Commercialization of a Novel Mobile Manipulator

Guest Lecture for Prof. Zackory Erickson's Class at CMU
16-887: Robotic Caregivers and Intelligent Physical Collaboration

April 11, 2022

Charlie Kemp
https://charliekemp.com

Charlie’s Conflict of Interest Statement

Dr. Kemp is both an associate professor at Georgia Tech and the chief technology officer (CTO) of Hello Robot Inc. where he works part time. **He owns equity** in Hello Robot Inc. and is an inventor of Georgia Tech intellectual property (IP) licensed by Hello Robot Inc. Consequently, **he receives royalties** through Georgia Tech for sales made by Hello Robot Inc. He also benefits from increases in the value of Hello Robot Inc.

Summary: If Hello Robot does well, Charlie does well.

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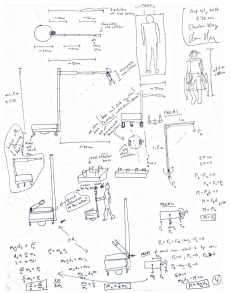
hello robot™

Commercialization

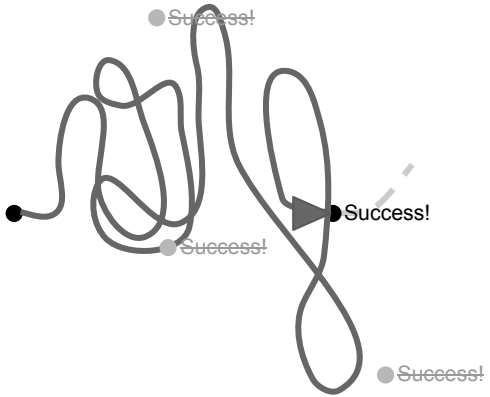
- Is open ended with many roads to success
- Depends on customers not investors
- Can empower people to create the future

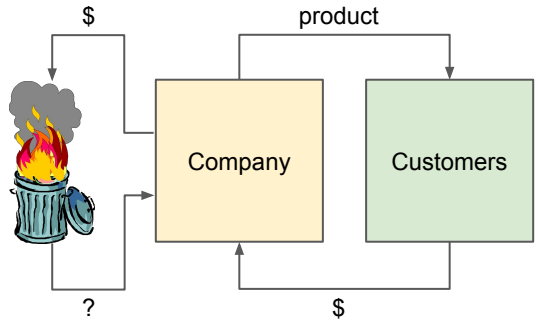


2016	2017		2018	2019	2020

Outline

- My commercialization story
- A simple startup model
- Challenges for emerging technology





Mobile Manipulators Can Provide Meaningful Assistance






research from the Healthcare Robotics Lab (healthcare-robotics.com) at Georgia Tech

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Commercial Assistive Robots

JACO by Kinova

- On your wheelchair
- On a table or desk
- On your body

DynamicArm by Ottobock

My Spoon by SECOM

Myomo by Myomo Inc.

Advantages of Mobile Manipulators

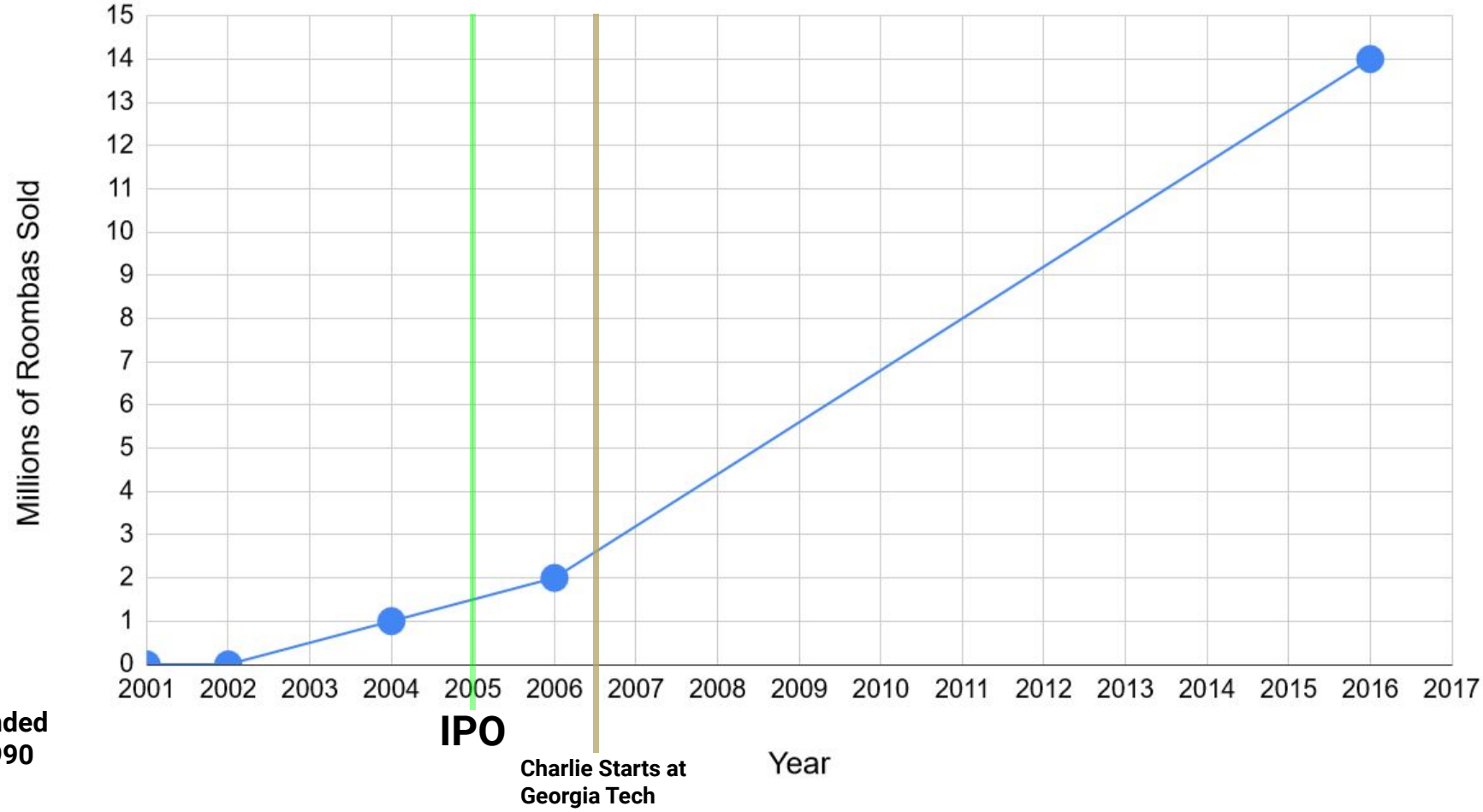
- Operate independently from the user
- No don/doff
- Assist diverse users
- Potential for mass market product

Photo Credit: Peter Menzel/Science Source
from https://robots.ieee.org/robots/cog/

Rodney A. Brooks, "How To Build Complete Creatures Rather Than Isolated Cognitive Simulators", Architectures for Intelligence, K. VanLehn (ed), Erlbaum, Hillsdale, NJ, Fall 1989, pp. 225–239.

The first Roomba from 2002.
20 years ago!

Millions of Roombas Sold vs. Year



Bodies and Brains Working Together

- Body matched to ecological niche
  - Small footprint
  - Circular and flat
  - Giant contact sensor
  - Easy for people to pick up and move
- Brain matched to the body
  - Haptic sensing as primary modality
  - Change direction on contact
  - Wall following
  - Spiraling

“Viewed as a geometric figure, the ant’s path is irregular, complex, and hard to describe. But its complexity is really a complexity in the surface of the beach, not the complexity in the ant.”

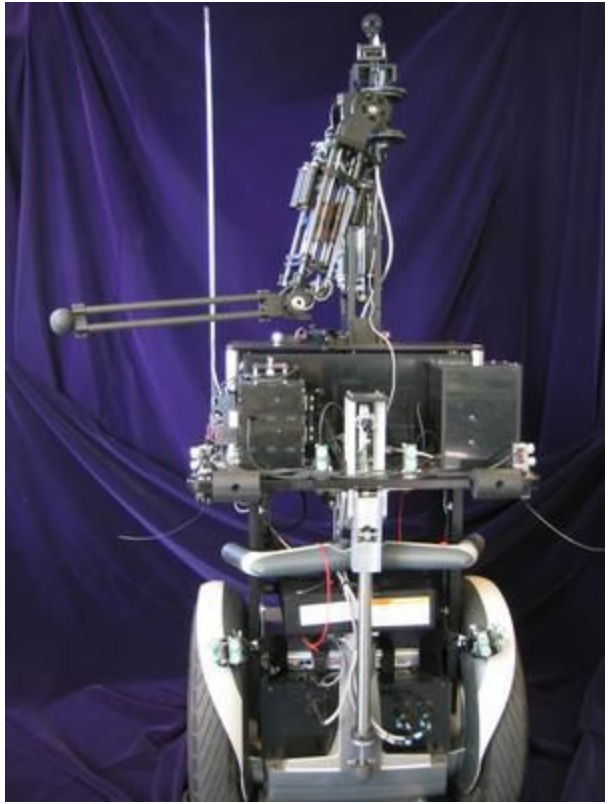
Herbert Simon,
The Sciences of the Artificial, 1969

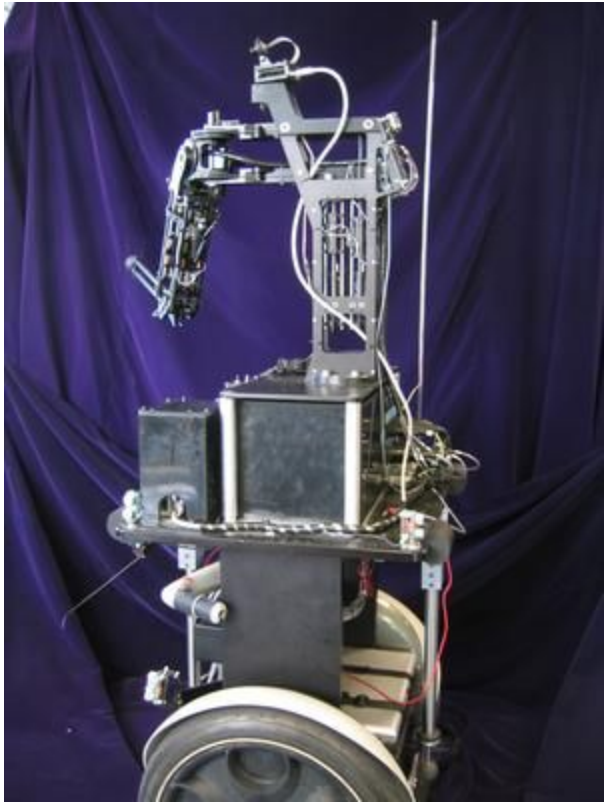
Photo Credit:
Andreas Dantz
Roomba, first attempt
Taken on April 14, 2013
https://www.flickr.com/photos/szene/8649326807/in/pool-roomba/

What is the Roomba of mobile manipulation?

What body for **indoor** mobile manipulation in homes and workplaces?

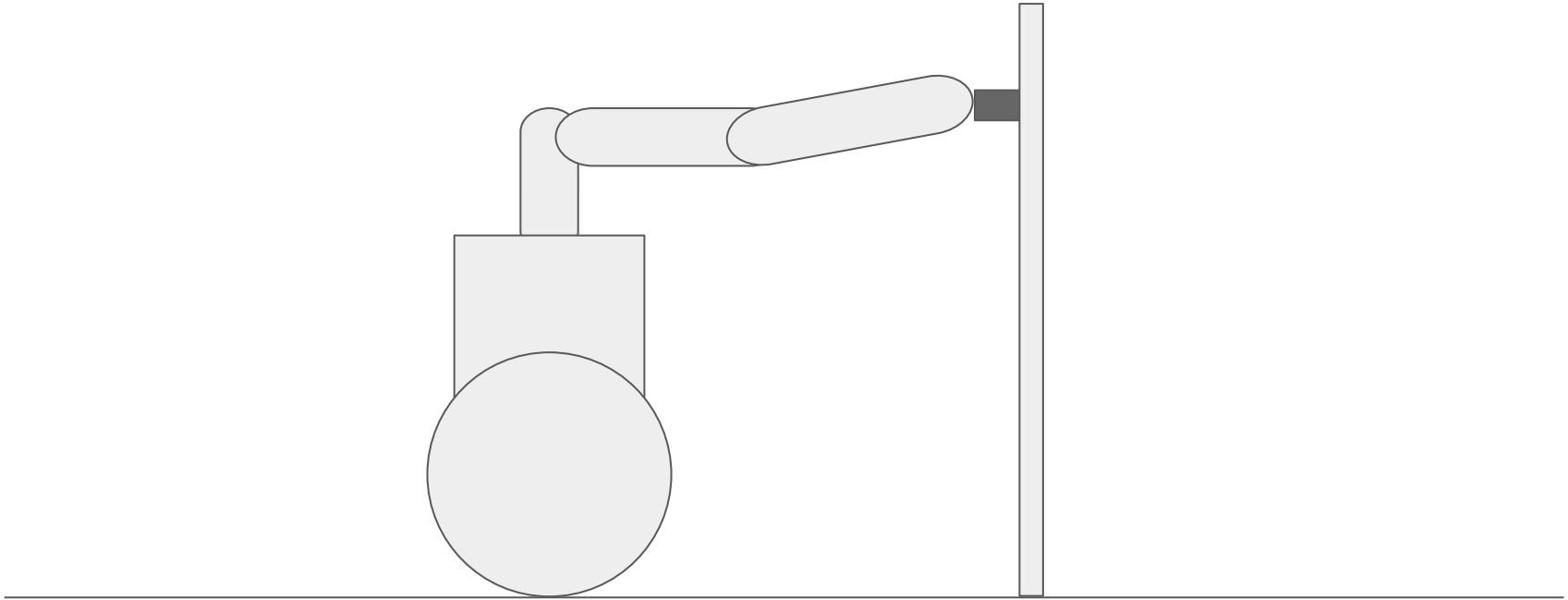
- Flat smooth surfaces
- Visible from human head height
- Reachable by human arms
- Children, older adults, and pets



