Robotics: Shaped By and Shaping the World in 2000 to 2050

Rodney Brooks

Panasonic Professor of Robotics, MIT CSAIL

Co-Founder, iRobot

CTO & Chairman, Heartland Robotics

iRobot®

Arthur C. Clarke said:

When it comes to technology most people overestimate it in the short term and underestimate it in the long term.

We are currently suffering from the fallout from that overestimate for robotics, and we are not yet beyond the world's underestimate.

"A SHOCKER!
FASCINATING!"
– New York Daily News
"A sizzler! Builds to high tension!"–
Smooth suspense! Full-out enter-
imaginative! The best I've seen in a long
"Practically perfect"–Vincent Canby, New York Times
Gene Shalit, NBC Radio Monitor "Razzle Dazzle!
tainment!" – Time Magazine "Wildly
time" – Bernard Drew, Gannett Newspapers
"Suspense is intense" – American Girl
THIS IS THE DAWNING OF THE AGE OF
COLOSSUS
THE FORBIN PROJECT
ERIC BRAEDEN·SUSAN CLARK·GORDON PINSENT
Screenplay by JAMES BRIDGES · Based on the Novel
"Colossus" by D. F. JONES · Directed by JOSEPH SARGENT · Produced by STANLEY CHASE · A UNIVERSAL PICTURE · TECHNICOLOR® PANAVISION®
GP

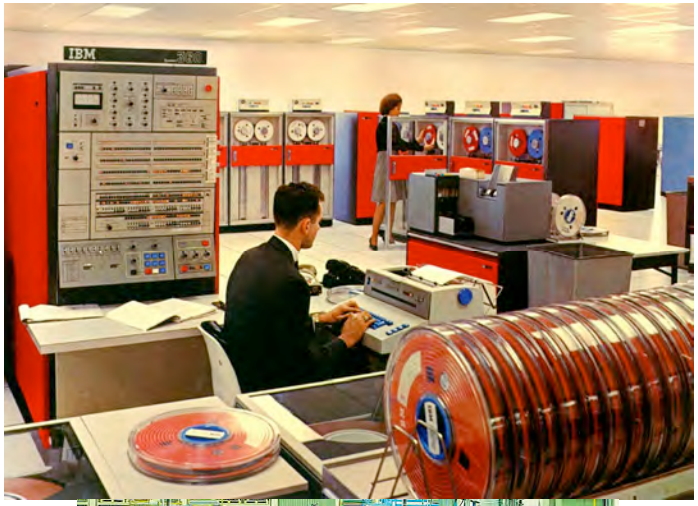
COLOSSUS TO GUARDIAN

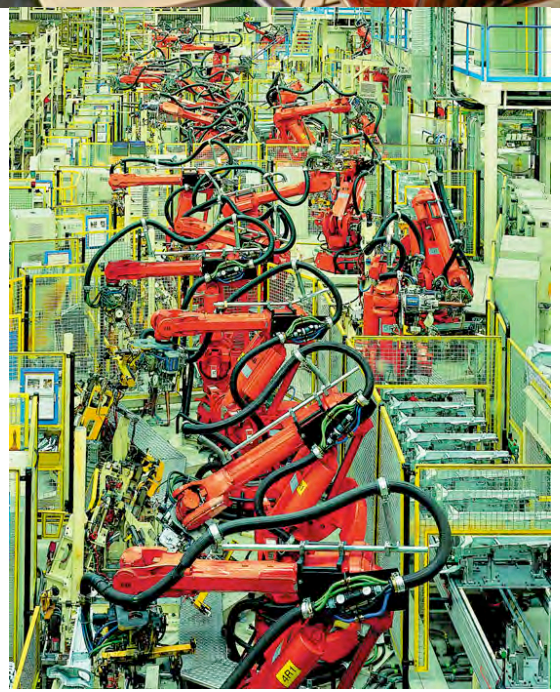
GUARDIAN TO COLOSSUS
6X1=6
5X1=5
COLOSSUS
GUARDIAN

© Paramount Pictures

9:42 AM
Frank's Pizza
The New York Times
John Appleseed
calling...
End Ca

Two Revolutions





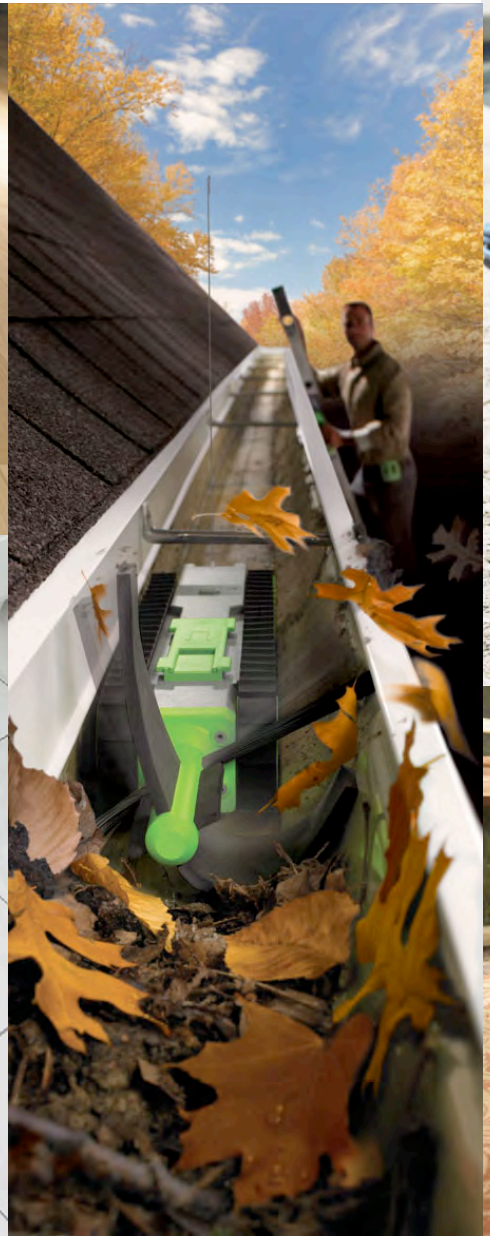
- Was
  - large corporate back room operation
  - automation slow and by specialized engineers
- Now
  - personal machines
  - office workers automate their own work and increase their own productivity

Who gets to directly interact with the robot???

Hockey Stick Growth: Deployed Mobile Robots

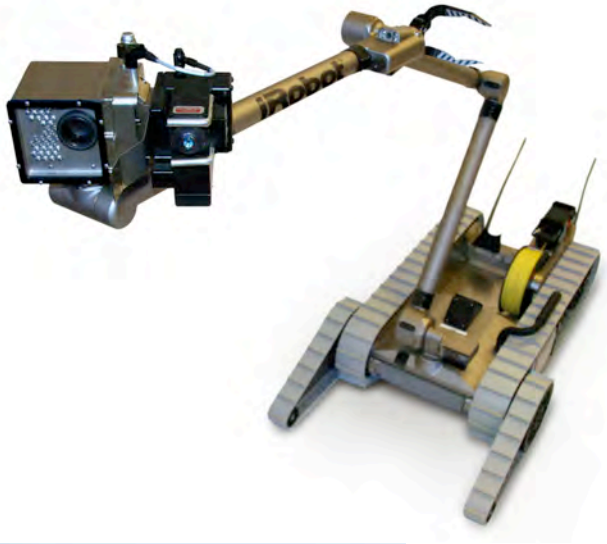
	US Military	US Homes
Summer 2002	0	0
December 2007	> 5,000	> 3,000,000

