by Noah's application of control theory to organismal biology, Dan Goldman's templates, Shai Revzen's general good-ness at everything, and we were all very excited. Of course, I think we do understand some things that we can't make, but you need to get attention first, then you can argue.

The power of mathematical insight, modeling and simulation, and robotics when applied to biological locomotion were in their early days (for me at least!), and working with Simon Sponberg was a real treat. For my own work, we were heavy into using the SLIP model to understand how animals control their locomotion on different surfaces, and so we ran cockroaches over condoms and dental dams, as you do, to see how you manage to make three legs act like one spring on elastic surfaces [4]. Although Dan wasn't on this paper, the SLIP modeling work with Justin Seipel was certainly influenced by his contributions in that area with Phil Holmes.

At this point what was exciting about the culture was the strength of integration between biology, math, control theory, robotics, and neuroscience, and how it really did strengthen each endeavour. You had a much larger toolbox to work with, more varied approaches to problems, and then testing things across animals and robots could be pretty convincing for demonstrating a principle.

The London Days

At this point my fledgling group at the Structure and Motion Lab at the Royal Veterinary started more earnest collaboration with Dan and Kod*lab, around 2009, when Dan, Kod*lab, and amazingly dedicated folks within including Justin Starr, Clark Haynes, Aaron Johnson, Jeff Dupperet, and Matt Hale (amongst others) provided us with an X-RHex Lite robot. Clark and Justin Starr came to London for fun visits, and we still have data to be analyzed and published beyond what we have, that's in [3, 10].

I can't emphasize enough how these folks at Kod*lab went over and above to help us with our robots. The selfless nature was incredible and set an example that we try to emulate. I remember at one point being nervous about doing work too close to Dan's and saying, "is this ok?" and he replied, "don't worry, there's plenty of room in the ocean!"

Stepping onto the scene at this point was Simon Wilshin. Simon's theoretical chops and modeling abilities really worked well with Dan, Clark, Shai Revzen, and more, and he really pushed some of the dynamical systems approaches to gait far along, and applied them to animal data in new and interesting ways. Simon's theoretical advances are still paying dividends across so many systems, from spiders to tardigrades, inspired by this fruitful time of collaboration.

We gathered a couple rich data sets from dogs making gait transitions and on rough terrain, and mined these data sets for some time (and continue to do so!) [6–8]

Temple – Mice, Earthquakes, Spiders

At Temple we began a great collaboration with Tonia Hsieh, and Simon's methods for gait along with a quick hint that I think came from Clark Haynes, saying "hey, people often forget about the temporal domain, why don't you see if they move more quickly over certain less stable leg configurations?" leading to a nice JEB paper [9]

We also utilized Dynamism and a "two legged X-RHex" to make an extremely quick earthquake treadmill for mice [5].

Future generations – collaboration with Qian Lab, Dog particle physics

Going forward we now have an exciting new collaboration with former Kod*lab postdoc Feifei Qian, taking predictions from her robot disturbance selection framework back to animals, to see what they do. We meant to test these predictions in rats, but then with COVID we ended up, to our benefit, using dogs, with remarkable efforts from students Michelle Joyce, Haodi Hu, and input from Matt Kvalheim. This exciting new collaboration is off to a great start and has a ton of directions to go in [1, 2]. Soon we will know if dogs, like photons and robots, build up interesting interference patterns where fired over lattice like obstacles, and can relay this information back to Dan Goldman.

Closing

In closing, I think it's fair to say that Dan is unique in his ability to create such an exciting, welcoming, diverse intellectual and collaborative environment, while also doing ridiculously high quality work.

I remember a colleague once saying, "advanced mathematics is like a four-wheeled drive vehicle – it just allows you to get stuck in more remote places."

I think one of the great strengths of the Kod*lab community is the ability to avoid the above – to really apply and get concrete progress out of what can seem like fairly esoteric math. Not always, and it's fun anyways, but it has been amazing to see how the right bits of theory can translate into a lot of great robotics and biology. Cheers to Dan for inspiring this!