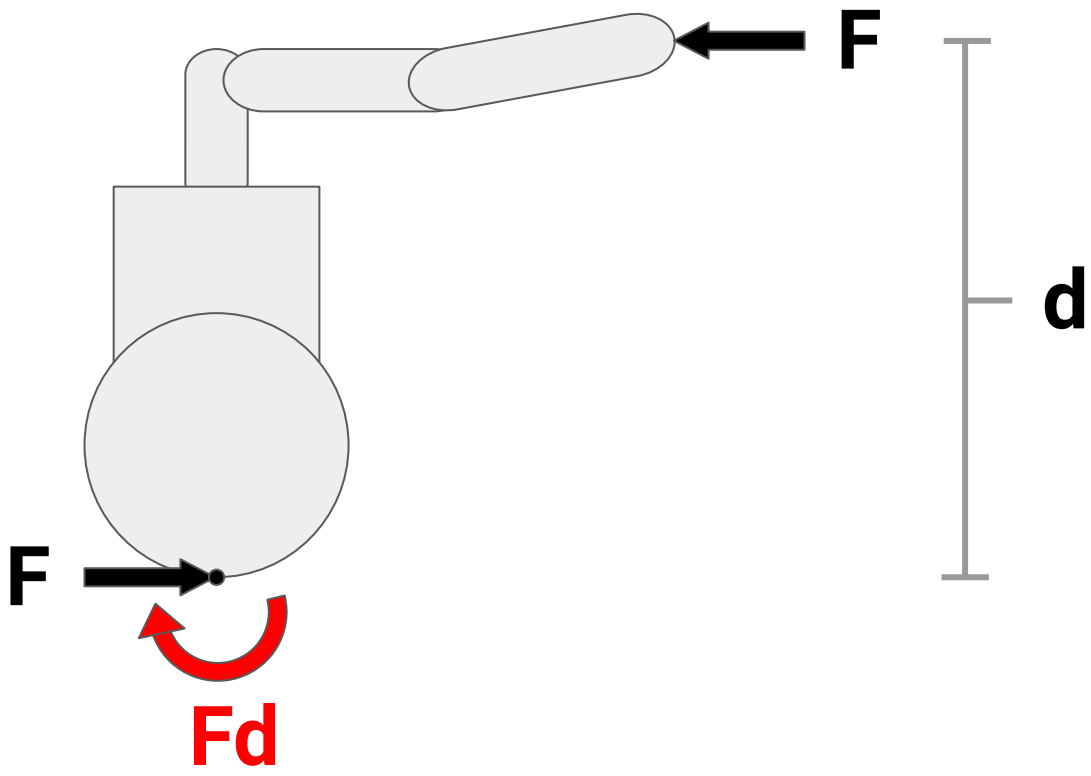


Sensing and Manipulating Built-for-Human Environments, **Rodney A. Brooks**, Lijin Aryananda, **Aaron Edsinger**, Paul M. Fitzpatrick, **Charles C. Kemp**, Una-May O'Reilly, Eduardo Torres-Jara, Paulina Varshavskaya and Jeff Weber. International Journal of Humanoid Robotics, Vol 1, Number 1, pages 1-28, 2004.

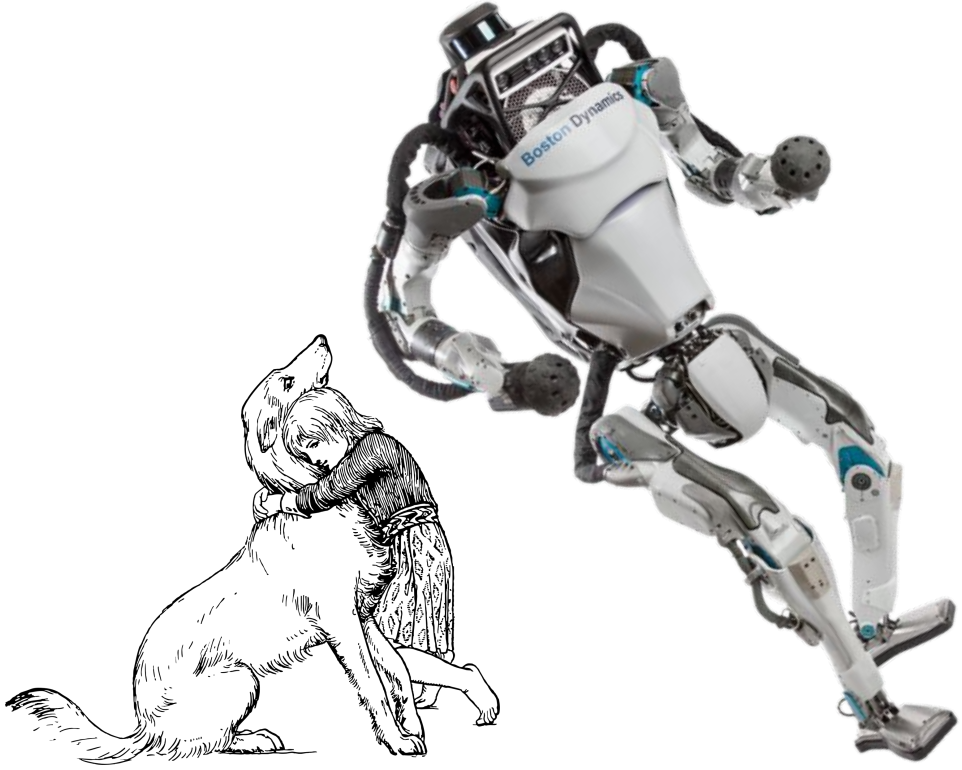
Momentary Problem when Balancing on Wheels



Momentary Problem when Balancing on Wheels



It Just Takes One Fall



Images from
https://openclipart.org/detail/314874/little-girl-hugging-dog
https://ozrobotics.com/tag/humanoid-robot/

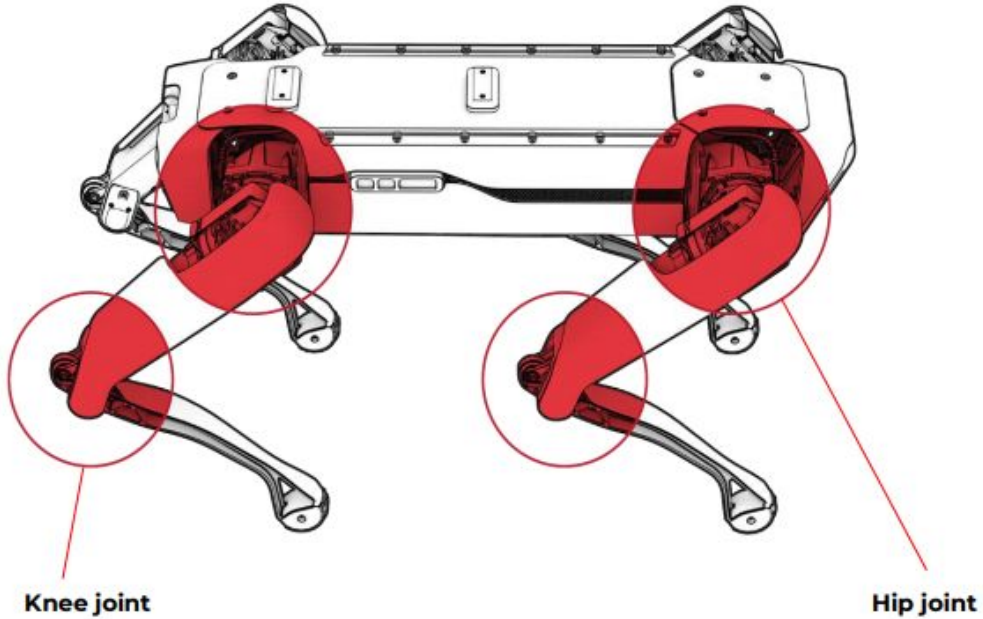
CSAIL

What about quadrupeds?

Image from
https://www.bostondynamics.com/spot

Pinch Points

Spot's joints can pinch fingers and other body parts and entangle loose clothing, long hair, and jewelry.



BostonDynamics

SPOT INFORMATION FOR USE

V1.0 - Original Instructions

https://www.bostondynamics.com/sites/default/files/inline-files/spot-information-for-use-en.pdf

Dynamic Stability Risks

Spot will always try to keep balance. This may result in high-acceleration motion of the legs

Failure in locomotion could happen unexpectedly and could result in de-energization of the robot's actuators.

A failure event may cause loss of stability and potential hazards associated with a fall or tipping over.

Always keep a separation distance of 2 m

https://www.bostondynamics.com/sites/default/files/inline-files/spot-information-for-use-en.pdf

What is the Roomba of mobile manipulation?

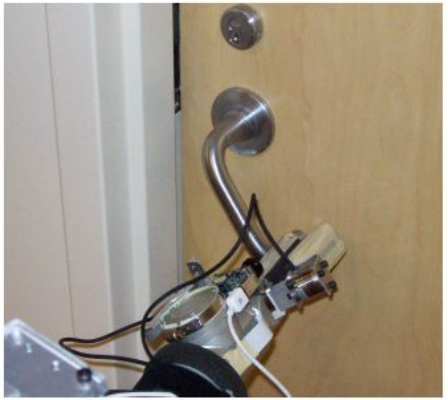
Stretch's Ancestor

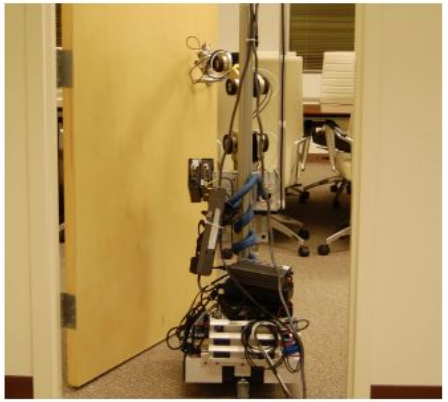
EL-E from 2008

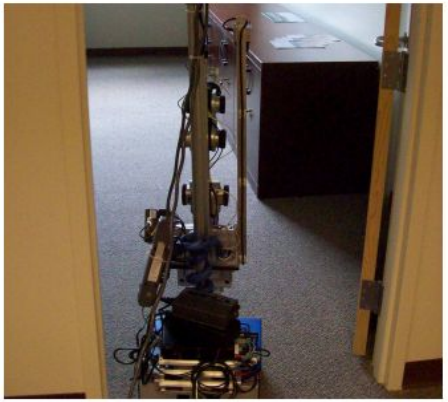
- Statically stable
- Small footprint
- Lightweight
- Cameras high
- Reach flat surfaces

A Point-and-Click Interface for the Real World: Laser Designation of Objects for Mobile Manipulation, Charles C. Kemp, Cressel Anderson, Hai Nguyen, Alex Trevor, and Zhe Xu, 3rd ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2008







Behaviors for Robust Door Opening and Doorway Traversal with a Force-Sensing Mobile Manipulator, Advait Jain and Charles C. Kemp, RSS Manipulation Workshop: Intelligence in Human Environments, 2008.

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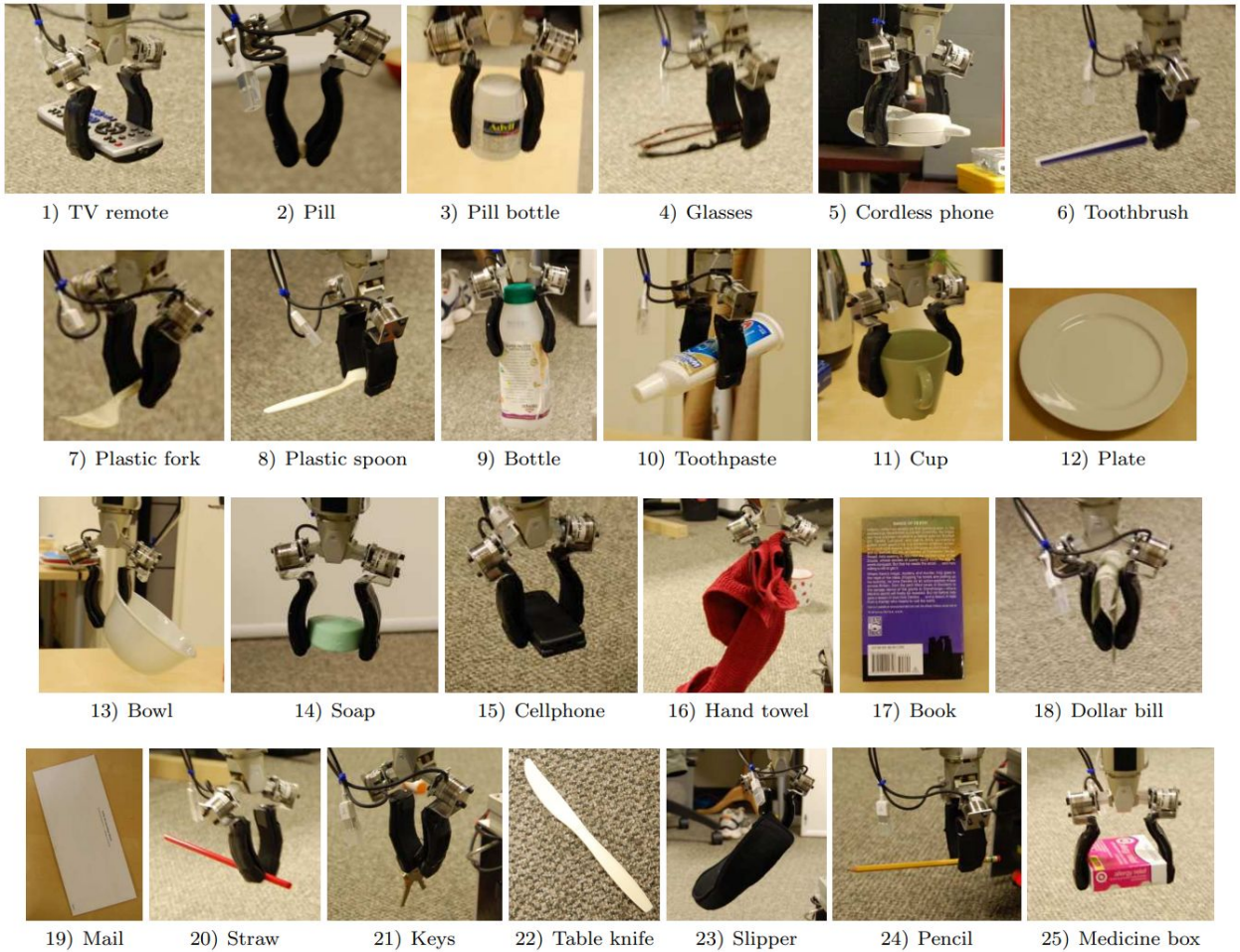

EL-E: An Assistive Mobile Manipulator that Autonomously Fetches Objects from Flat Surfaces, Advait Jain and Charles C. Kemp, Autonomous Robots, 2010

PPS-Tags: Physical Perceptual and Semantic Tags for Autonomous Mobile Manipulation, Hai Nguyen, Travis Deyle, Matt Reynolds, and Charles C. Kemp, IROS 2009 workshop: Semantic Perception for Mobile Manipulation, 2009.