iRobot: Home Robots

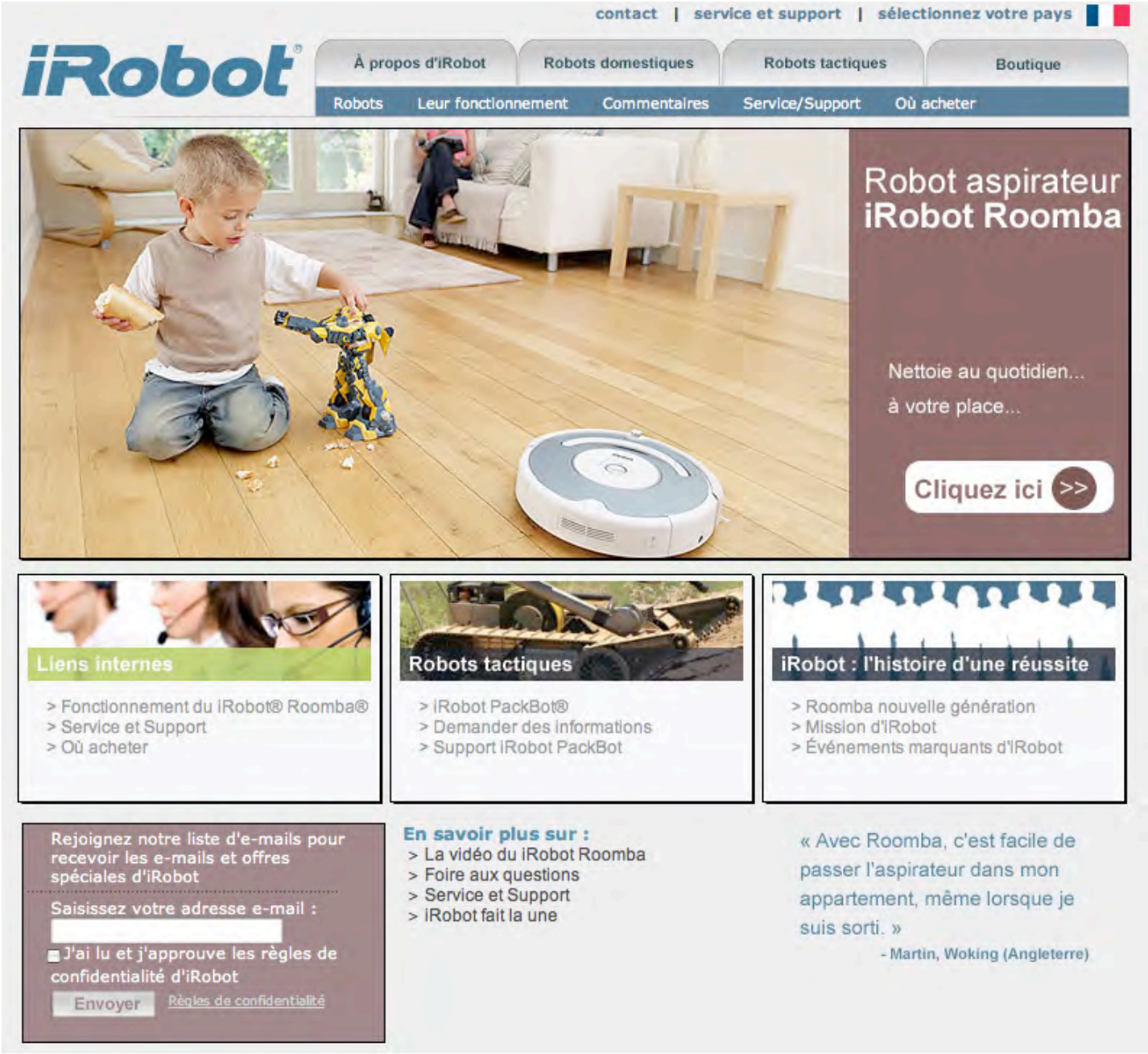


Crossing the Chasm

iRobot: Military Robots



http://www.irobot.com/fr



CSAIL

From DARPA

1998 Concept

To AFGHANISTAN

2002 Reality

Some Learning Curve

PackBot EOD

Two way audio

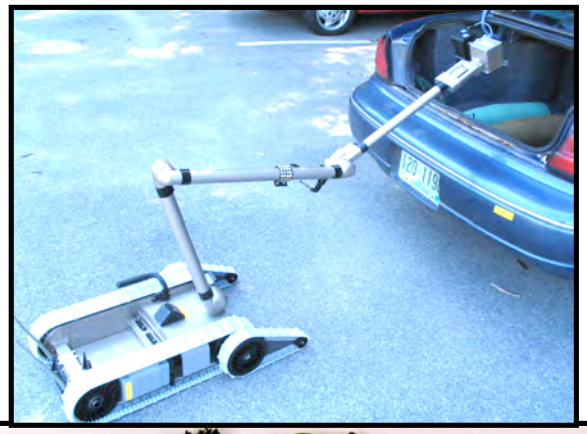
LED illumination bank

2 Gripper Cams w/ illumination

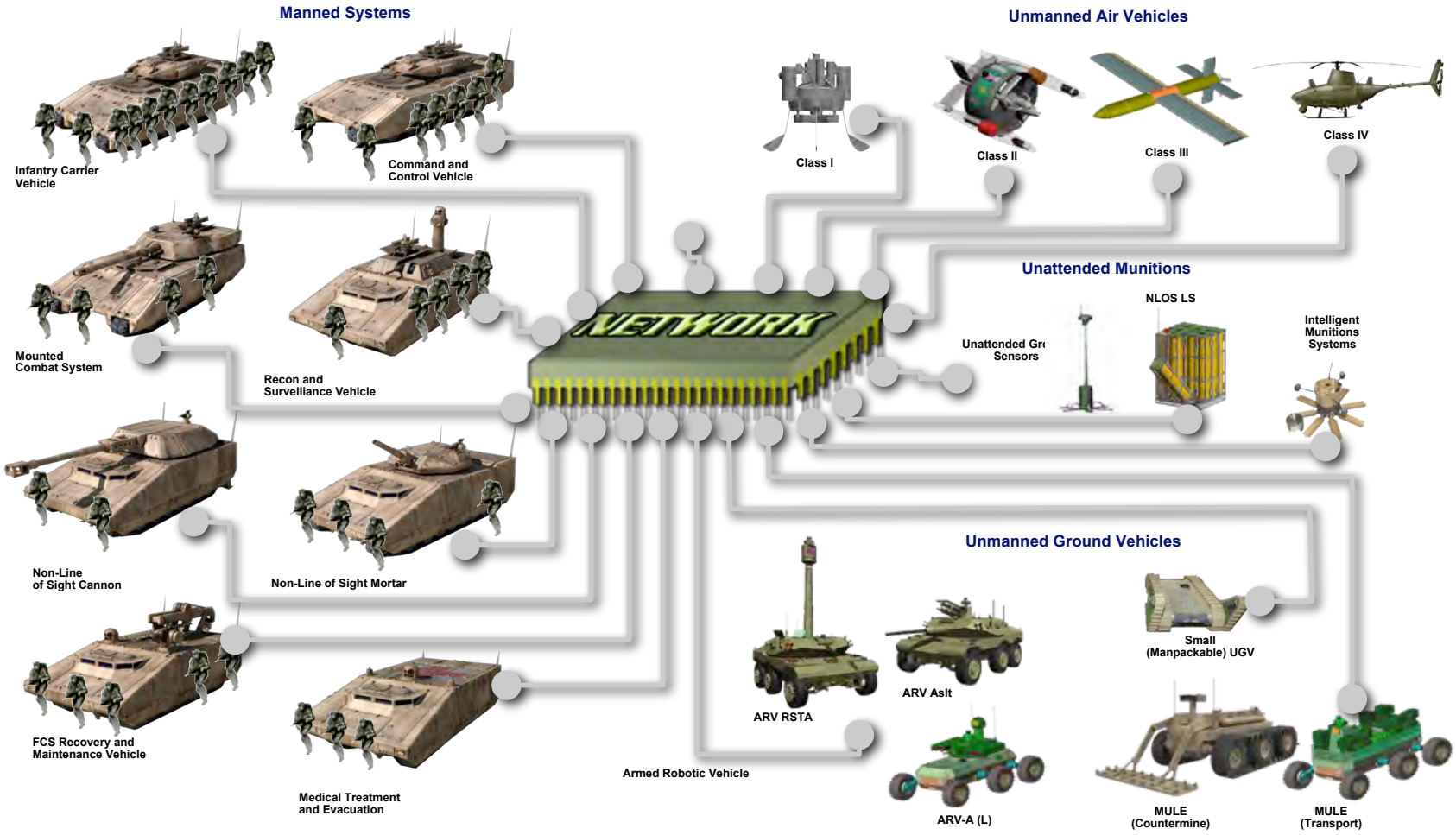
300X Zoom Camera with Low Light mode

115deg FOV Drive Camera on rotating mount

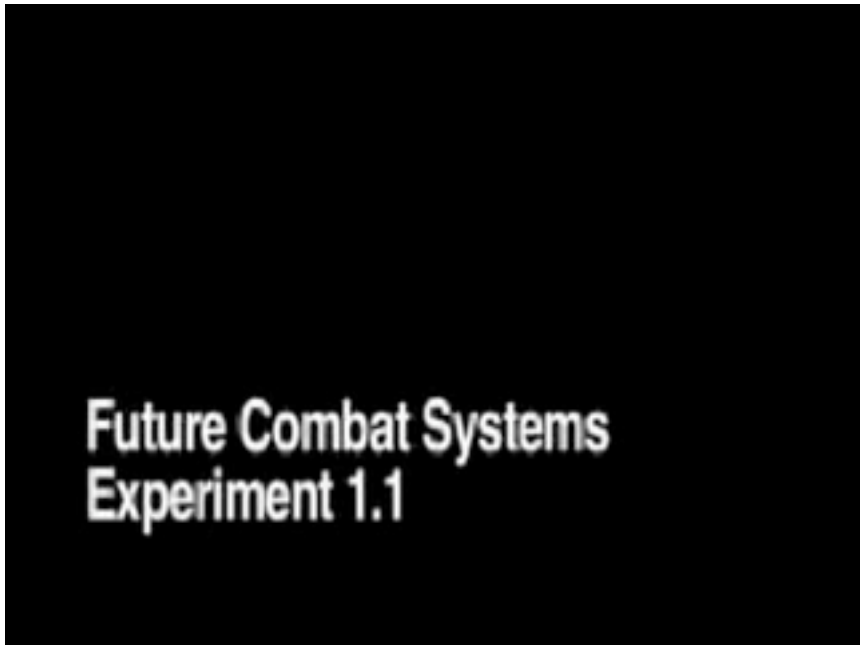
PackBot in Iraq



Future Combat Systems



FCS Experiment 1.1, Jan 2007



SUGV in Media from Exp. 1.1

Army News Service, Feb. 13, 2007

"Instead of sending 'Private Snuffy' in the room to see if there is a booby trap, you send a robot in there." ...COL. Bush

"It would have saved our lives."... Soldier

SUGV at Exp. 1.1

After Action Review

Big Trends for Robotics

- Technology exponentials driven by others
- First technology exponentials driven by robots

- Large scale military robot deployments
- Larger scale home robots deployments

- Aging population
- Increased health costs
- Immigration backlash
- Globalization backlash
- Future of transportation
- Carbon neutral energy