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The Art of Dan's Koan

Yuliy Baryshnikov
Listener to Dan since around 2007

When I met Dan, at a workshop in Zurich in 2006, I think he more or less thought that I am an aggressive ignoramus in all things around robotics. And he was, of course, right: I was just entering the area, and a lot of things I was thinking about were, one way or another, known in the trade. But Dan still started to talk to me. I think now this was about the language: my metaphors (and anyone doing anything real never mentally manipulates definitions and rules of assembly and suchlike, but with images, and glimpses and flashes) were different, and Dan, as we all know, loves a good metaphor...

So, he started to talk to me, about what is called today barrier functions, and one thing led to another, and by now we went through a series of experiences that all go through the cycle of

- what he is talking about?
- isn't this trivial?
- wait, no, there *is* some trouble here,
- huh, this is actually quite interesting,
- ...perhaps even a definition, theorem or something...

In this way I got to think about beasts I would never dream of in my worst nightmares: topological perplexity, governing Buridan's donkey misery, or how directed percolation accounts for power-intelligence trade-offs, or what flags of subbundles have to do with the knee-jerk motion, or what role homotopy limits of diagrams of spaces have in understanding of the topology of the phase spaces...

We have this saying in Russia, *to each wise man, a simpleton is enough.* I never bought into this nomenclature: asking right question is always way more difficult than produce some answer. Alternatively, the Socratic tradition presumes that whoever asks knows the right direction and steers the students towards the truth. I think what Dan did was something else: like a Zen scholar, he was posing questions pushing the interlocutor *and* himself towards the (intellectual) danger, towards those proverbial dragons that guard the answers. The questions he asked were like koans, impossible to answer correctly, but lifting you to the next level of understanding the ever deepening meaning of this or that construct.

For that, - thank you, Dan.

From autonomous crabs to leaping squirrels. . . thank you!

Lucia F. Jacobs, University of California, Berkeley
Kod*lab Collaborator, 2010–2022

I am thrilled to add my most sincere congratulations on this celebratory occasion to my favorite fearless leader! On this august day, let me express first my thanks and gratitude to you. You have led me on winding paths through fields I never thought I would encounter, generously including me in over a decade of inspired, intellectual adventure. Beginning with ghost crabs and the origins of autonomy, now in the midst of the fearless leaps and bounds of gap-crossing robotic rodents, your brilliance, generosity and enthusiasm have led me (and all of us!) to unsuspected treasure islands and troves.

My journey I know has been shaped in ways that I could never have imagined – way back in 2010! – when we first met through Bob. How could I have known that our discussions on the origins of autonomy would have led me to olfaction, a path I still tread. Or that after decades of studying squirrels, that our second team – the Dream Team! – would have opened up so many new vistas and challenges, to understand squirrels from completely new perspectives, from the neuroscience to the biomechanics to their ontogeny.

With so many changes in the air, here's to many more conversations to come! And in the meantime, my most hearty and sincere congratulations on your brilliant path traveled (and the many lives influenced) thus far!

All my warmest congratulations to you on this occasion of your Fest!

Walking in the footsteps of geologists: From White sands to the Wissahickon

Thomas F. Shipley, Temple University
Kod*lab collaborator 2015–present

*Reflections on being on one of Dan's teams

The following is excerpted from a chapter entitled, "Walking in the footsteps of geologists: From White sands to the Wissahickon," that recounts some of the insights about how geology and psychology have merged to do better science. Dan is responsible for one of the merged streams - one that brought Cristina, a psychologist who wanted to do something with psychology, to work with a skilled roboticist with a background in the biological sciences, Feifei, and a geologist who thinks like a physicist, Doug.

Working with robots and confronting the challenge of what might be going on in the mind of a field geologist hiking through their field area on a quest for data, we had two insights. First, that sensory information could provide guidance on the affordances of objects in the world meant that the information we use to coordinate our actions is also data about physical properties of the world, and thus potentially data that a geologist could use to advance their science. Second, in thinking about how to move through the world to collect that data we realized that the scientists' data search problem was analogous to foraging in useful ways.