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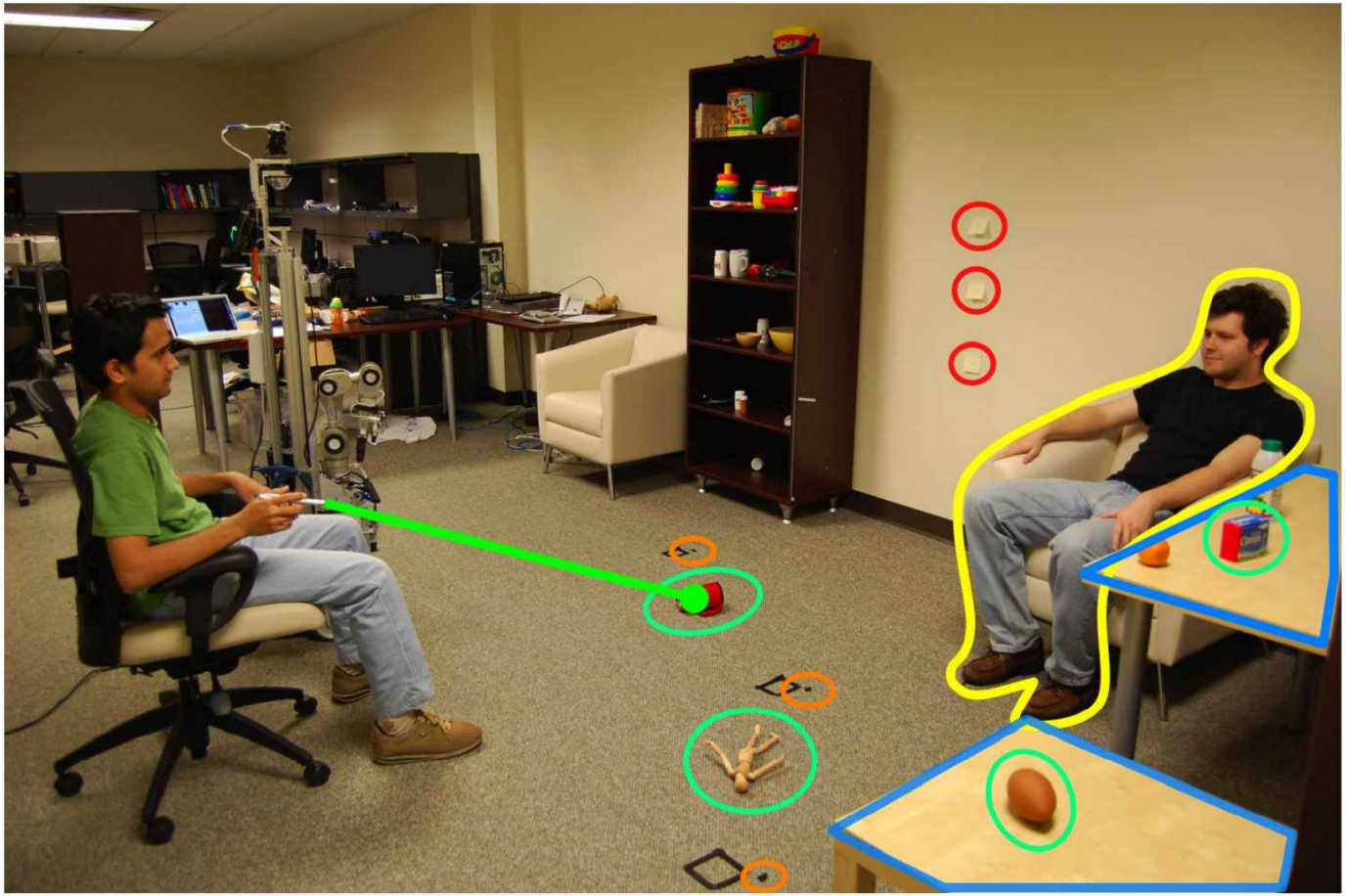
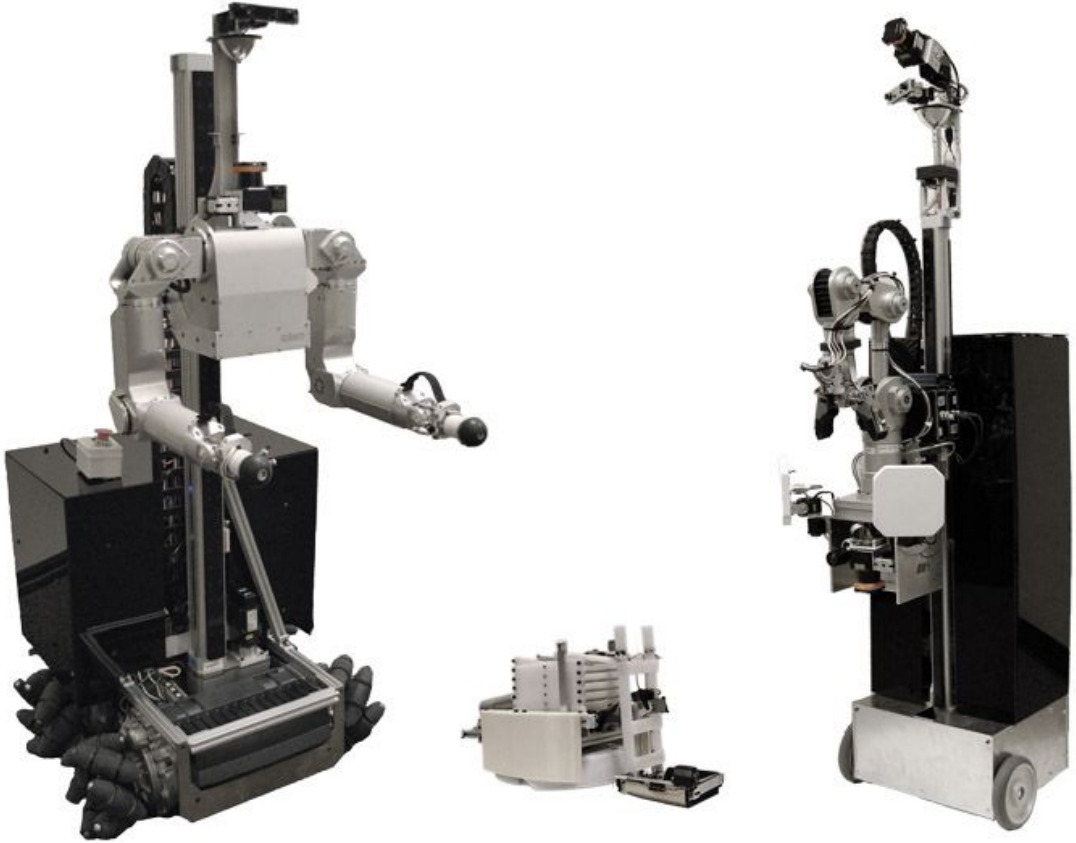


A Clickable World: Behavior Selection Through Pointing and Context for Mobile Manipulation, Hai Nguyen, Advait Jain, Cressel Anderson, and Charles C. Kemp, IEEE/RJS International Conference on Intelligent Robots and Systems (IROS), 2008.

Georgia Tech

Hand It Over or Set It Down: A User Study of Object Delivery with an Assistive Mobile Manipulator, Young Sang Choi, Tiffany L. Chen, Advait Jain, Cressel Anderson, Jonathan D. Glass, and Charles C. Kemp, IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2009.

Georgia Tech



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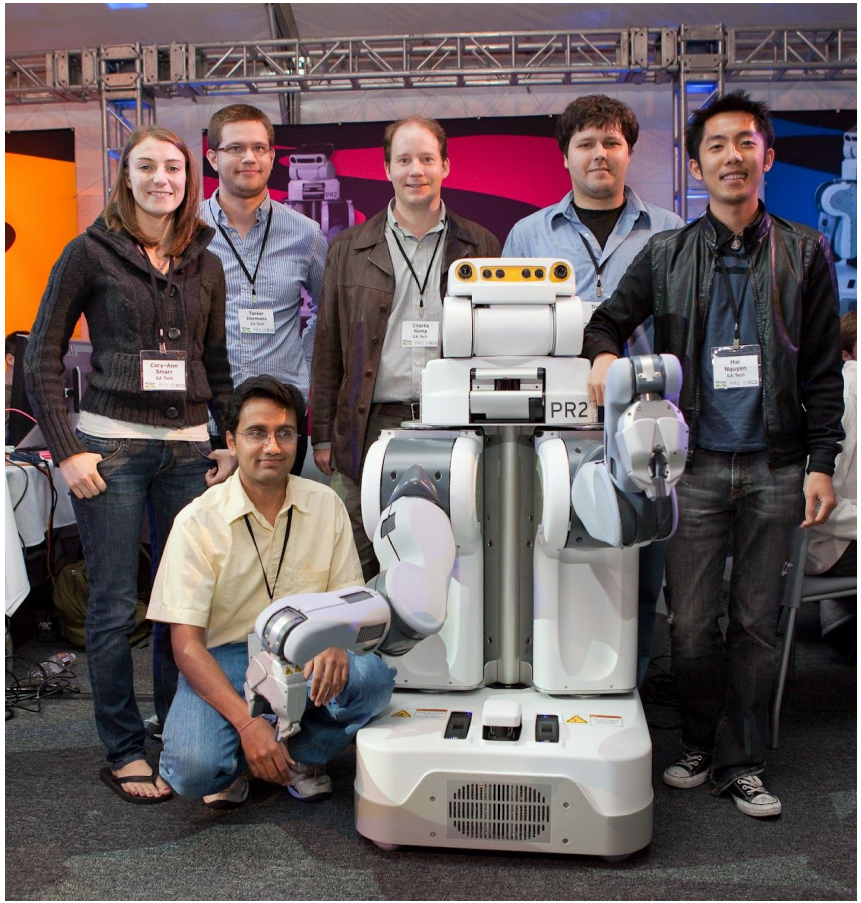
In 2010 the World Changed

Image from
https://www.roboticstoday.com/institutions/willow-garage

Photo from
https://www.flickr.com/photos/willowgarage/4675655695/



Domestic robots for older adults: Attitudes, preferences, and potential, Cory-Ann Smarr, Tracy L. Mitzner, Jenay M. Beer, Akanksha Prakash, Tiffany L. Chen, Charles C. Kemp, and Wendy A. Rogers. International Journal of Social Robotics, 6(2):229–247, 2014.

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Photo from
https://www.flickr.com/photos/willowgarage/4648144203/

Mobile Manipulators Can Provide Meaningful Assistance






research from the Healthcare Robotics Lab (healthcare-robotics.com) at Georgia Tech

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Mobile Manipulators Can Provide Meaningful Assistance

research from the Healthcare Robotics Lab (healthcare-robotics.com) at Georgia Tech

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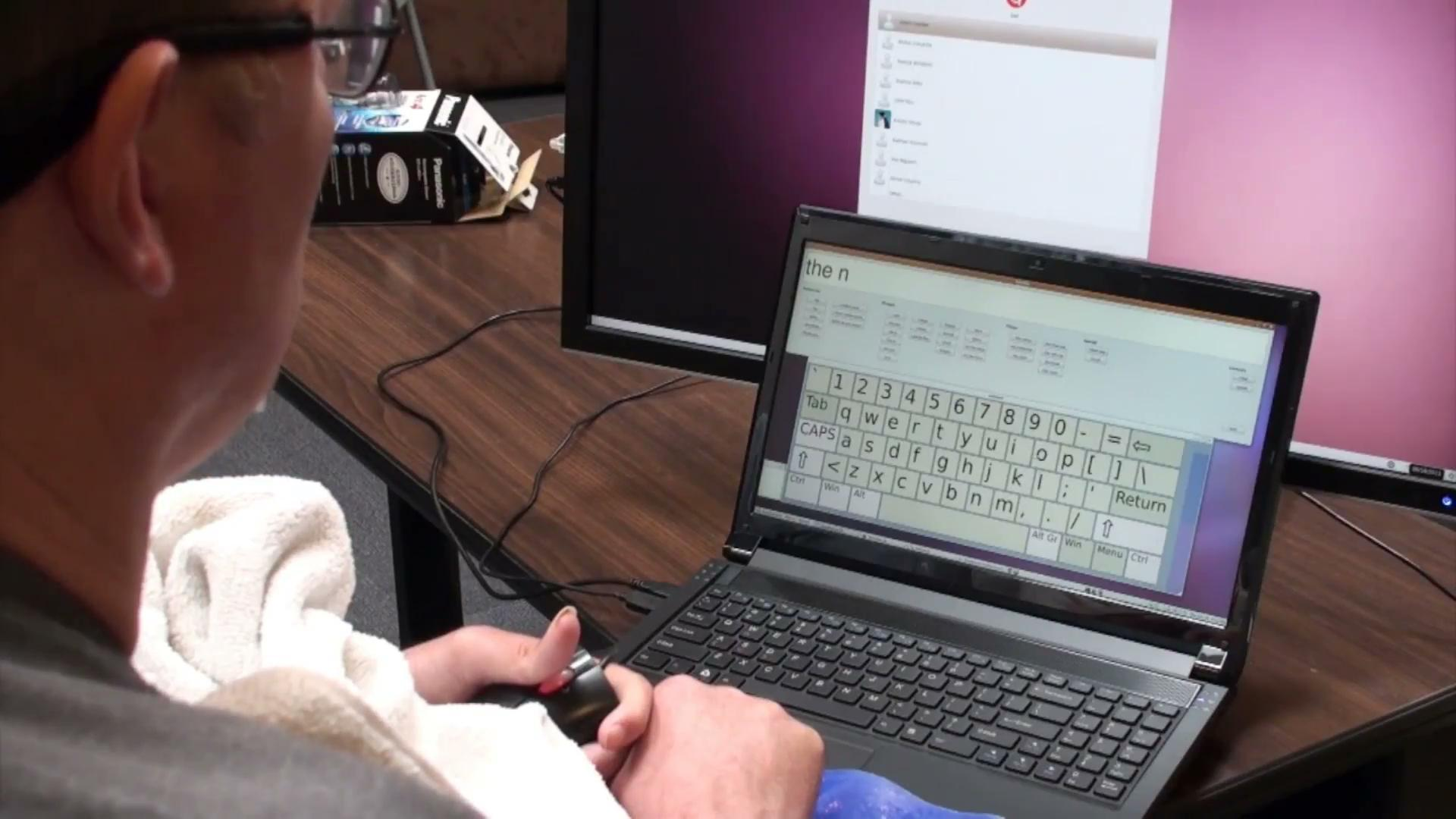
The Robots for Humanity Project

Robots for humanity: using assistive robotics to empower people with disabilities, Tiffany L. Chen, Matei Ciocarlie, Steve Cousins, Phillip Grice, Kelsey Hawkins, Kaijen Hsiao, **Charles C. Kemp**, Chih-Hung King, Daniel A. Lazewatsky, Adam Leeper, Hai Nguyen, Andreas Paepcke, Caroline Pantofaru, William D. Smart, and Leila Takayama, IEEE Robotics & Automation Magazine, 2013

Photo taken on June 16, 2011 at Willow Garage. Image from https://www.flickr.com/photos/willowgarage/5941309642 .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Panasonic

Assistive Mobile Manipulation for Self-Care Tasks Around the Head, Kelsey Hawkins, Phillip M. Grice, Tiffany L. Chen, Chih-Hung King, and Charles C. Kemp, 2014 IEEE Symposium on Computational Intelligence in Robotic Rehabilitation and Assistive Technologies, 2014.