The experts look ahead

Electronics, Volume 38, Number 8, April 19, 1965

Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

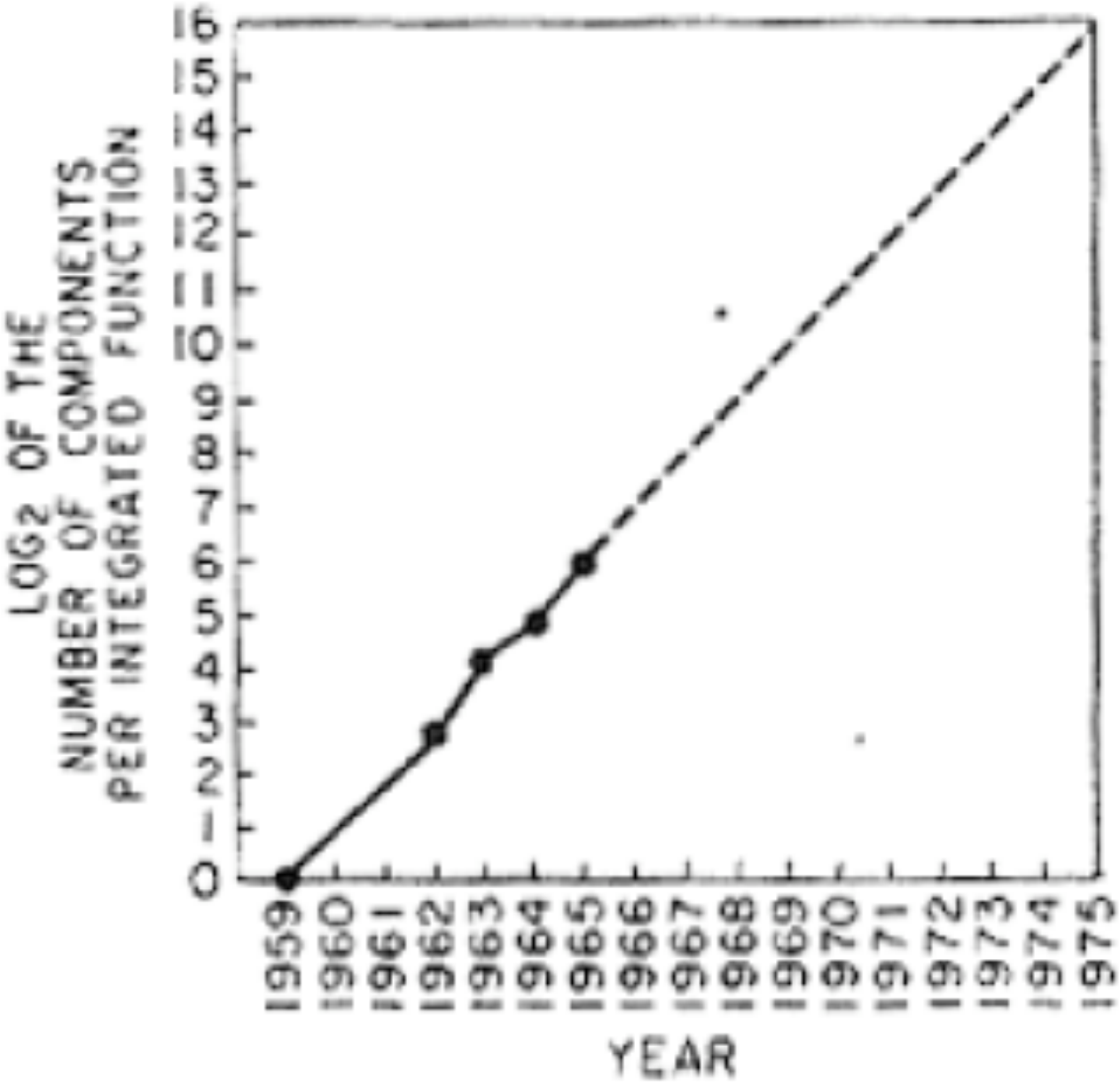
Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

Radical Insights

The future of integrated electronics is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

Integrated circuits will lead to such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today.

The Key Graph

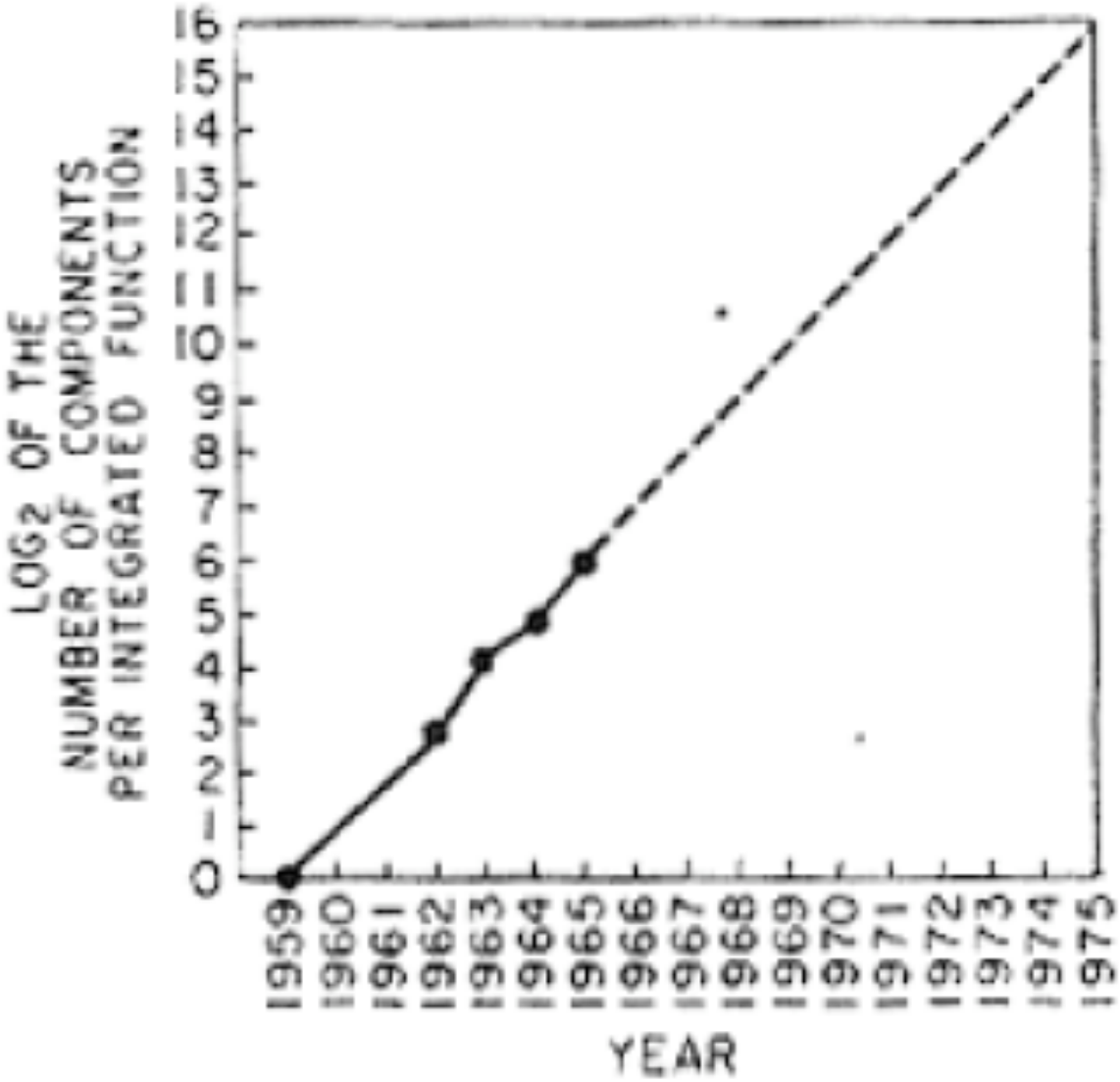


What Defines an Exponential?

$$\frac{ds}{dt} = \alpha s$$

- The rate of change of "stuff" is proportional to the instantaneous amount of "stuff" that is around already
- Is this the explanation for how computer power has been an exponential?
- Does the presence of computers of power P make it easier to build a computer of power wP, where w>1?

But Not in Play in 1965



Stories We Wish Were True

This part is true:

In the 80's Steve Jobs bought the latest Cray Supercomputers to simulate Macs ahead of time to develop software

The part that one hopes is true:

On hearing this Seymour Cray said: "That's funny, I just bought a Mac to design the next Cray."