I warn the students in my perception class to be prepared for a disconnect between how easy it seems to see and hear and how complicated the explanations will be for how humans see and hear. That disconnect is because our conscious mind is protected from all the calculations that the brain is doing to achieve an understanding of what is out there in the world. The lack of conscious access in to how we perceive could be frustrating to anyone trying to design a robot to perceive, but the upside is that the robot does have direct access to the sensory information it is using to act. The concept of affordance – seen as passe among many in psychology – is likely recognized as still valuable in robotics where one must work had to find, encode, represent and use the rich environmental information that guides and supports action including walking on the Earth. Feifei and Doug realized that each step the robot took offered a potential bit of data about the Earth it stepped on.

If my aim is to understand how geology and thinking interact you might think that erodibility of soil is pretty far away from understanding the relationship between Earth and mind. Yet it could hardly be more direct - erosion occurs right at the point of contact between the body and the Earth. Each step we take must take into account the erosion caused by the action. Walking on cement where there is effectively no erosion is simple compared to walking on a beach. Each step on a beach causes erosion, and that erosion makes each step a challenge in not falling. If you slowly stick a probe into sand the grains move about to accommodate the intruder. As long as the force of intrusion is below a critical level the friction among grains allows their movement. But once the force exceeds that level the grains lock up. You can feel this as you walk on a beach, as the foot descends the grains slide to the side, and the sand feels mushy, but at some point the lockup occurs and the sand is firm enough to stand on. You take the step and begin the series of sensations again. You may have noticed that near the wave line the sand is particularly mushy and your foot sinks further into the sand where the water has reduced the friction and thus more force is required before the critical lockup is reached. Thus, a robot successfully walking the world is also successfully negotiating the erosion problem associated with walking and each step is a potential data point about how erosion at that location would occur. Step by step a robot could build up a dream data set, far larger than any that exist with which one could make inferences about how the various environmental variables of the world influences erosion. The tourist robot could change the way science of soil is practiced by leveraging how the (robot) mind uses environmental information to act.

But where should the robot walk to pick up all this lovely new data scattered around the world? There are better methods for finding valuable things than randomly hoping you find the best data. Anyone who has picked berries knows that foraging is more strategic than wandering until one encounters berries, sitting down, and then picking until done. A good search concentrates on places where the berries are most likely, and then as collecting begins demands a running sense of how well picking is going to inform the decision to stay and pick some more here or get up and search for a better new patch. Both the rate of gathering berries and the statistics of how berries are distributed go into this calculation, but these critical variables are not something that is knowable before you begin and must be developed as you pick. Cristina realized that field scientists face an analogous problem: How to search for and collect data in the field where there is an unknown heterogeneous distribution of data with varying value. Conceiving of the problem as a foraging problem offered a path forward as foraging is a well-structured problem where a lot of thought has gone into understanding how to find optimal or near optimal paths. It was an important reminder that the challenges of life on Earth can help us understand the mind and how sciences of the Earth could benefit from insights into how organisms fit in the systems of our world.

By confronting the problem of where in the vast wilderness a scientist should collect data to yield the greatest value, we realized how little we really understood about how scientists use their minds to guide them in their quest for data, and how they might change their minds once they saw their data. By thinking like a robot, a robot in desperate need of guidance by a human mind, we realized that this was not a question that should be answered by philosophy of science or by an analytic approach that sought the optimal search strategy for a given environment, but rather that we needed to first understand what scientists were thinking, and then ask if their strategies were optimal or hodge-podge. In retrospect an obvious research problem that should have been better studied, put bluntly is, we needed some data, data about how people search for data. We should ask expert geologists how they would collect data and then having seen the data do they change plans if there is something unexpected in the data?