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Assistive Mobile Manipulation for Self-Care Tasks Around the Head, Kelsey Hawkins, Phillip M. Grice, Tiffany L. Chen, Chih-Hung King, and Charles C. Kemp, 2014 IEEE Symposium on Computational Intelligence in Robotic Rehabilitation and Assistive Technologies, 2014.

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In-home and remote use of robotic body surrogates by people with profound motor deficits, Phillip M. Grice and Charles C. Kemp, PLoS ONE 14(3), 2019.

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Control Interface
Phillip
monty1wan.bme.gatech.edu:8008/assistive_teleop/vci.html
Main Menu
Look
Spine
Left Hand
Right Hand
Drive
Controls
Step Size
XS
S
M
L
Position/Rotation
Hand Position
Wrist Rotation
3D Peek
Move Aside
Move to Setup
Re-zero Skin
Gripper
4x


Realtime
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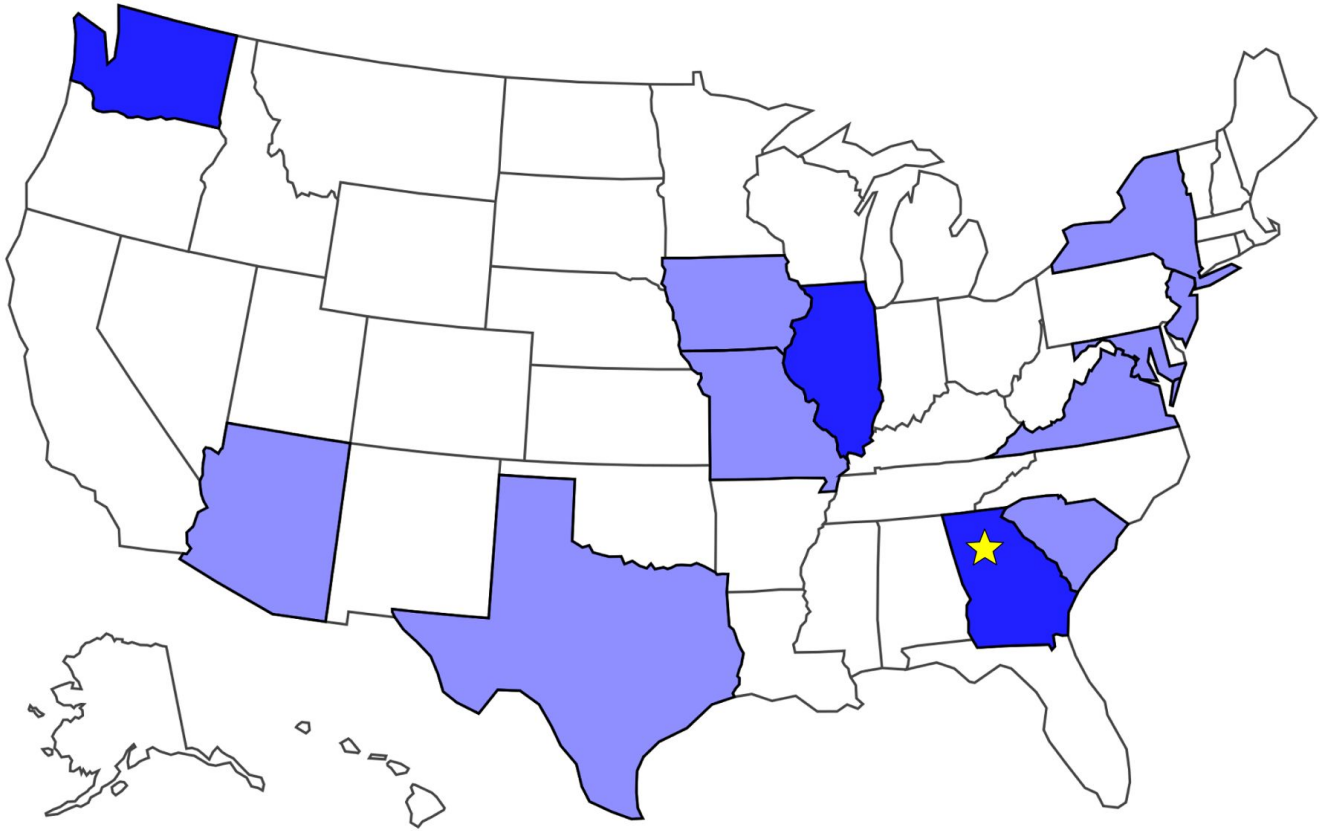
15 Participants



In-home and remote use of robotic body surrogates by people with profound motor deficits, Phillip M. Grice and Charles C. Kemp, PLoS ONE 14(3), 2019.

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Causes of Motor Impairment

6 Spinal Muscular Atrophy (SMA)

3 Muscular Dystrophy (Duchenne/Becker)

3 Spinal Cord Injury

1 Amyotrophic Lateral Sclerosis (ALS)

1 Arthrogryposis

1 Dejerine-Sottas

ARAT Threshold: 9/57 with best arm

Computer Access Devices

4 – Trackball

3 – Touchpad

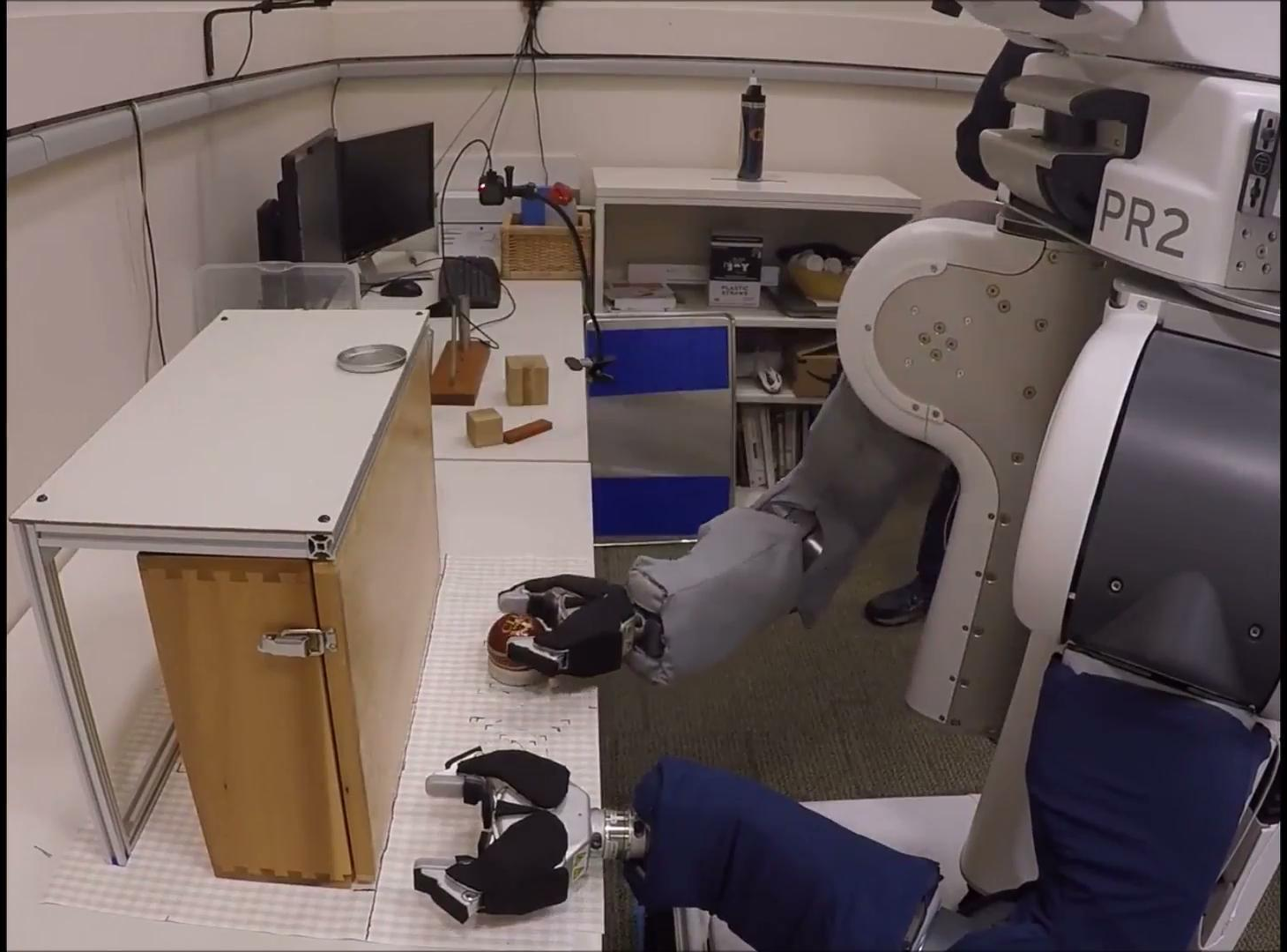
3 – Head-mouse (TrackerPro, 2x HeadMouse Extreme)

2 – Standard mouse

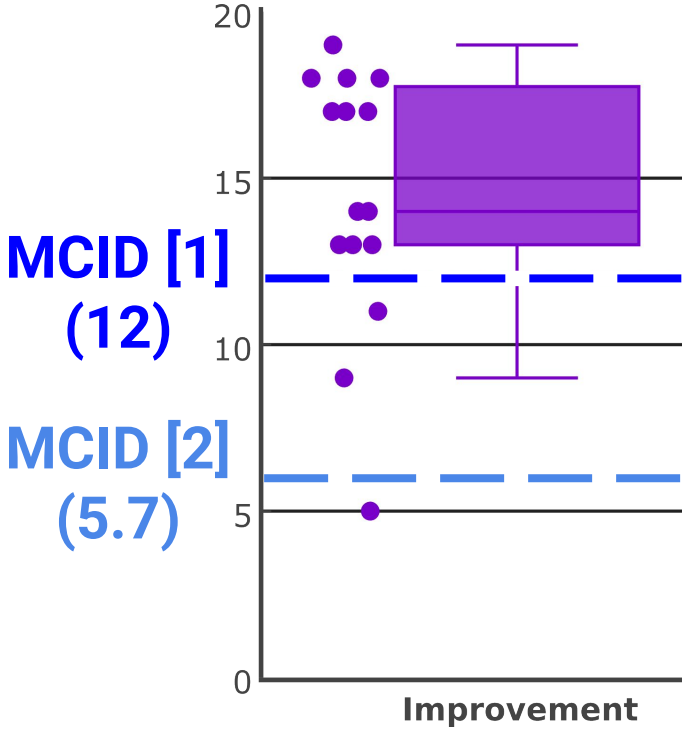
1 – Eye-gaze (Tobii)

1 – Touchpad w/Stylus held in mouth

1 – Speech (Dragon MouseGrid)


40x
PR2
Georgia Tech

Improvement Exceeded Conservative Minimal Clinically Important Difference (MCID)

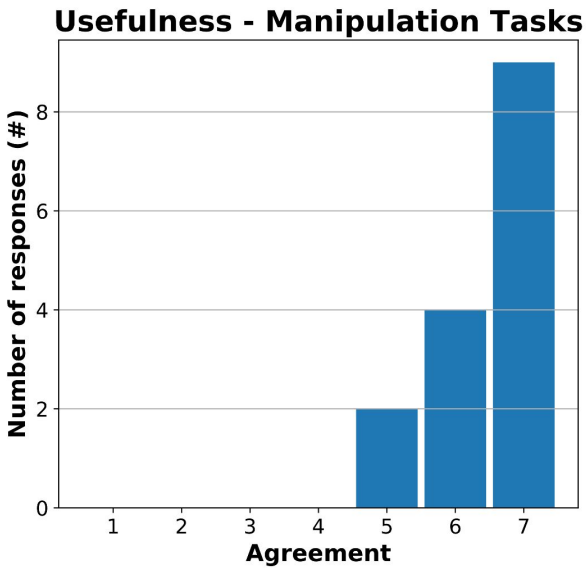


[1] C. E. Lang, D. F. Edwards, R. L. Birkenmeier, and A. W. Dromerick, **"Estimating minimal clinically important differences of upper-extremity measures early after stroke,"** Archives of physical medicine and rehabilitation, vol. 89, no. 9, pp. 1693– 1700, 2008.

[2] J. H. Van der Lee, V. De Groot, H. Beckerman, R. C. Wagenaar, G. J. Lankhorst, and L. M. Bouter, **"The intra-and interrater reliability of the action research arm test: A practical test of upper extremity function in patients with stroke,"** Archives of physical medicine and rehabilitation, vol. 82, no. 1, pp. 14–19, 2001.