Three Exponential Forms

1. Rate of improvement is proportional to the current level of adoption

2. The existence of the law tells everyone what level to aim for when

3. Someone else is driving an exponential and you get to hop on it for free

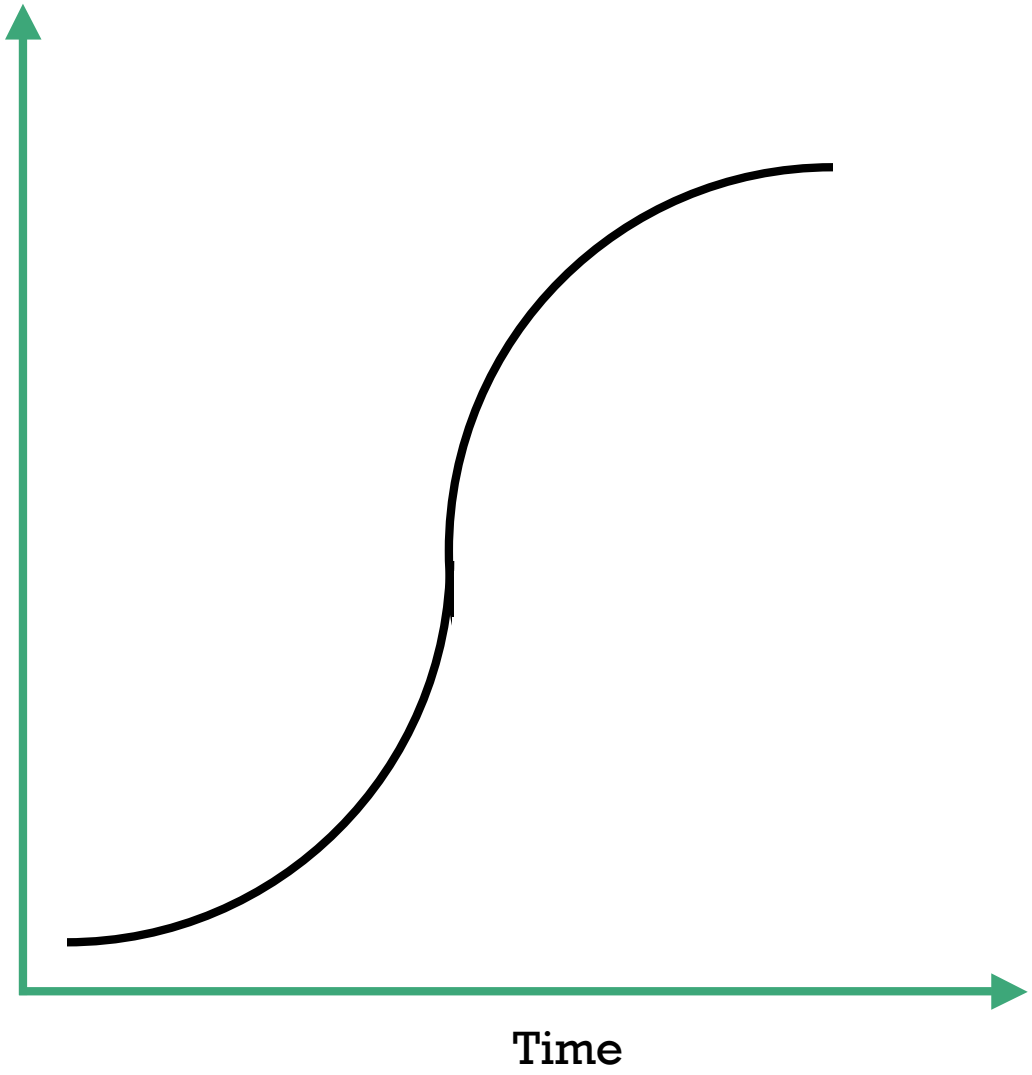
Moore's Law

- Even Gordon Moore is worried there is only another 10 years left
- "Solution" is multi-cores
  - BUT, parallel programming is not solved
- [At the same time handhelds are driving down power consumption]
- BUT, BUT, our robots can probably easily utilize 8 or so cores, without general parallel programming
  - dedication of individual cores to full blast processing (e.g., video comp., SLAM, etc.)
  - i.e., good days are here for robots

iPod as Current Storage Standard

- Mid 2003: 10 Gigabytes -- teenager price ($400), fits in pocket. Enough for most people's personal music collection.
- Mid 2004: 20 Gigabytes
- Mid 2005: (on Apple Web site):
  - 20 GB = $249
  - 30 GB = $349
  - 60 GB = $449 (sold as iPod Photo)
- Jan 2006 (on Apple Web site): 60 GB, $399 (thinner)
- Sept 2006 (finally): 80 GB, $349 [20,000 songs, 100 hrs video]
- Sept 2007: 160 GB, $349 (same Aug 20, 2008)
- Doubling every year $\$400 = 2^{(\text{year}-2003)} \times 10 \text{ Gigabytes}$
- That means an iPod in 2025, $400, will have
  - 40,000,000 Gigabytes
  - or 40 Petabytes
- Sept 2008: 120 GB, $249
- Now Flash size is following, lagging by exactly four years

Exponential Reality -- S Curve



Exponential Consequence

Future robots, disconnected from the net, can have enormous onboard databases.

Exponentials and pseudo-E's for Robots

- Amount of computation
- # of cores on chip
- Onboard memory
- Pervasive wireless communication bandwidth
- Cost of sensors
  - cameras
  - auto collision sensors
  - nanotech-based sensors
- Installed base
  - user acceptance/familiarity
  - # of offerings
- Massive data sets on the WWW
  - machine learning
  - new vision algorithms
- Performance of speech systems
  - vocabulary, speaker independence, noise env.
- Smart automobiles
- Robots as teaching vehicles
  - college and high school

Costs of Mechanical Components

	1993	1999	2000	2001	2003	2005	2006
Linear Bearing	$9.69	$10.02	$10.42	$10.71	$10.71	$11.60	$12.00
Ball Screw / inch	$2.12	$2.26	$2.26	$2.34	$2.39	$2.75	$2.75
Ball Nut	$124.09	$131.84	$131.84	$136.72	$139.46	$153.35	$155.65
Flexible Coupling	$17.58	$21.75	$22.30	$22.85	$22.85	$22.85	$22.85
Miter Gear	$11.57	$15.06	$13.02	$13.02	$13.40	$15.05	$15.76
100 MIPS[4][1]	$47.62	$2.78	$1.72	$1.06	$0.41	$0.16	$0.10
Relative C.P.I.[2]	1.000	1.055	1.138	1.222	1.219	1.305	1.476

Table A.1: Price trend data of precise mechanical parts and computation over time.[2]

Name	Description	McMaster-Carr
Linear Bearing	1/4"x1/2"x3/4" Frelon Lined Linear Bearing	#5986K2
Ball Screw / inch	1/2" Ball Screw (0.5" lead, 4150 Steel)	#5966K25
Ball Nut	1/2" Ball Nut (Mates with #5966K25)	#5966K15
Flexible Coupling	1/4"x1/4" (7 degree max) precision coupling	#6208K22
Miter Gear	Steel 20 degree Miter Gear (12px15x1/2" bore)	#6529K15

Relative Mechanical Costs over Time

	1993	1999	2000	2001	2003	2005	2006
Linear Bearing	1.000	0.980	0.945	0.904	0.907	0.917	0.839
Ball Screw/inch	1.000	1.010	0.937	0.903	0.925	0.994	0.879
Ball Nut	1.000	1.007	0.934	0.902	0.922	0.947	0.850
Flexible Coupling	1.000	1.173	1.115	1.064	1.066	0.996	0.881
Miter Gear	1.000	1.234	0.989	0.921	0.950	0.997	0.923

Yearly increase multiplier for [instructions executed/second/$]

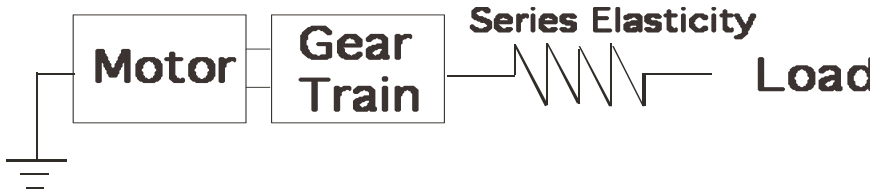
- Based on 1950-2000 data; perhaps it is getting faster, but assume constant (consv.).
- Factor is 1.45/year. Doubles in 1.88 years.
- E.g., 1MIP/$ in 1998 ==> 1.45MIP/$ in 1999
- Compared to a robot in 2008 this is how much computer power we'll have for same priced robot if we spend the same portion of COGS on computation

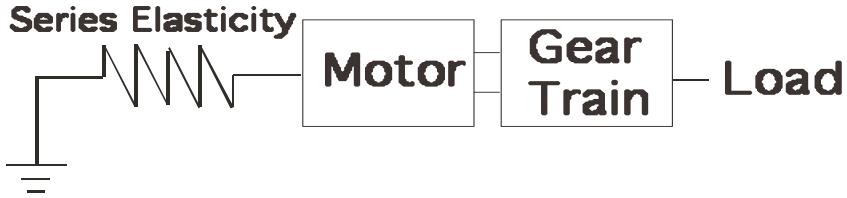
2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
1.00	1.45	2.09	3.02	4.37	6.31	9.12	13.2	19.1	27.5	39.8

Exponential Consequence

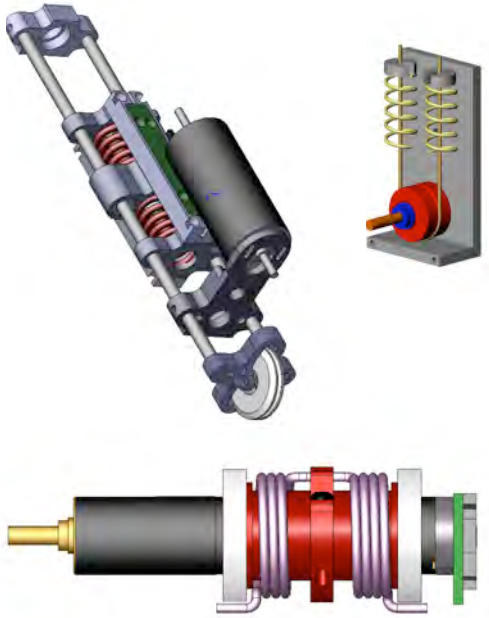
When computation can be used to replace mechanical precision robots will get cheaper over time.