By taking a robot into the field with a geologist and asking him where should the robot go, how much data should it collect, and why there, and why that much, Feifei and Cristina discovered that in an environment with some variability a single data point was insufficient. For Doug, the right number of observations was 4. This was a magic number. Why this number? Well two is the minimum number to give an average, and three the minimum number to estimate variability, and four was the minimal improvement over that. Very interesting. Perhaps not coincidentally, four is approaching the upper limit of what most of us can keep in working memory, the area of the mind that is the mental workspace where one can process the meaning and relations among the memories. For Doug, the magic number of data points at each stop was small enough to be mentally manipulated, perhaps into a single value and then held to be assimilated into a hypothesis about potential patterns in the data as he explored the space.

Joined by the practical demands of engineering, two sciences that rarely talk with each other were given a new perspective on their own disciplines to ask questions and advance their science. Perhaps more importantly the mutual respect within Dan's interdisciplinary team eroded barriers that have kept the natural and social sciences apart, to an advanced unified science.

MURI-ly we roll along: Dan and control theory approaches to cognition

James Knierim, Johns Hopkins University
Years of collaboration: 2017–present

Midway through my career as a neuroscientist, I began to interact with some control system engineers who had this audacious notion that they could understand high-order neural mechanisms of cognition by using the same types of control theory and system identification techniques that they used to understand motor systems. This started one of the most intellectually stimulating and fun collaborations I have had in my career, and eventually led me to meet Dan Koditschek. The engineers were the members of Noah Cowan's Locomotion in Mechanical and Biological Systems (LIMBS) Laboratory, and Noah had been one of Dan's star Ph.D. students. I got to know Dan when Noah approached me about a MURI grant that Dan was putting together, with his "Dream Team" (Dan's words) of engineers, behavioral psychologists, mathematicians, and neuroscientists. Dan wanted to use the new, virtual reality Dome system that Noah's students had built for our collaboration, and Noah graciously insisted that I be part of this team (playing the Freddy Krueger role of the Dream Team?) I can't say enough how much I enjoyed interacting and learning from all of the amazing scientists that Dan assembled; they have opened my eyes to brand new ways of thinking about how to tackle biological questions and exposed me to completely new fields of investigation on engineering and robotics. In turn, Dan was always eager to learn and discuss how rats navigate and solve spatial tasks.

In addition to his great intellect and curiosity, one thing that stood out about Dan is his dedication to mentoring "the next generation." He always made sure that the trainees in the MURI grant were part of the discussions and given the opportunity to present their own ideas to the group. A scientist's impact encompasses not only their own discoveries during their career but also extends (to some degree) to the achievements of those they have trained. My own research has benefitted enormously from Dan's academic progeny. Noah has engineered completely new directions in my lab's research, and the work was accomplished by the incredibly talented individuals that Noah has trained (originally Manu Madhav and Ravi Jayakumar, and more recently Shahin Lashkari, Brian Woronowicz, Gorkem Secer, and Bharath Krishnan). Early on, I would sit in our conference room with Noah, Manu, Ravi, and Francesco (my brilliant postdoctoral fellow) and listen to them discuss the data, how to mathematically analyze it, how to theoretically interpret it, and how to apply engineering principles to it. I felt like the dumbest person in the room—and I loved it! It was exciting to be learning so many new things from the best. And this all started with Noah's PhD work on navigation in Dan's lab. Who would have thought that Noah's research in Dan's engineering lab and my work in Bruce McNaughton's neurophysiology lab would converge years later so perfectly? But this is part of Dan's legacy, exemplified by the interdisciplinary team he assembled for the MURI grant. I am honored to have gotten to know, and learn from, him.

The Legend of Dan

S. Tonia Hsieh, Temple University
Kod*lab Collaborator

I first heard of "Dan Kodischek" while I was an undergraduate at UC Berkeley, under the fine tutelage and mentorship of Bob Full. Bob often spoke of Dan's creativity and innovative spirit, elevating him to a position of legend in my young, impressionable mind. Scroll forward many years as I found myself at Temple University as a young assistant professor in the Biology department in 2010. Shortly after arriving, I discovered that Dan was no longer at the University of Michigan and had moved to the University of Pennsylvania, just "down the street" from me.