1-tailed Wilcoxon signed-rank test vs MCID: W=96, **p=.021**

Perceived Usefulness

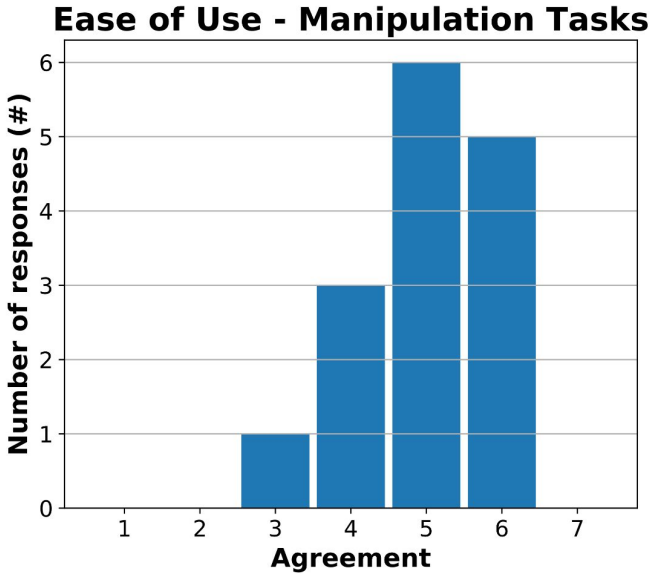


Wilcoxon signed-rank test vs neutral:
W=120, p=.000258

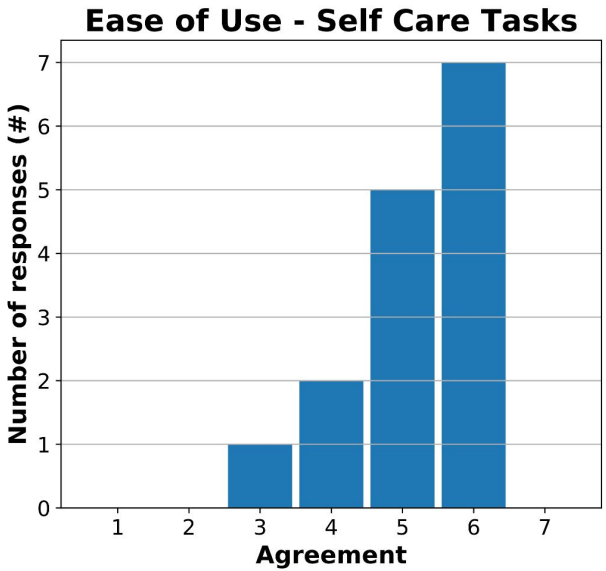
Wilcoxon signed-rank test vs neutral:
W=105, p=.000402

1: Strongly Disagree
2: Disagree
3: Somewhat Disagree
4: Neither Agree nor Disagree
5: Somewhat Agree
6: Agree
7: Strongly Agree

Perceived Ease of Use



Wilcoxon signed-rank test vs neutral:
W=74, p=.00264



Wilcoxon signed-rank test vs neutral:
W=87.5, p=.00142

1: Strongly Disagree
2: Disagree
3: Somewhat Disagree
4: Neither Agree nor Disagree
5: Somewhat Agree
6: Agree
7: Strongly Agree

Limitations

- Slow operation
- Errors
- Depth perception

Limitations

- Slow operation
- Errors
- Depth perception
- **The robot**

Two Problems

- Willow Garage shut down in 2014
- PR2 was impractical
  - $400,000
  - 227 kg (~500 lb)
  - 67 cm wide (~2.2 ft)

Photo from Willow Garage

2002

2010

2008

?

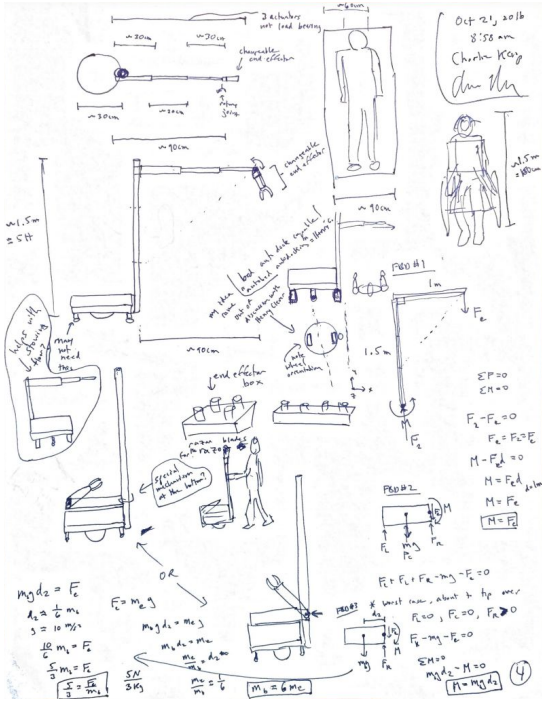
2016

Hourglass photo from https://commons.wikimedia.org/wiki/File:Wooden_hourglass_3.jpg

Frustration Leads to Invention

Minimize the actuator requirements while maximizing the capabilities.

- **affordable**
- compact
- lightweight
- humancentric
- capable



My Initial Georgia Tech Notes
October 2016

[The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments](), Charles C. Kemp, Aaron Edsinger, Henry M. Clever, Blaine Matulevich, preprint on arxiv.org, 2021.

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Georgia Tech's Prototype
March 2017

Hello Robot's Product - A Robot for Research
July 2020

2016	2017		2018	2019	2020

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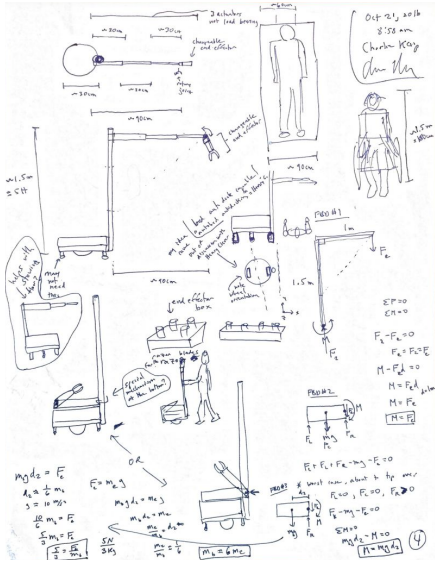
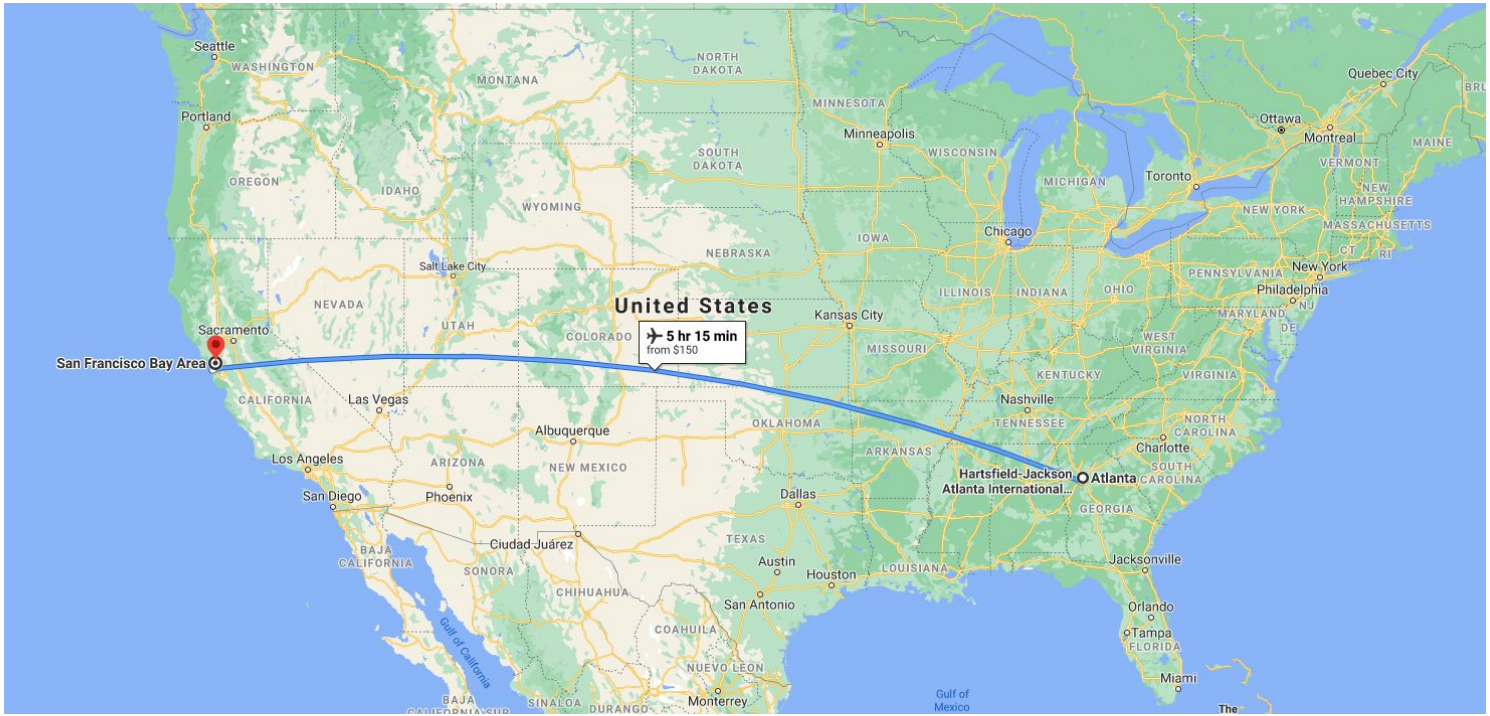


Technical Inspiration!

Public Launch

2016	2017		2018	2019	2020

~3.8 years



2016	2017		2018	2019	2020

Technical Inspiration!

Bay Area Roadshow

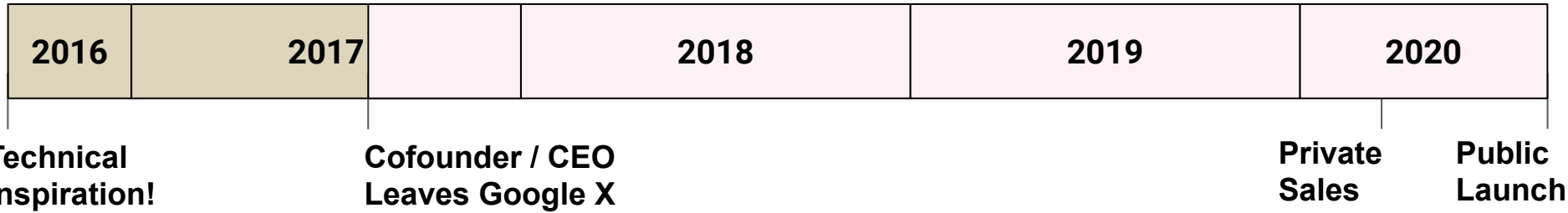
Private Sales

Public Launch


Healthcare Robotics Lab @ Georgia Tech
7x speed, able-bodied user, teleoperated, 3/21/2017

Aaron Edsinger, PhD

- World views aligned
- Commitment to a long-term vision
- Successful prior collaborations
- Business experience
- Strong technical skills



2016	2017		2018	2019	2020

Technical Inspiration!

License Agreement with Georgia Tech

Private Sales

Public Launch

Too late for naive funding,
too early for consumers

MAYFIELD ROBOTICS

Funded by Bosch
Founded 2015
ceased operations August 2018

$73M raised
Founded 2012
sold assets June 2018

anki®

$260M raised
Founded 2010
bankrupt April 2019

2016	2017		2018	2019	2020

Technical Inspiration!

Pitching for Venture Capital

Private Sales

Public Launch

Pivot to a longer-term plan starting with a robot for researchers and educators.

2016	2017		2018	2019	2020

Technical Inspiration!

From Venture Capital to Self Funded

Private Sales

Public Launch

Where did I get the money?

- Supportive spouse
- Frugality
  - Enjoy life with less
  - Lived on single income of dual income household
  - Careful with large financial commitments (e.g., house & car)
- Investing
  - Long-term value investing
  - Asset allocation strategy
  - Reallocation when markets are down (e.g., 2008, 2020)
- Time
  - 11 years for compounding returns
  - Patience and exponentials pay off