Series Elastic Actuators



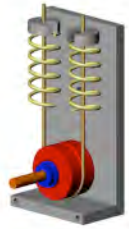


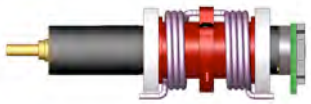
$$F=-kx$$



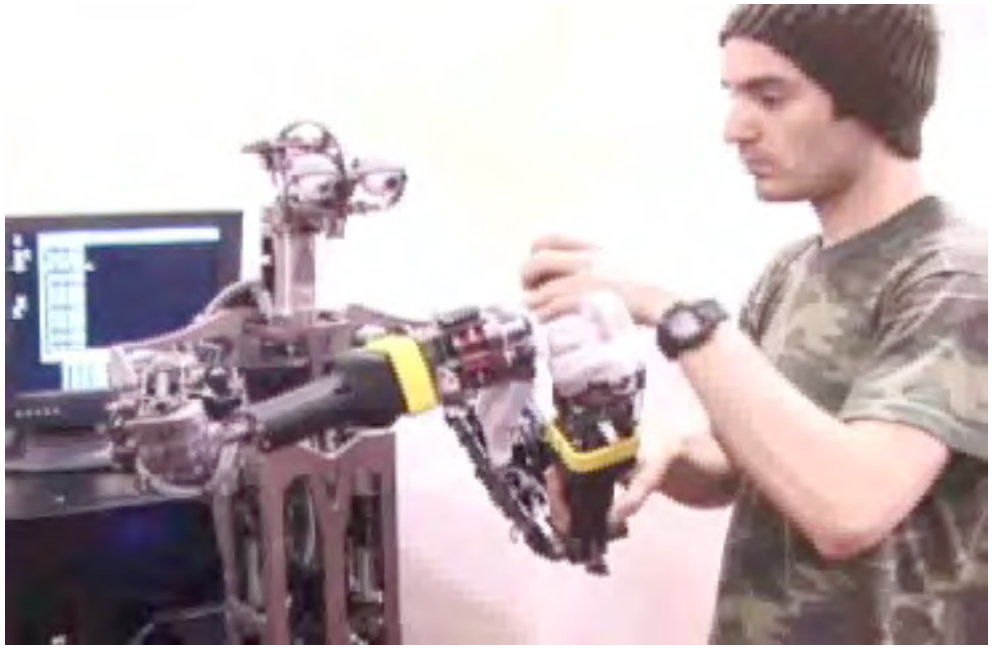
Features of SEAs

- Mechanically simple
- Improved stability
- Shock tolerance
- Highly backdrivable
- Low impedance at high frequencies