When I finally did meet Dan, he was just as Bob had described him to be: warm, engaging, and very smart! What I didn't expect—especially for someone so accomplished and revered in his field—was how modest and almost self-deprecating he is, and how generous he is with his time. This is a man who schedules his days in 15–30-minute meeting blocks; and yet, every time that I have needed his advice or help, he has made himself available to me, even at 8 or 9 o'clock at night in the midst of a pandemic on Zoom... so that I could first get my kids to bed.

During the last 12 or so years that I now have known the actual Dan, I have been extraordinarily fortunate—and honored—to have him as a supporting and sage mentor to me, who has helped me through many particularly rough spots as a woman trying to fight my way through academia. During one particularly difficult period, he spent nearly two hours with me carefully dissecting my career and considering strategies for how to proceed to achieve my greatest potential. His ability to listen and draw upon his past experiences while recognizing that his identity and stature secure him privileges difficult or inaccessible to someone like me has helped to catch me multiple times as I have questioned my career choices and my abilities as a scientist.

Scientifically, Dan is focused and shrewd—able to seemingly effortlessly drill right down to the core of a project while still seeing the big picture. Being an invited speaker at his lab meeting was both a thrilling and terrifying experience. He challenged me to view my own research from perspectives I had not considered and then explained my own research to me in new ways that were more profound and insightful than I had realized myself. Equally impressive, Dan also readily admitted ignorance about topics that were routine to me, expressing genuine curiosity and an interest to learn. I realized that *this* is what intellectual exchange is all about, and it is also why discussing and debating with Dan is so exceptionally rewarding.

Over the years, we have strived to find ways to officially collaborate, siccing students and post-docs on each other with varying levels of success. In doing so, I now find myself also elevating Dan to a legendary status among *my* students. Considering all the inspiration, support, and guidance that he has so generously shared with me and undoubtedly countless others, and all the lives that he consequentially has shaped for the better, what a well-deserved spot this is for him.

Part VI

Other Unique Perspectives

Lord Kelvin taught us that...

Professor Daniel E. Koditschek

A Lab Coordinator's Perspective of Kod*lab

Diedra Krieger, University of Pennsylvania
Kod*lab Coordinator, 2012–Present

Kod*lab has been a welcoming place since I joined in November 2012. Early on it became evident Dan and his students would be open to creativity and art experiments that interact or engage with their work [3]. They have continued to be open to ideas and generous in their explanations and explorations [1]. A recent one that I had that I have yet to realize – Can I make a robot walk over me, around me if I lay on the ground? – was shown a genuine interest and willingness to make it happen.

Pinch points, gaits, linear algebra, deep time, thinking like an engineer, clever solutions, origami, olfactory, spines, degrees of freedom, legged locomotion...glimpses into these worlds continue to fascinate me. Dan has been truly generous too, like his students in any meeting if I ask an off-topic-from-administrative-lab-support question, it is welcomed with thoughtfulness and taken seriously. These conversations often lead to action, and as a result in recent years we have hosted several artist talks at Research Group.

Dan's support has impacted my art practice, enabling projects to be realized that would not have existed had I not worked at Kod*lab, such as the Nomadic Monument for Women in Robotics [2], the Robotics Art Residency[1] and the exhibition, Expressive and Meditative Machines for Imagining New Futures With Technology[2]. Strategies from my art practice have been useful to the lab as well – we now have a small repository of video portraits of Kod*lab students and postdocs.[3]

Dan works hard for his students. He worries for them. He respects them. He challenges them, believing it should be a struggle; if it's easy then you're not doing the work. (That was transformative for my thinking!) Dan says he's never worked a day in his life as a professor. But of all his amazing achievements, Dan will say they are nothing compared to his kids. He puts family and health first. Dan likes to mention he was once a labor organizer. If you're worried about a presentation, he says put yourself aside and bring your ideas into the world. They deserve to be there. These ways of thinking come through in his compassion, and often that brings the best out of the people in his lab.