Georgia Tech's Prototype
March 2017

Hello Robot's Product - A Robot for Research
July 2020

2016	2017		2018	2019	2020

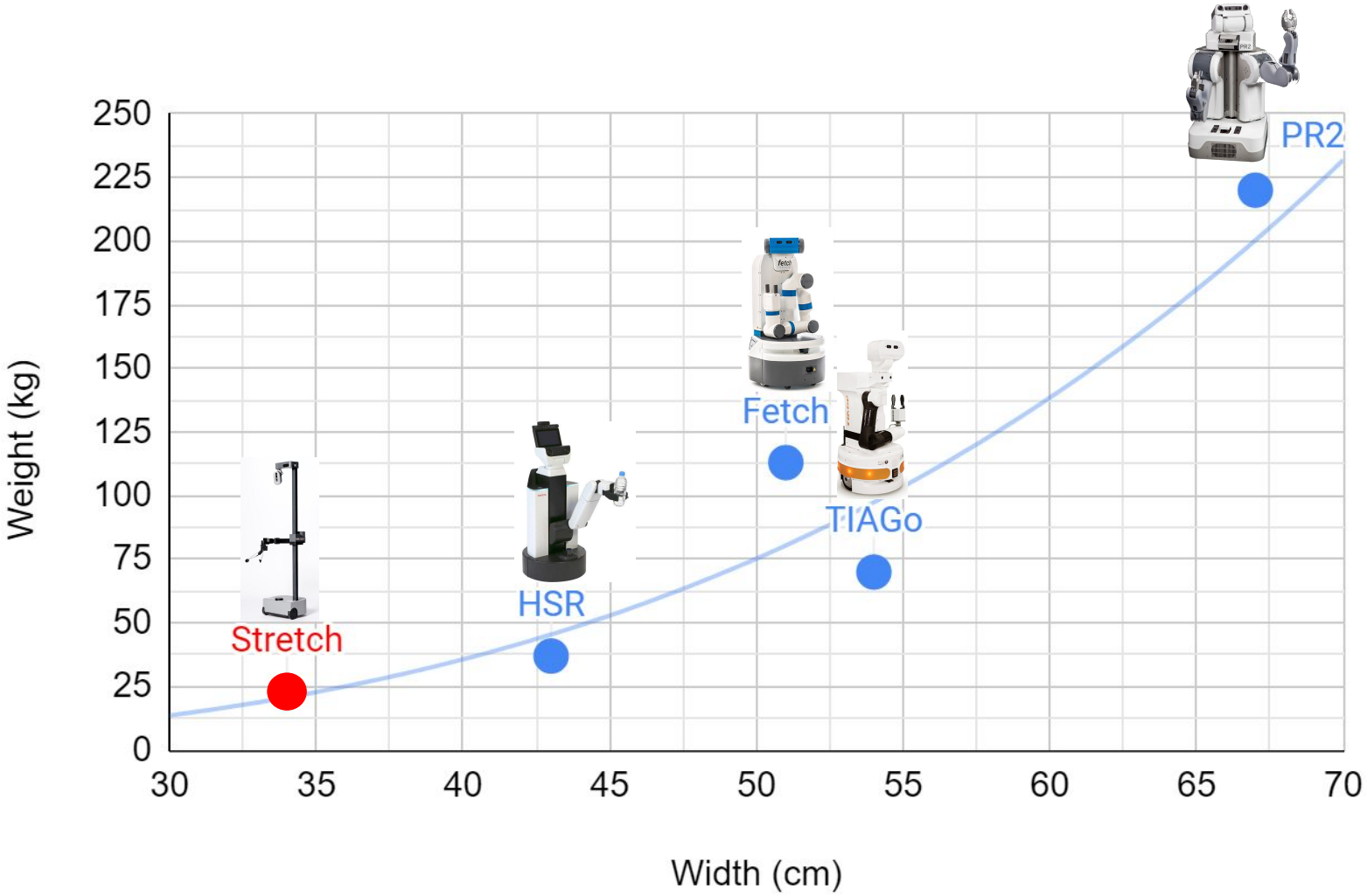
Georgia Tech

hello robot™

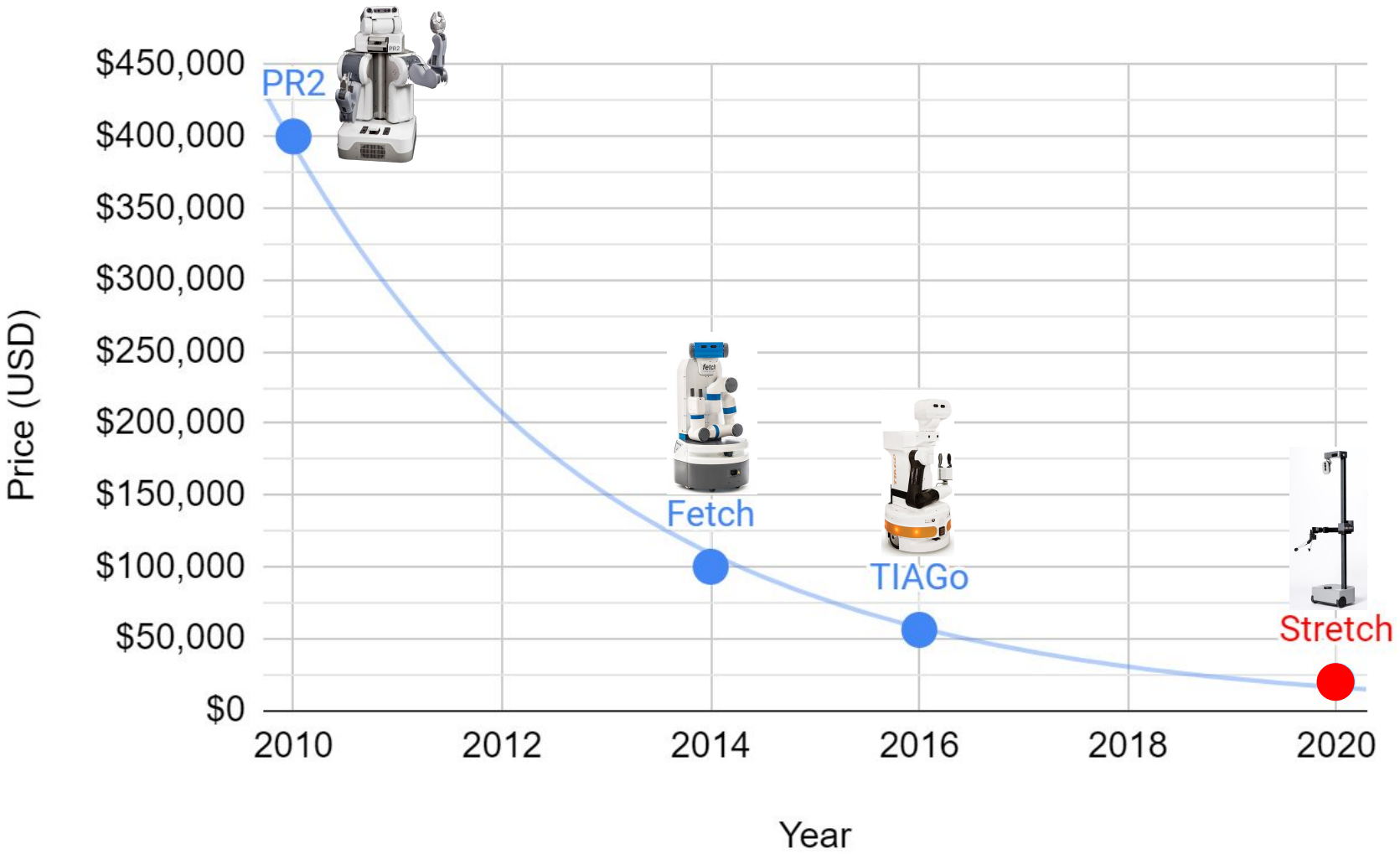
Smaller, Lighter, More Affordable

- 34 cm wide (~1.1 ft)
- 23 kg (~51 lb)
- $20,000

Photos from Willow Garage, https://fetchrobotics.com/fetch-mobile-manipulator/, https://pal-robotics.com/robots/tiago/, https://global.toyota/en/download/8725328



Photos from Willow Garage, https://fetchrobotics.com/fetch-mobile-manipulator/, https://pal-robotics.com/robots/tiago/



Successful Launch in July 2020

IEEE SPECTRUM Topics Reports Blogs Multimedia

Automaton | Robotics | Home Robots

14 Jul 2020 | 4:01 GMT

Ex-Googler's Startup Comes Out of Stealth With Beautifully Simple, Clever Robot Design

Hello Robot's Stretch wants to reinvent how mobile manipulators perform tasks in home environments

By **Evan Ackerman and Erico Guizzo**

Photo: Hello Robot

Hello Robot, founded by former Google robotics director Aaron Edsinger and Georgia Tech professor Charlie Kemp, is introducing Stretch, a mobile manipulator that weighs only 23 kg and costs less than $20,000.

SVR Silicon Valley Robotics

supporting the innovation and commerc

Hello Robot wins Innovation Award in SVR 'Good Robot' Industry Awards

Posted on December 14, 2020 by Andra Keay

RBR 50 INNOVATION AWARDS

BBC Sign in Home News Sport Reel Wo

NEWS

Home | Prince Philip | Coronavirus | Video | World | US & Canada | UK | Busines

Tech

Research robot helps with housework and other news

hello robot™

www.hello-robot.com

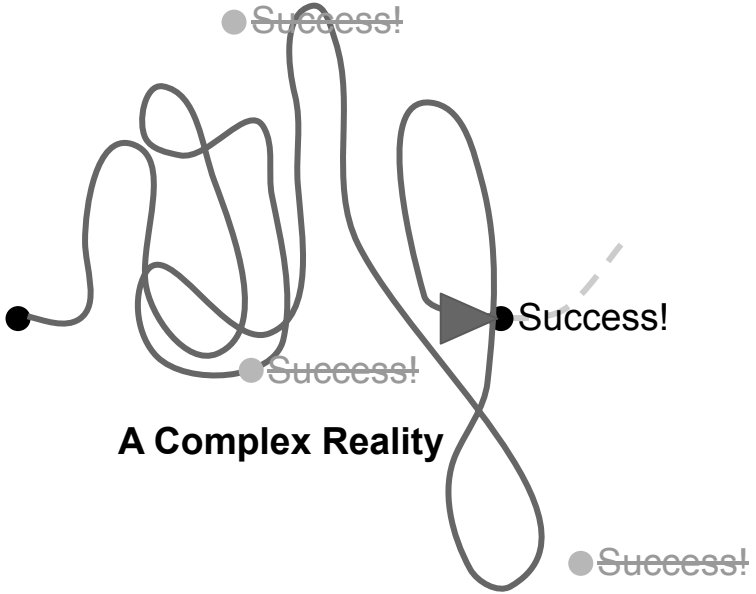
hello robot™

What have I learned?

Commercialization is truly open ended.
There are many roads to success.

Commercialization Trajectories

A Simple Story



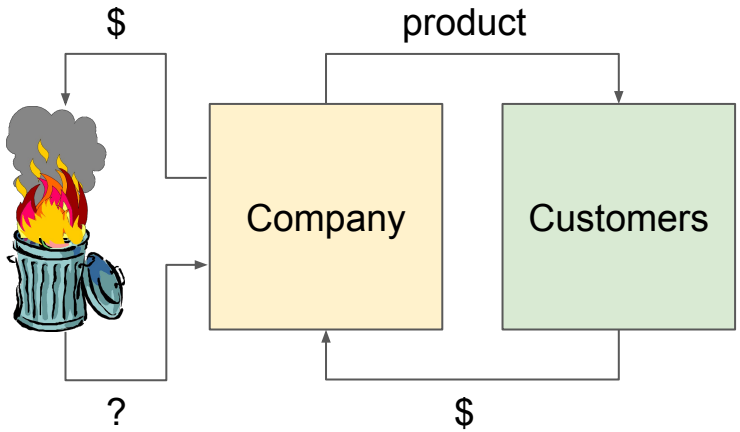
A Complex Reality

The Basics

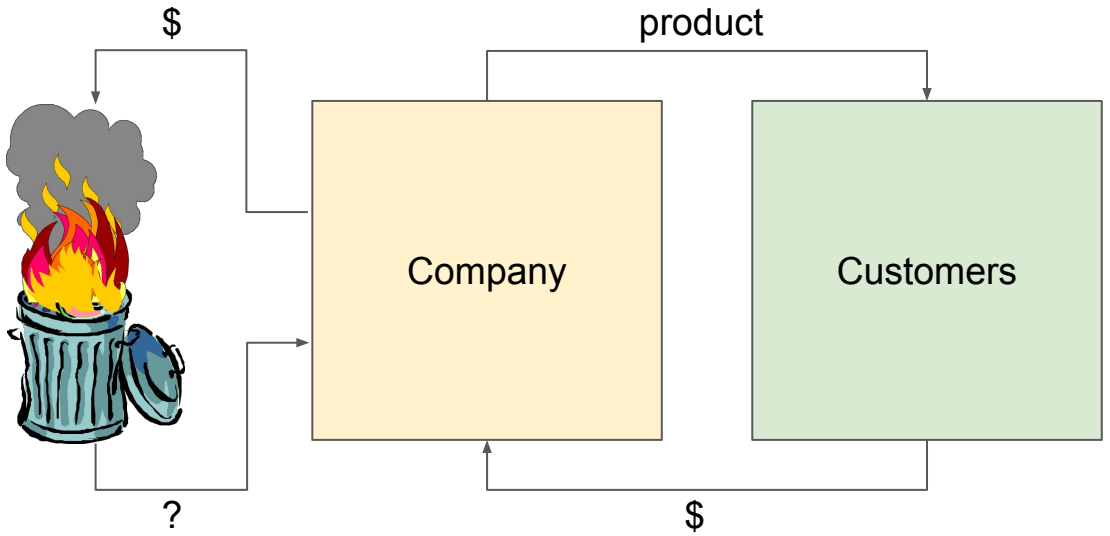
What is the product?

Who are the customers?

Can you make the math work?