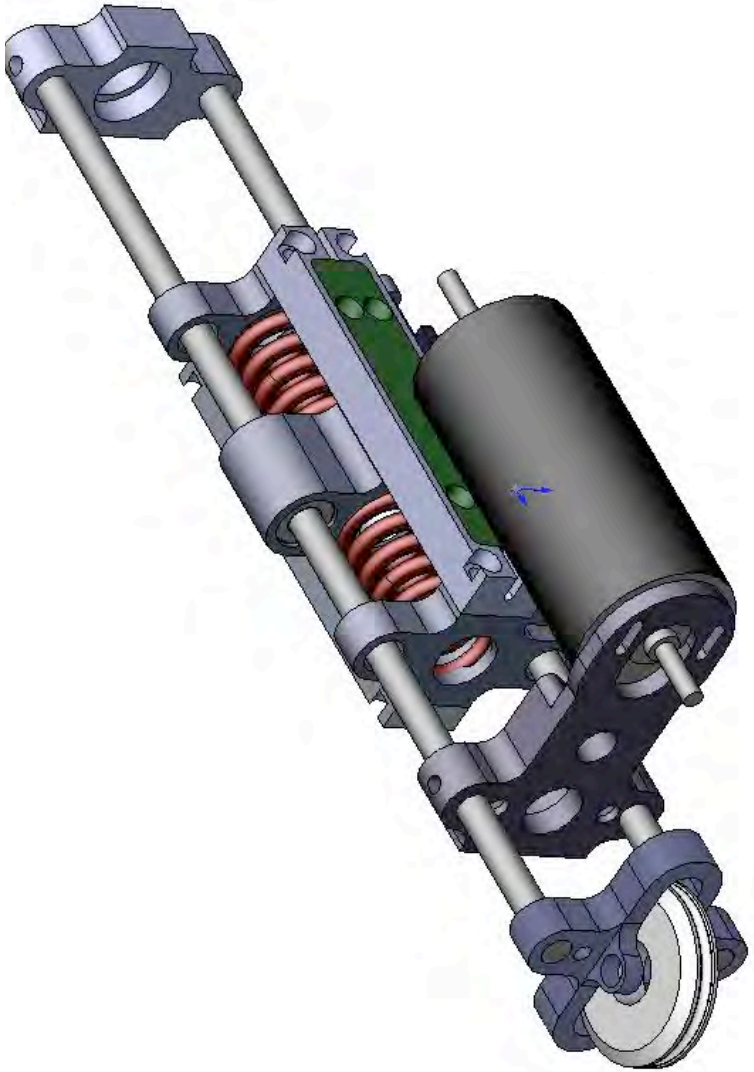


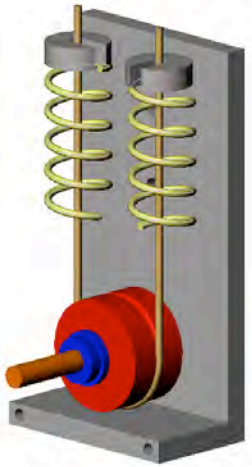


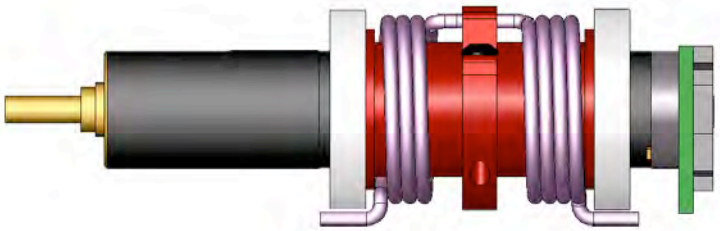
Safe For Human Interaction



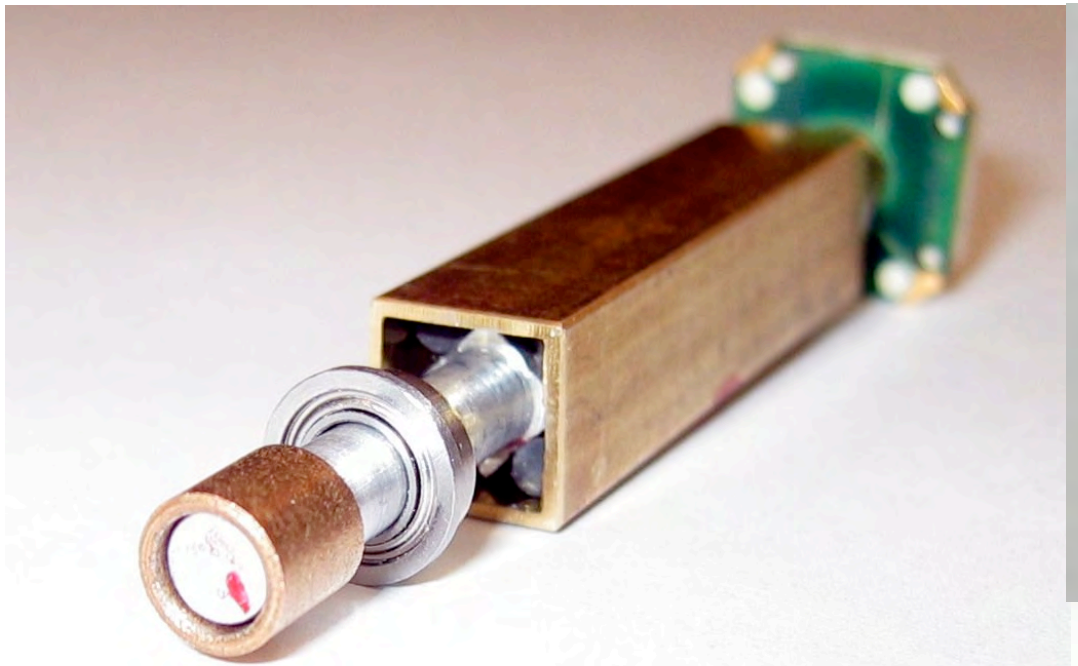
Series Elastic Actuators

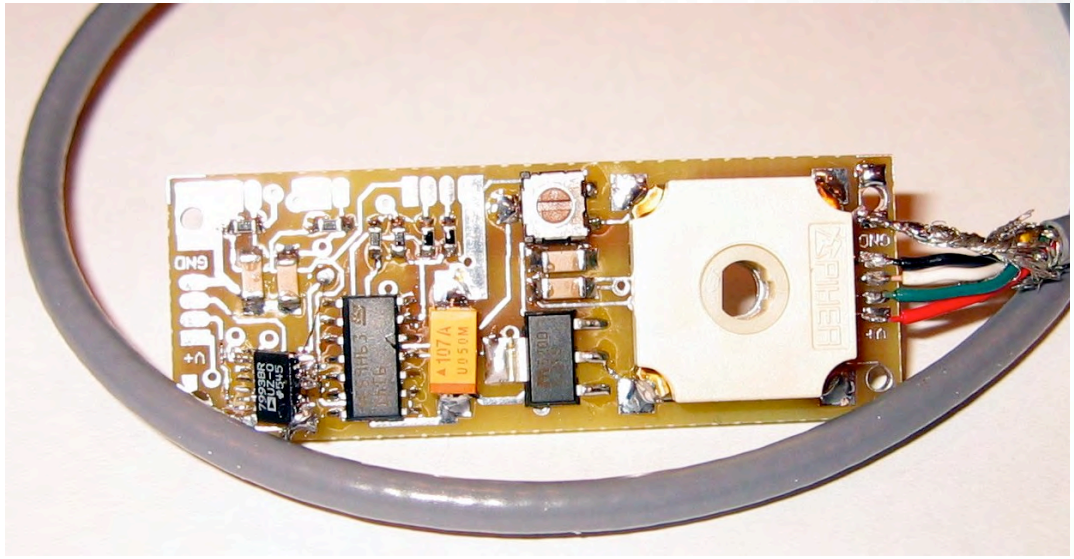


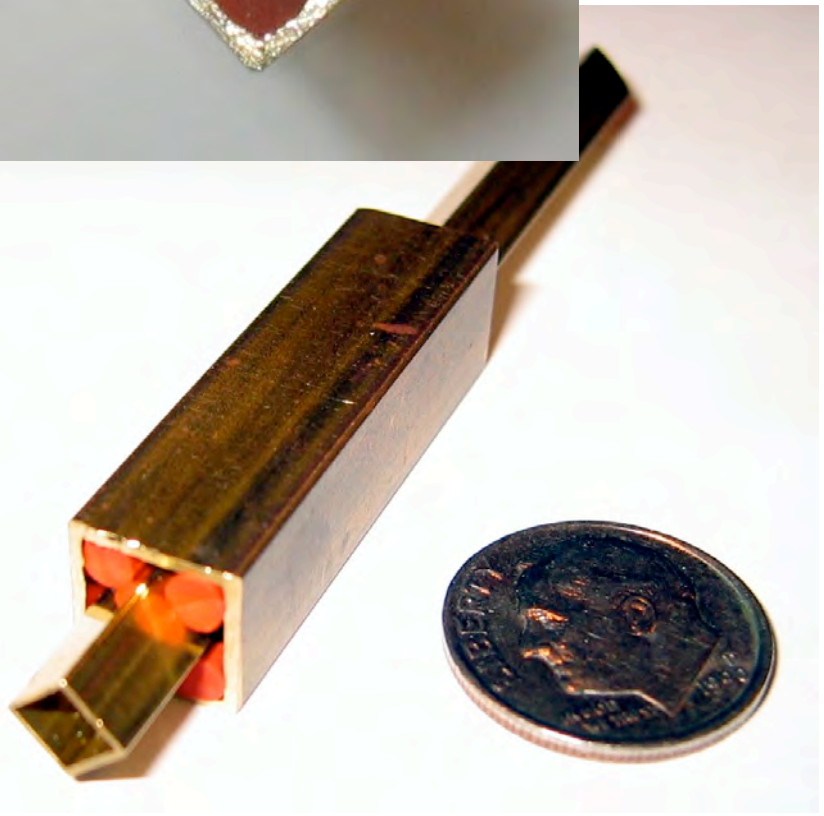




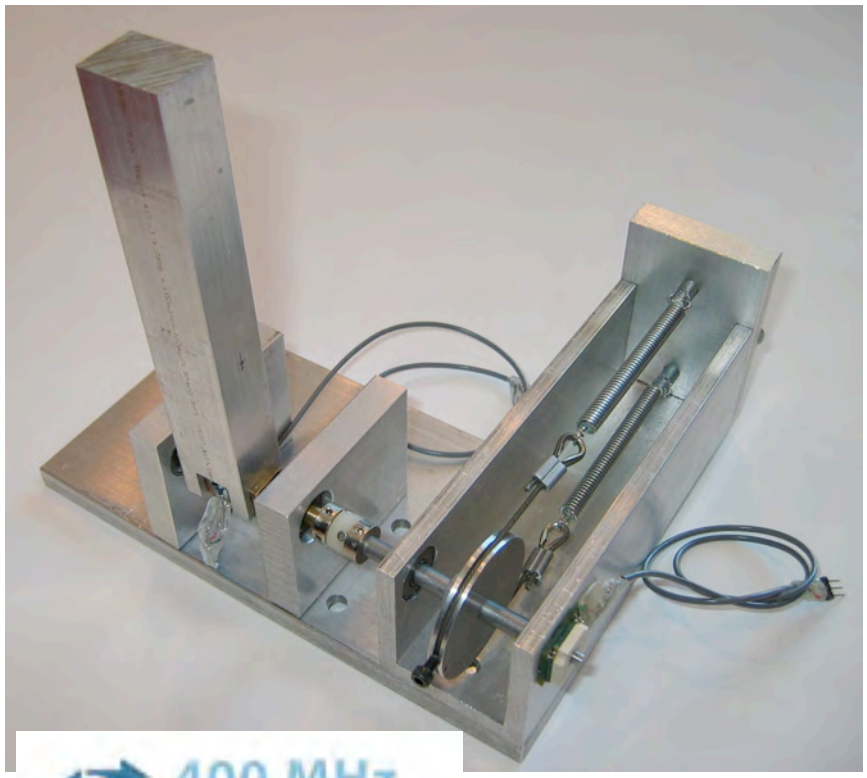
“Low Cost” Series Elastic Actuators





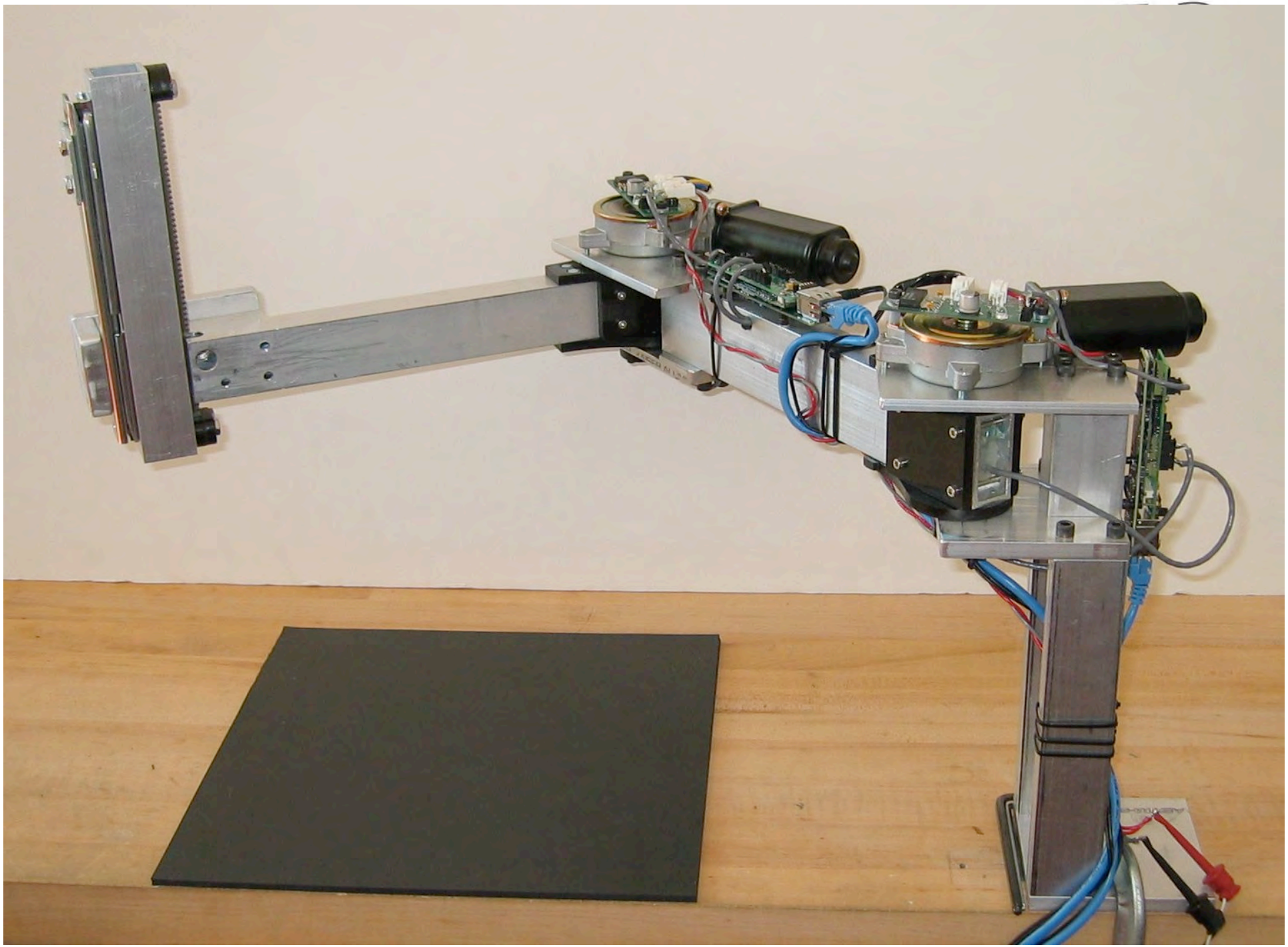


Characterization of Low Cost SEA



- Very large hysteresis
- Simple model accounts for almost all of it
- Self-calibration of model parameters
- Small change to standard SEA algorithm