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Topology and Robotics

Michael Farber, Queen Mary University of London

Many thanks for the invitation and for organising this wonderful event!

Unfortunately, for geographical reasons, I am unable to attend the dinner and the other activities celebrating Dan's work and achievements.

I feel honoured for being invited. I consider myself a friend and a scientific follower of Dan Koditschek. I admire his work and the profound influence his work had on mathematics and on modern topology.

In 2006 we organised jointly with Dan a workshop "Topology and Robotics" in ETH Zurich. This was a meeting hosting mathematicians and engineers, and Dan's contribution was crucial. After the meeting we had a hike in Swiss mountains, and I remember how Dan jumped into the water of the coldest and deepest Swiss lake, Walensee. The water was 11 degrees Celsius. No other person from our group was able to join Dan who spent some time swimming and enjoying himself. This was very impressive!

A volume "Topology and Robotics" was published by the American Mathematical Society afterwards; Dan was one of the editors of this volume.

Dan Koditschek, one-man welcome wagon

Shmuel Weinberger, University of Chicago

While I wish I could be present in person to celebrate Dan, I cannot. Besides missing the opportunity to celebrate Dan, I am sorry to miss the chance to learn a lot from being there and hanging out at the meeting.

I met Dan first at a conference in Zurich that Michael Farber organized at ETH, I believe around 15 years ago, that was one of several devoted to connections between topology and robotics. I knew nothing about the latter subject, and was so insecure, and nothing about the "and" connecting the two nouns of the title, that I insisted that Michael declare the conference in recess before my talk and reconvene after, so that there would be no pretense that what I was discussing would have any connections to robotics.

It was great meeting Dan. I experienced him as a compact moving tornado of enthusiastic friendly energy – whose broad point of view of what's interesting and what could be relevant was both inspiring and welcoming. He explained navigation functions and Morse theory to me and how they could be useful and explained that what I had spoken about was really highly relevant. I loved the movies he showed me of ping pong playing robots and stable hopping pogo sticks, and, of course, Rhex. We've been in touch over the years, and he's influenced my attitude towards applied math generally (indirectly leading me to take part in the founding of the Journal of Applied and Computational Topology) and to modifying Farber's notion of Topological complexity (in joint work with D. Cohen and M. Farber) to try to take into account issues that Dan kept trying to get me to think about: variability of the environment and the need to sense it. [I added references to our first two papers [1, 2] on this direction and a YouTube video[1] about topological football at the end, so this note can more closely resemble a scientific contribution.]

I had a great time visiting Kod*Lab, and when my son as a junior in high school was looking for a summer activity, I asked Dan – I was at a meeting he organized in Washington focused on the interaction between robotic and biological solutions to the problem of moving in an environment (again, what was a topologist doing there? Ask Dan – he thought it was a good idea, and I had a blast following him), and Dan was immediately infinitely hospitable inviting my son to work in the lab over the summer. It was great – my son learned how to program, some ideas about optimization and experiment; he interacted day to day with graduate students and postdocs (who either picked up their warmth from Dan, or were picked by him by a set of criteria that must have included personal ones), and he changed his mind about how lame math was – indeed, at the end of the summer, he decided to major in applied math when he got to college.

So besides being an admiring colleague, I am also a grateful father.

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Robotics Fair

Jorge J. Santiago-Aviles, University of Pennsylvania

My name is Jorge Santiago and I am an emeritus from the department. For several decades I was faculty director of a college house. I was involved in organizing a group of student residents (mostly from engineering) called the Science and Technology Wing (STWing). For nearly a decade the group celebrated an annual event called the ROBOTICS FAIR. It is important to acknowledge that Koditschek was at the time the strongest supporter of the residential program, helped us financially and his students were the usual presenters in the event in terms of robotics technology. All the STWing students (from engineering or not) owe a great deal to Kodlab and Professor Koditschek. That was an important contribution to University life and should be publicly acknowledged.