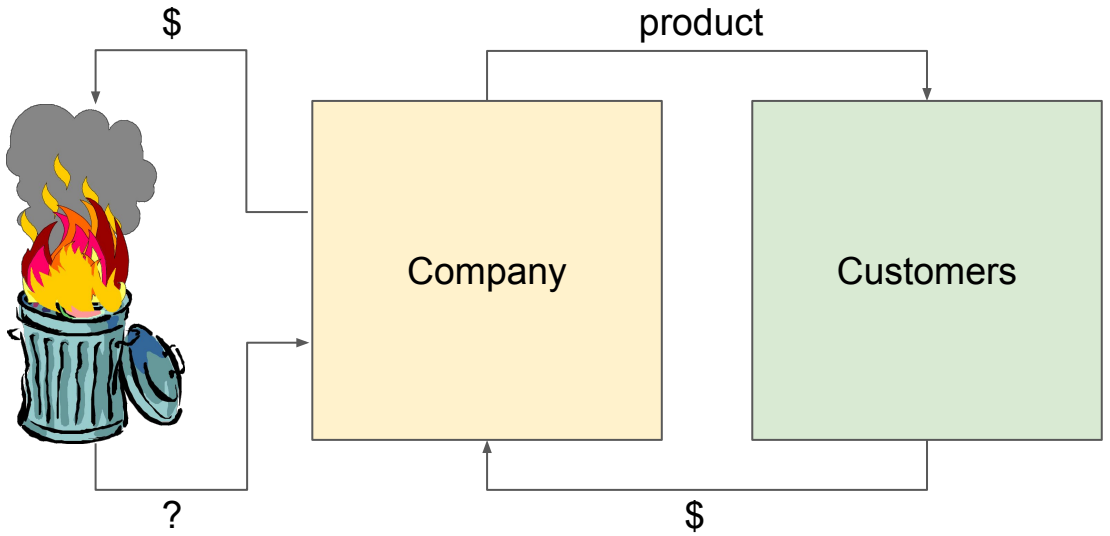


A Simple Model of Success



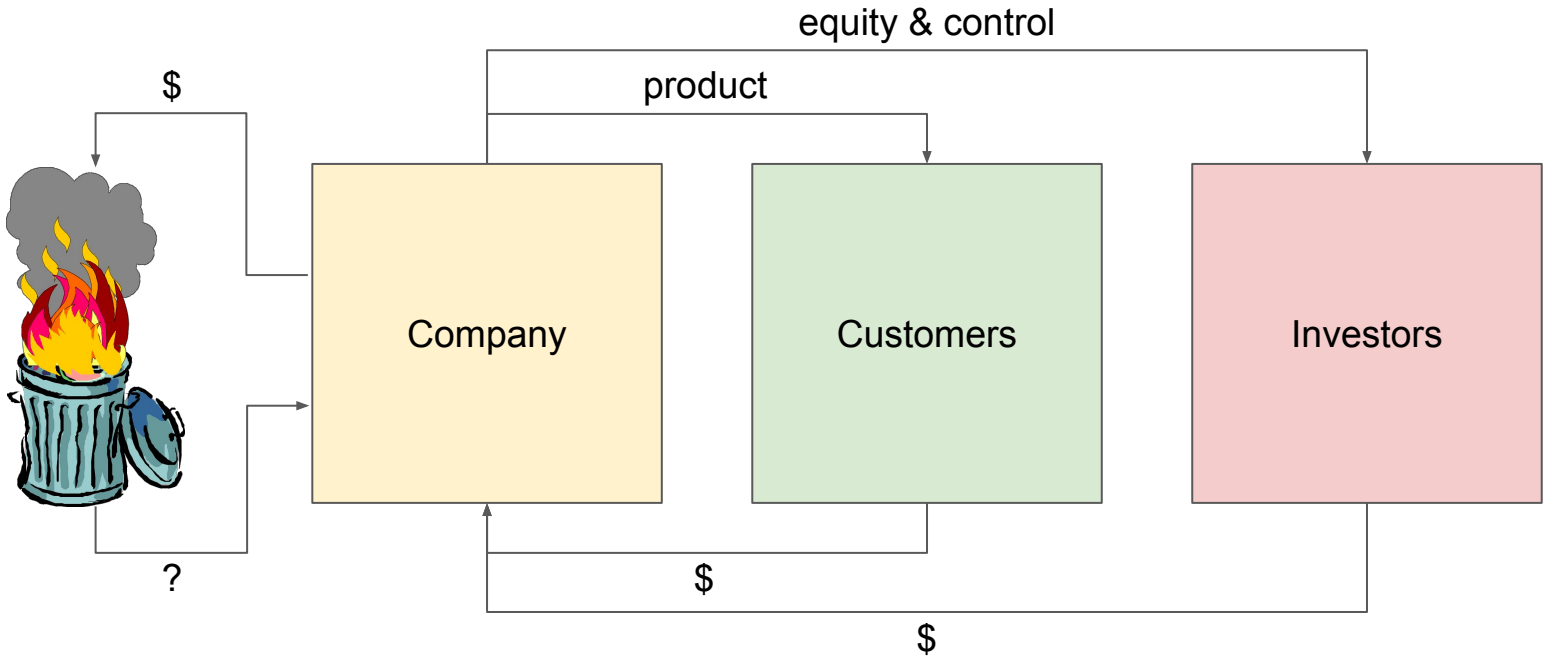
$$\int_0^T \$_{burned}(t) < \int_0^T \$_{from\_customers}(t)$$

A Simple Model of Success



$$reward = \int_0^T \left(\$_{from\_customers}(t) - \$_{burned}(t) \right)$$

Getting Started is More Complex



$$\int_0^T \$_{burned}(t) < \int_0^T \left(\$_{from\_customers}(t) + \$_{from\_investors}(t)\right)$$

Investment is Not Enough

anki®

$260M raised
Founded 2010
bankrupt April 2019

rethink robotics®

$150M raised
Founded 2008
sold assets October 2018

$73M raised
Founded 2012
sold assets June 2018

Mark Cuban

@mcuban

raising money isn't an accomplishment, its an obligation

https://twitter.com/mcuban/status/1373751313134202887

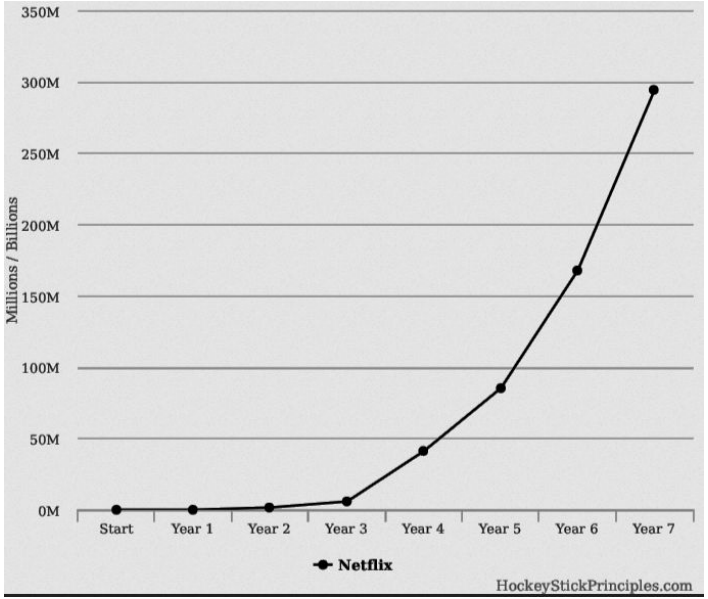
Venture Capital Funding Risks

- Lose control of the company
  - Board control
  - Ability to make big decisions
  - Equity ownership
- Lose focus on customers
  - Raising money takes resources
  - Optimize for investors instead of customers
  - Depend on investment instead of sales
- Raise the bar for success
  - Founders & employees get nothing if the company sells for less than the total money raised
  - High expectations
  - Increased burn rate ← **idle money has low return**

https://www.crunchbase.com/

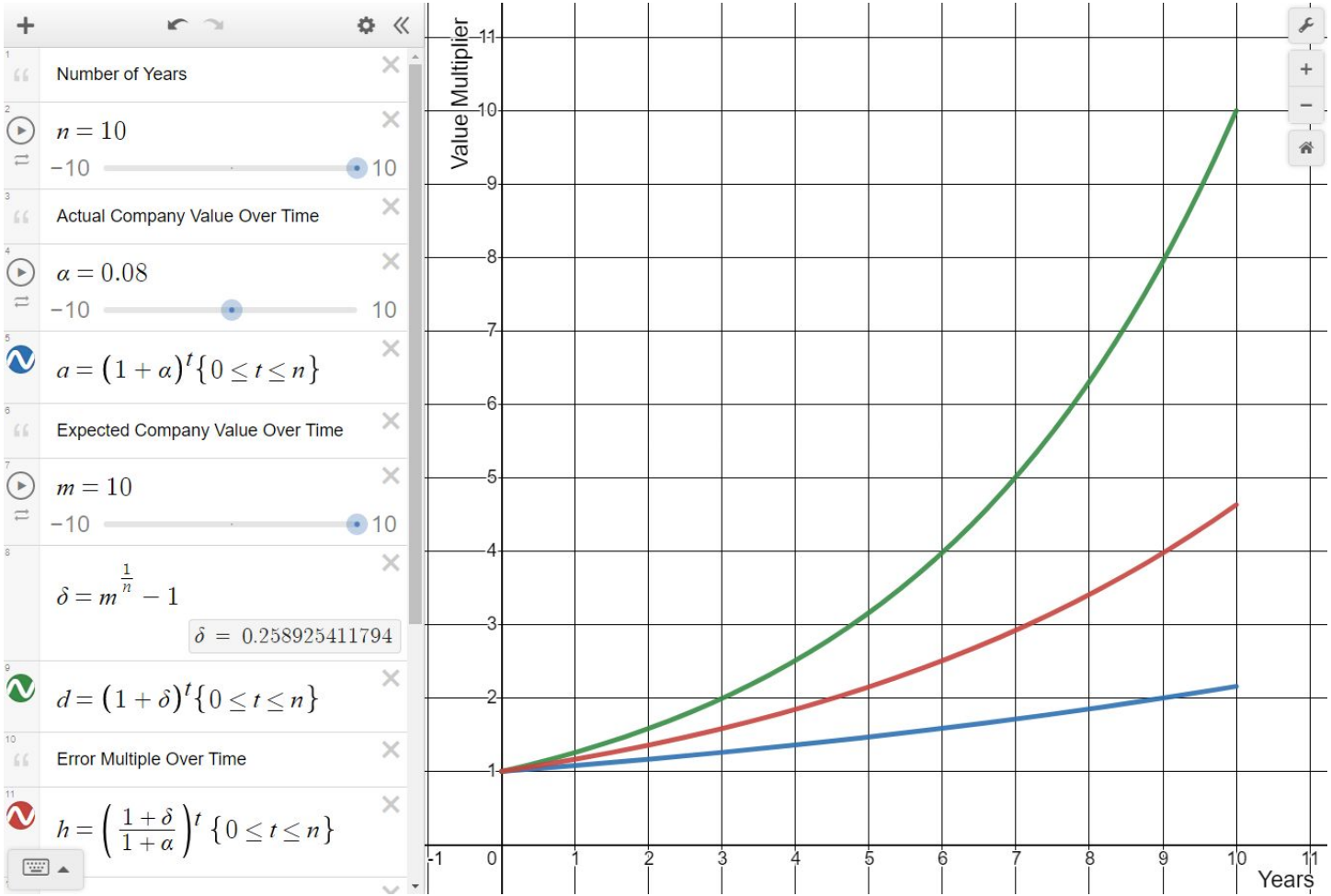
Do all investors expect a 10x return in 10 years?

- They expect most startups to die
- Their goals vary
  - Don’t just sell them on your company
  - Ask the hard questions
  - Assess how well your goals are aligned with theirs
  - Be honest with yourself about the match, it’s a long journey
- Most are looking for extreme returns
  - High-risk implies many investments go to zero
  - They need big wins for the numbers to work
  - 10x or greater is typical for venture capitalists
    - https://kruzeconsulting.com/blog/post/what-VCs-Return-Expectations/



A Common Goal: The Hockey Stick Chart

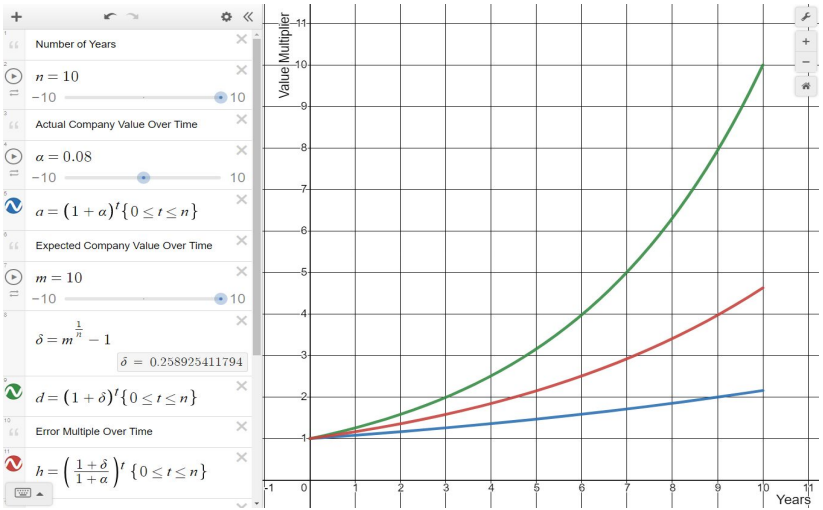
Exponential Error Between Investor Expectations and Reality

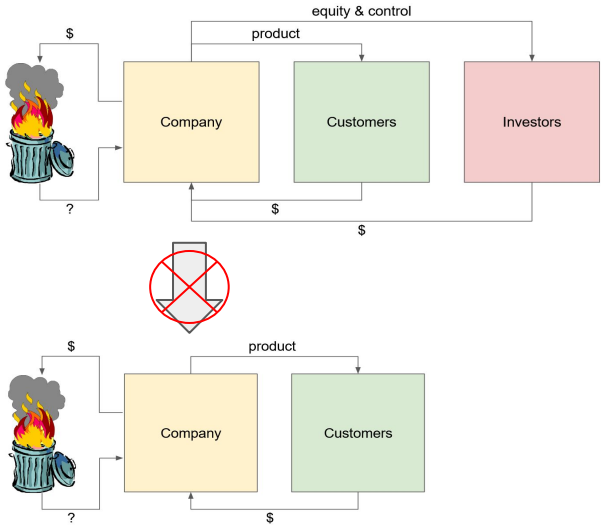


https://www.desmos.com/calculator/gdzwgcrbbl

Death of a Startup

- Valuation too high for new investors
- Unable/unwilling to switch to revenue-based business
- Reduced options due to lack of control
- There can be a real business inside with too many obligations





“For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.”