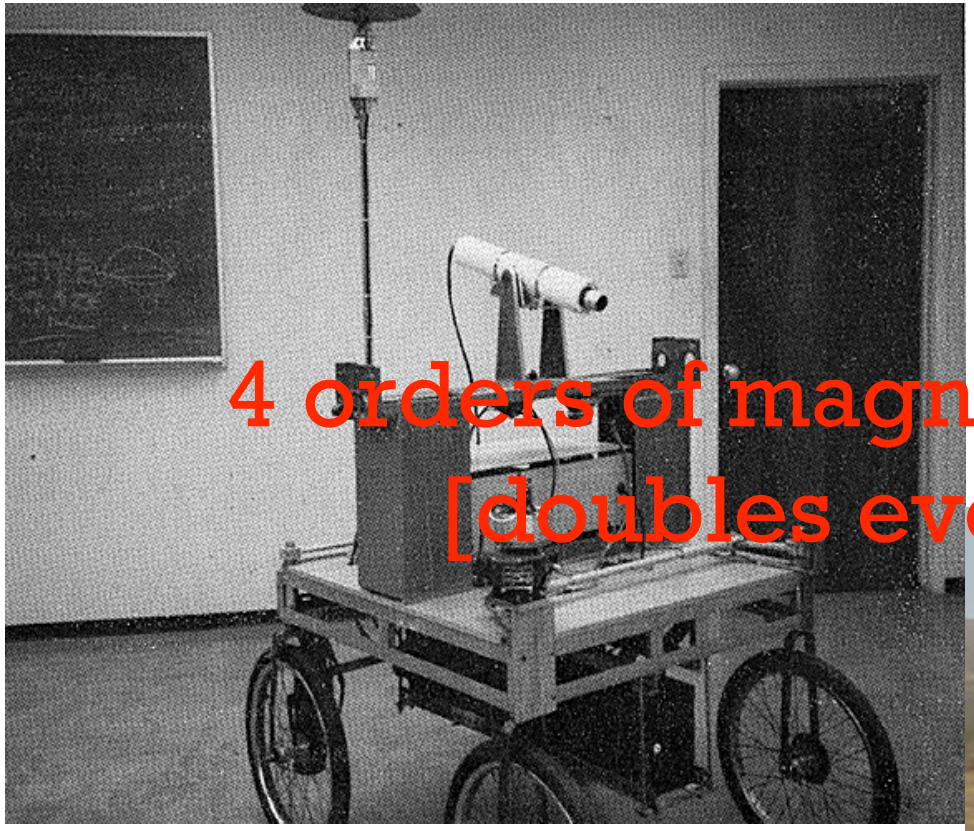
- Easy to do on cheap Linux box
  - size of stick of gum
  - ~$100 retail (3 years ago)
  - handles all joints real time



$150 Force Controlled Arm

The Cart, in 1979

Stanford AI Lab



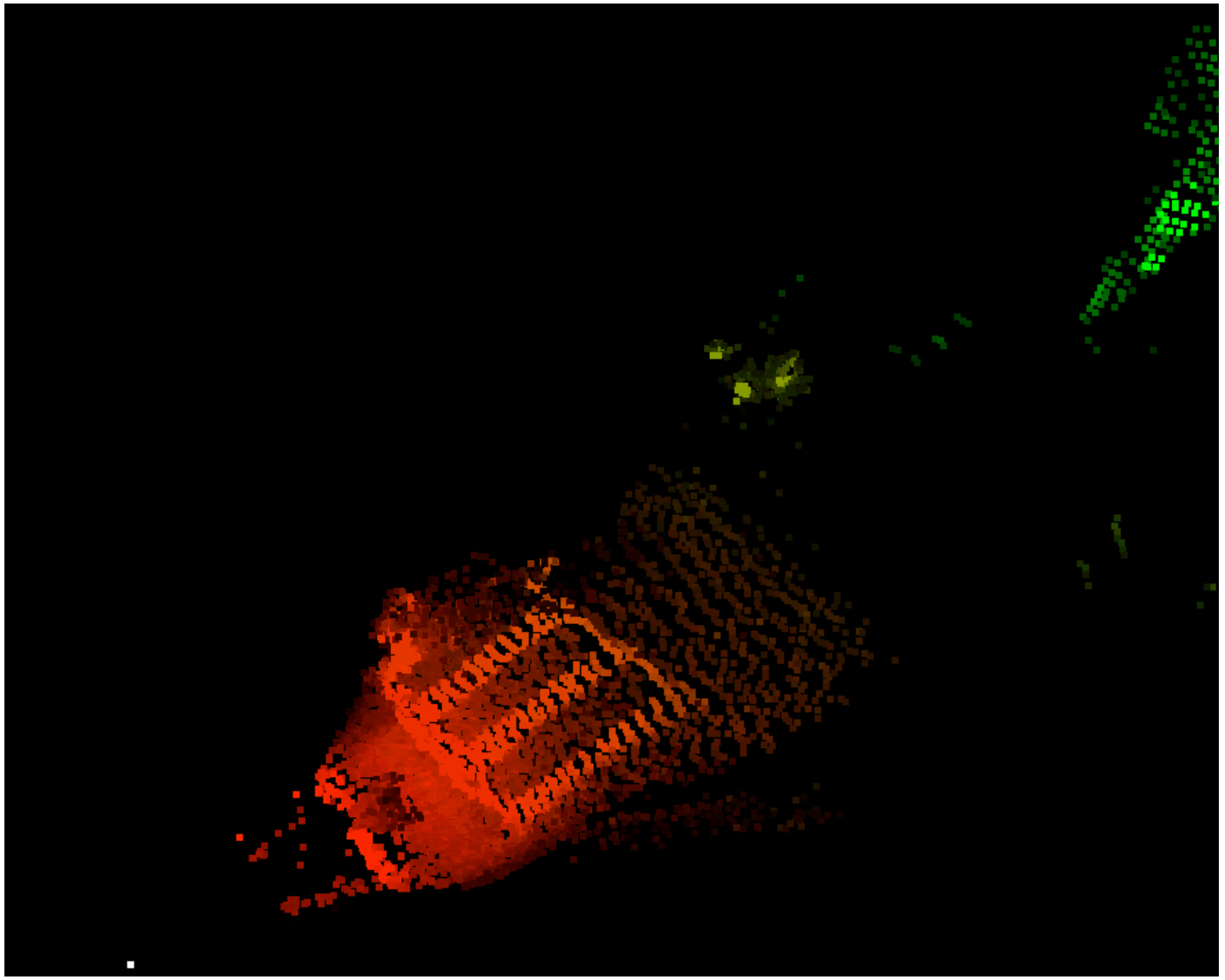
1979: 20 meters/6 hours

4 orders of magnitude in 26 years
[doubles every 2 years]