Richard P. Feynman, "Appendix F – Personal Observations on Reliability of Shuttle", NASA,1986.

https://en.wikipedia.org/wiki/Rogers_Commission_Report#Role_of_Richard_Feynman

Challenges for Robotics Companies

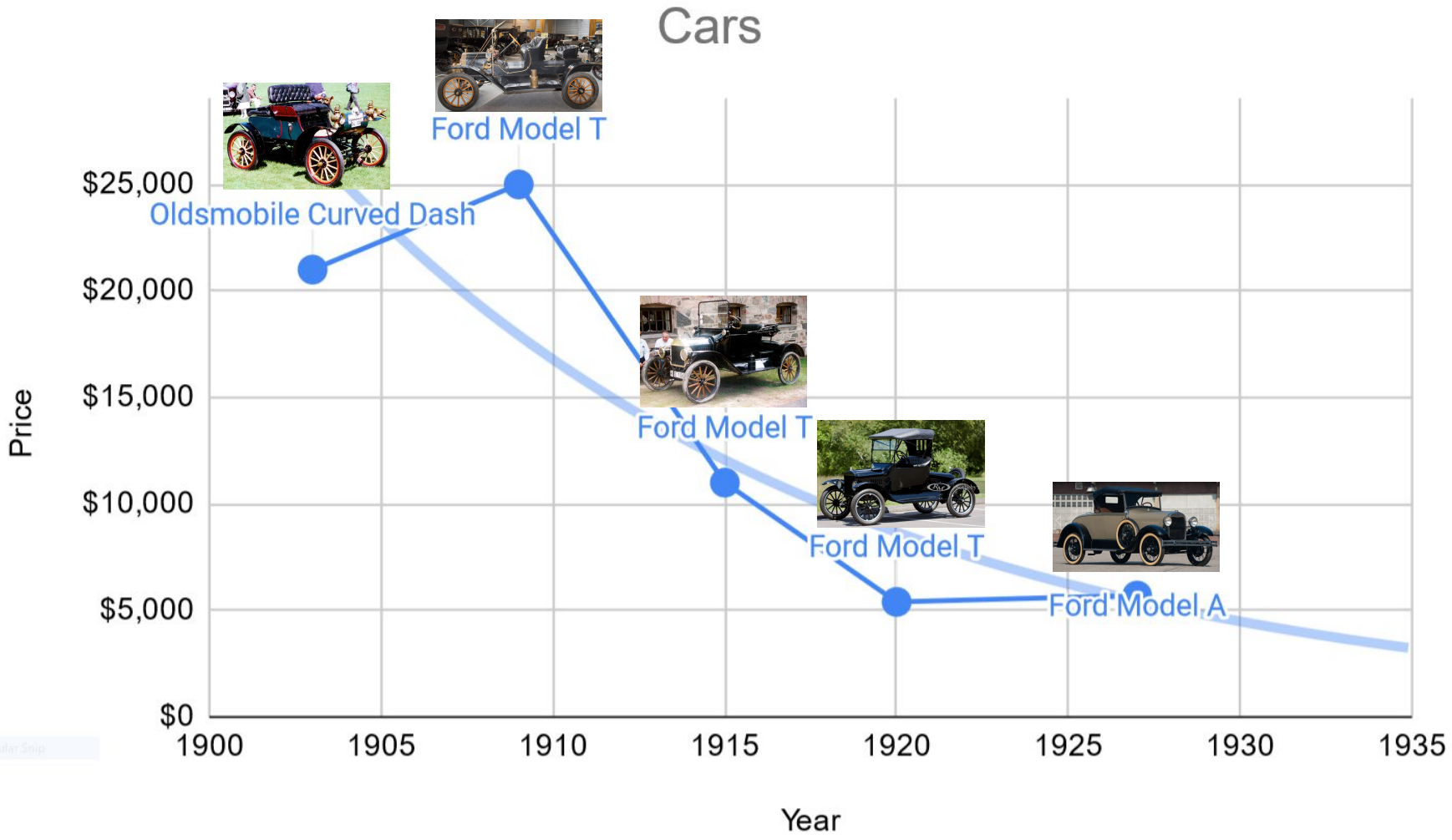
- You need more than a good robot
- Easy to overpromise
  - Humans make navigation and manipulation look easy
    - Driving cars
    - Picking up toys
  - Experts forget how hard the real world is
  - Videos hide complexity
- “Hardware is hard.”
  - Once it’s shipped, it’s hard to fix
  - Production & inventory
  - Many components
    - One USB 3 cable can kill
    - 50 parts with 99% yield => 39% chance of failure! = 1.0 - (0.99)^50 = 1.0 - 0.61

Challenges for Emerging Technologies

All prices inflation adjusted to 2020-2021 US dollars
Google Spreadsheet Used to Generate Graphs

Chicken-or-Egg Problems

- Which comes first?
  - Supply or demand?
  - The problem or the solution?
  - Applications or the robot?
- Emerging technologies
  - Are novel, reducing understanding
  - Are scarce, inhibiting learning and exploration
  - Have uncertain value, reducing demand that could increase prevalence
- Iteration is a useful heuristic for solving these types of problems


Cars
Ford Model T
Oldsmobile Curved Dash
Ford Model T
Ford Model T
Ford Model A
$25,000
$20,000
$15,000
$10,000
$5,000
$0
Price
1900
1905
1910
1915
1920
1925
1930
1935
Year

Cars

Ford Model T

Oldsmobile Curved Dash

Ford Model T

Ford Model T

Ford Model A

Price

$20,000

$15,000

$10,000

$5,000

$0

1900 1905 1910 1915 1920 1925 1930 1935

Year

Ford Model T Runabout

Price

$25,000
$20,000
$15,000
$10,000
$5,000
$0

1908 1910 1912 1914 1916 1918 1920 1922 1924 1926 1928

Year

Computers

DEC PDP-8

DEC PDP-11

Apple II

IBM PC

Apple IIe

Price

$160,000
$140,000
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$0

1965
1970
1975
1980

Year

Mobile Phones

Motorola DynaTAC

Nokia 1011

Treo 650

iPhone

Price

$11,000
$10,000
$9,000
$8,000
$7,000
$6,000
$5,000
$4,000
$3,000
$2,000
$1,000
$0

1980
1985
1990
1995
2000
2005

Year

Robot Arms

Unimate

PUMA

Kinova Jaco

Panda

Price

$280,000
$260,000
$240,000
$220,000
$200,000
$180,000
$160,000
$140,000
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$0

1970
1980
1990
2000
2010
2020

Year

Mobile Manipulators

PR2

Fetch

PAL Tiago

Stretch

Price

$450,000
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0

2010
2012
2014
2016
2018
2020

Year

Not All Emerging Technologies Become Personal

1903,The Wright Flyer
https://en.wikipedia.org/wiki/Wright_Flyer

Only 16 years!

1919 - Today
https://en.wikipedia.org/wiki/Airliner

2018 - Today, Volocopter 2X
https://en.wikipedia.org/wiki/Volocopter_2X

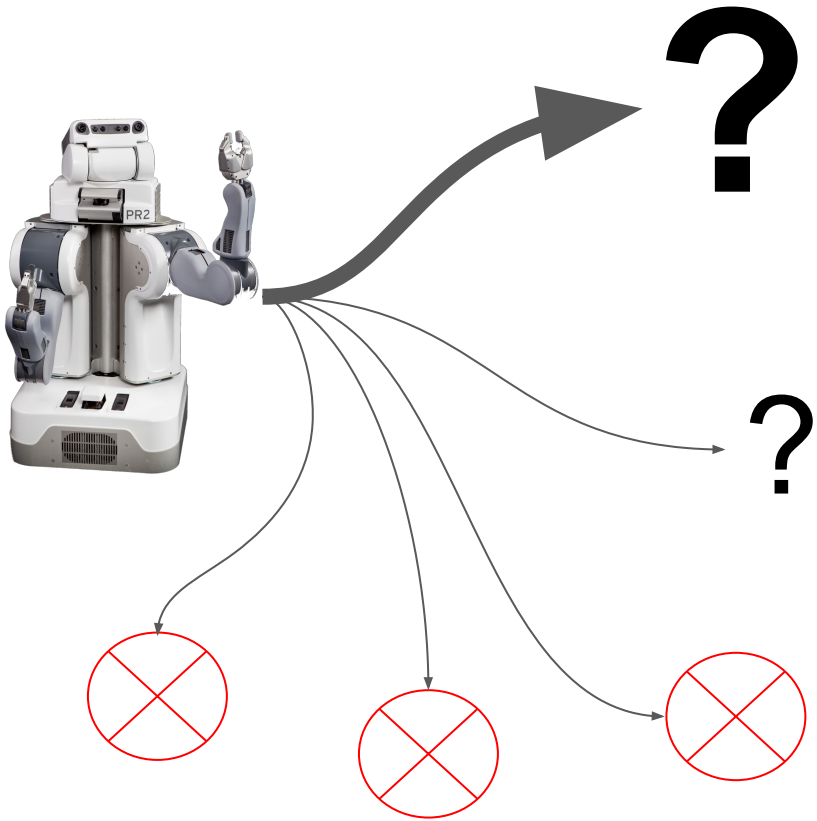
1940, Jess Dixon's flying automobile
https://en.wikipedia.org/wiki/Flying_car

1947, Convair Model 118
https://en.wikipedia.org/wiki/Convair_Model_118

1973, AVE Mizar
https://en.wikipedia.org/wiki/AVE_Mizar

https://en.wikipedia.org/wiki/Flying_car
https://en.wikipedia.org/wiki/The_Jetsons

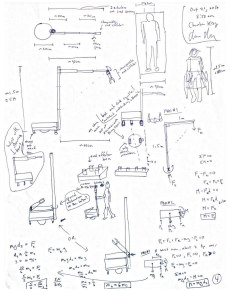
Society has to Discover Where An Emerging Technology Fits In



New Devices are Just the Foreground

Commercialization

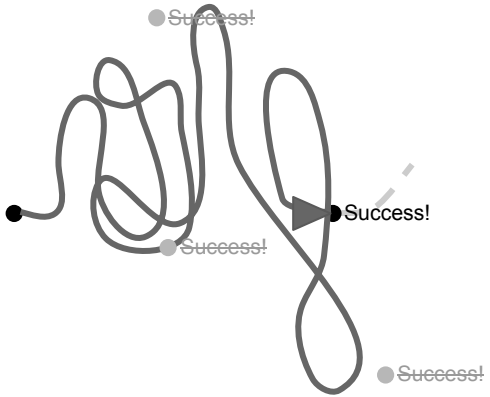
- Is open ended with many roads to success
- Depends on customers not investors
- Can empower people to create the future

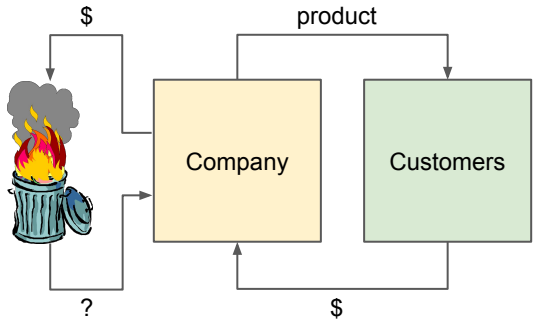


2016	2017		2018	2019	2020

Outline

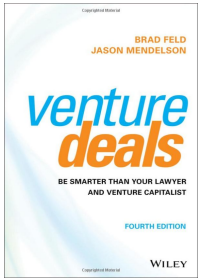
- My commercialization story
- A simple startup model
- Challenges for emerging technology

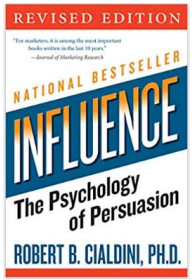


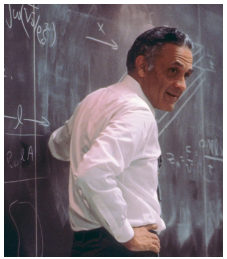


Question & Answer Session

Learning Resources I've Found Valuable

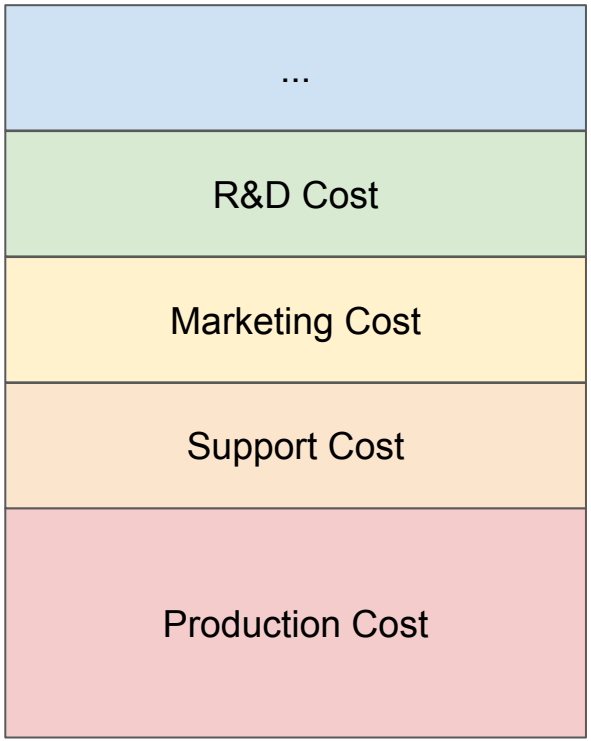


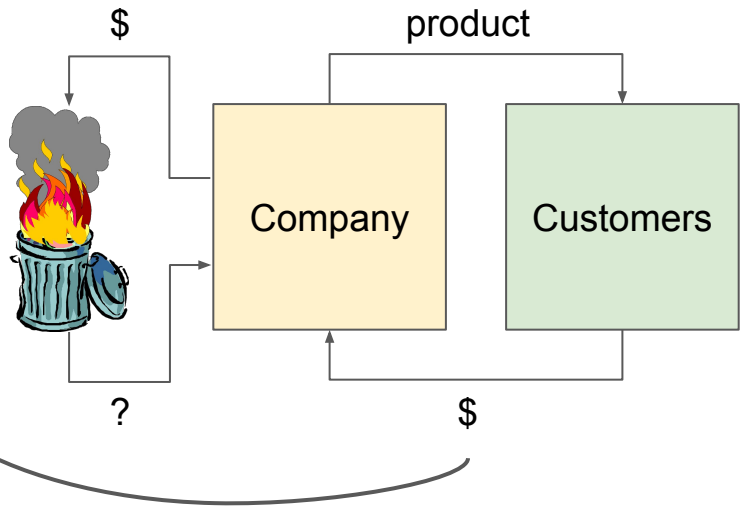




- Shark Tank
- How I Built This with Guy Raz
- Venture Deals
  - by Brad Feldman and Jason Mendelson
- Influence: The Psychology of Persuasion
  - by Robert B. Cialdini
- The late Prof. Amar Bose
  - I took his class in the fall of 1994, and still think of it often.
  - https://teachingexcellence.mit.edu/category/inspiring-teachers/amar-g-bose-6-312-acoustics

What's in a price?





$$\int_0^T \$_{burned}(t) < \int_0^T \$_{from\_customers}(t)$$

Is the price right?

- Take your customers' perspective when selecting a price
  - What is their price sensitivity?
  - What are their alternatives?
  - Will they decide to buy and be happy with their purchase?
- Too high
  - Not enough people buy the product
  - Limited growth in terms of revenue and profit
  - Risk of competitor capturing the market
- Too low
  - Risk of selling the product at a loss
  - Risk of misestimating the true cost
  - Customers have less incentive to make a careful decision, so they may be a poor match for your product.

https://en.wikipedia.org/wiki/The_Price_Is_Right_(American_game_show)
Image from: https://www.buzzfeednews.com/article/terripous/showcase-showdown