2005: 200 kilometers/6 hours

Robots As Drivers of Exponentials

Robots Requirements as Driver: ASC Sensor



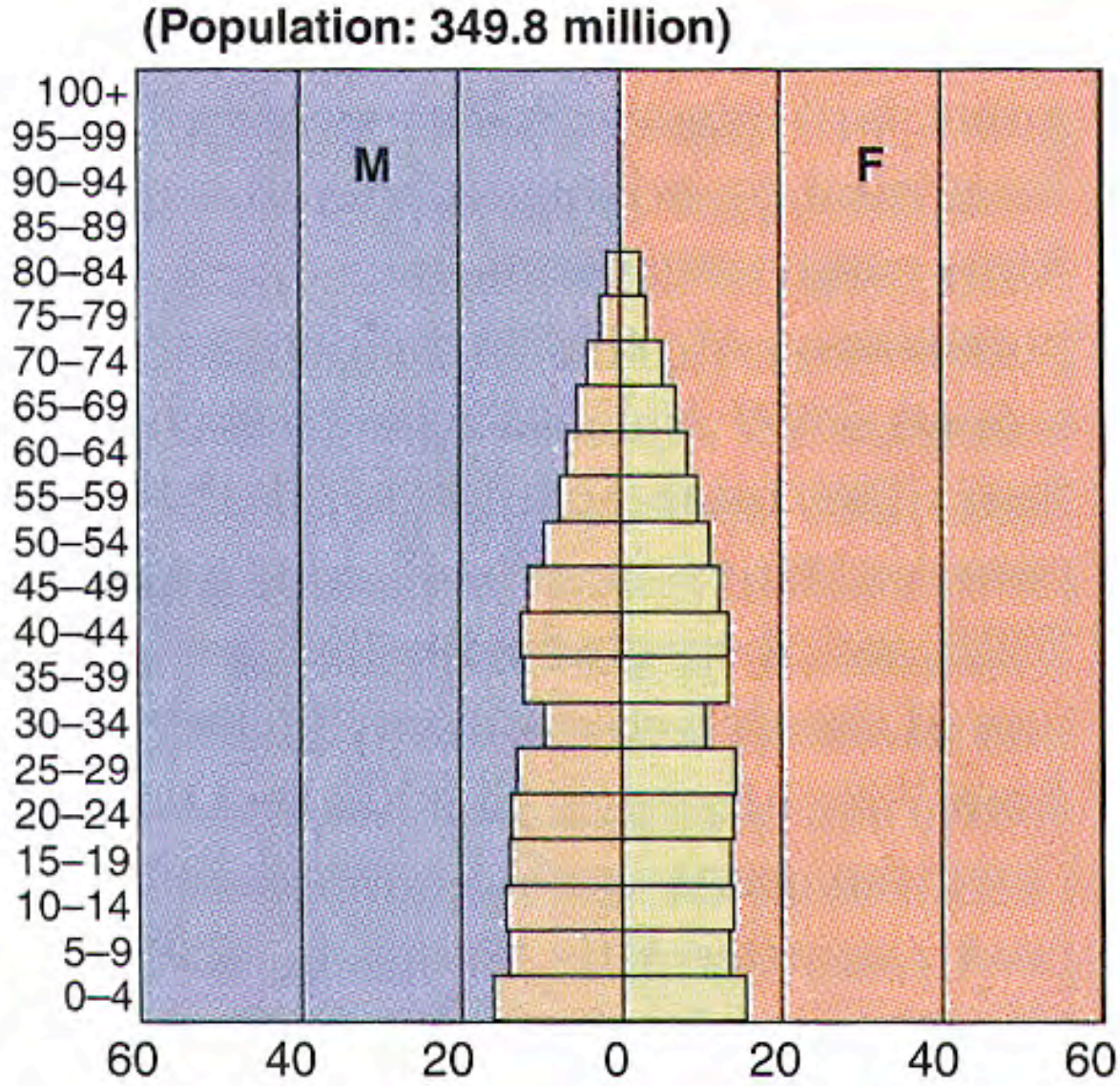
Big Trends for Robotics

- Technology exponentials driven by others
- First technology exponentials driven by robots

- Large scale military robot deployments
- Larger scale home robot deployments

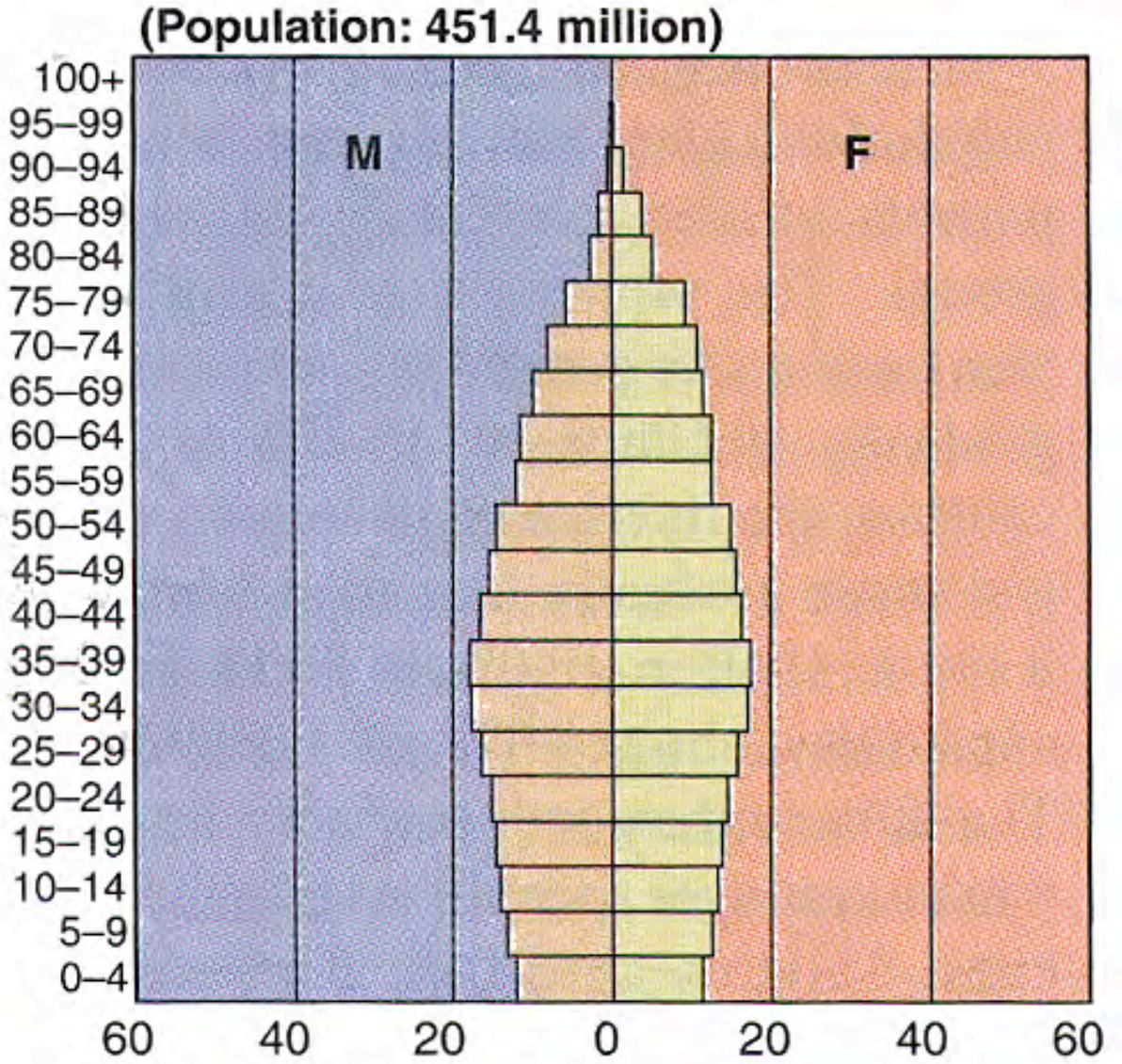
- Aging population
- Increased health costs
- Immigration backlash
- Globalization backlash
- Future of transportation
- Carbon neutral energy

Europe - 1950



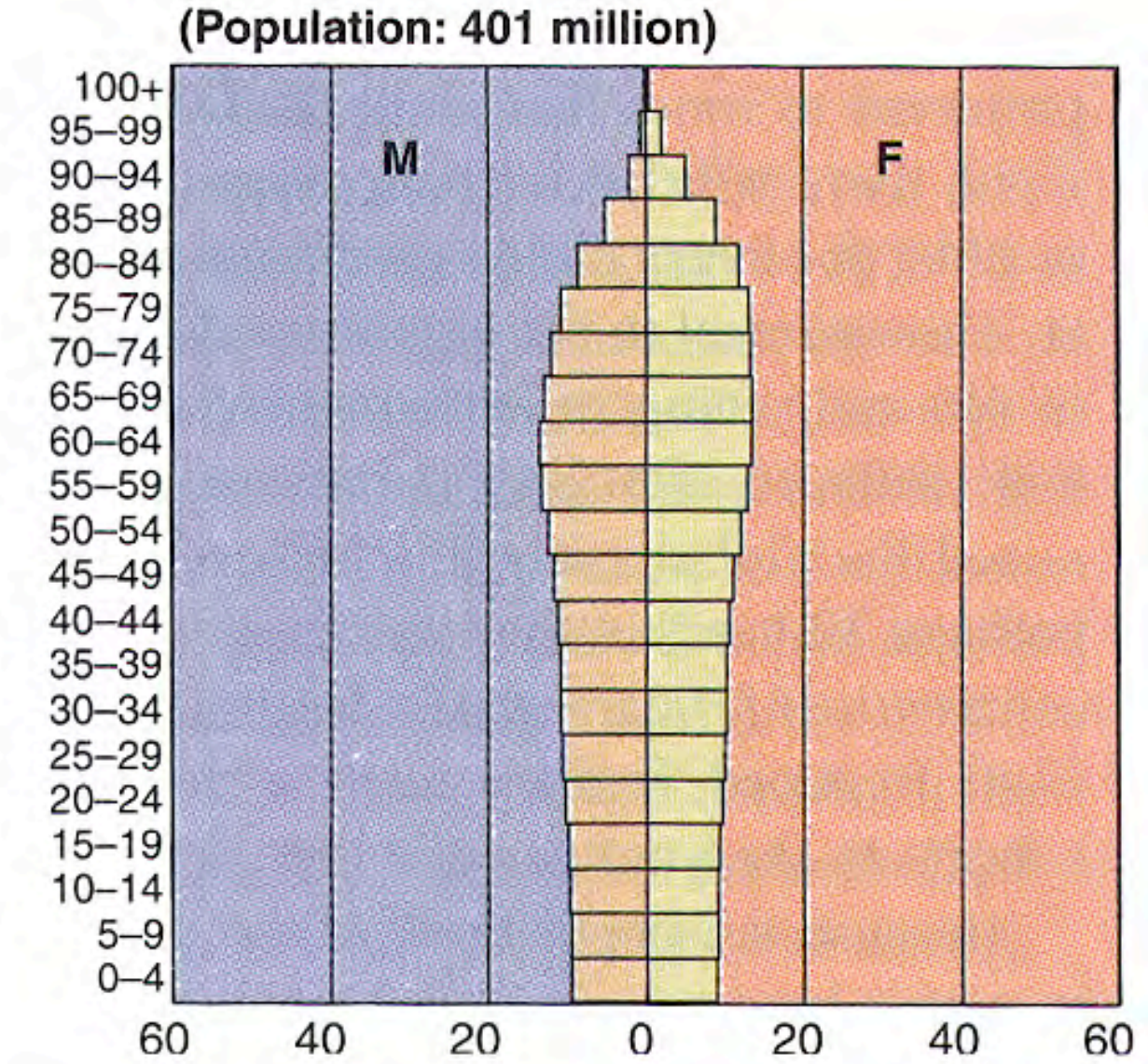
JE Cohen, Science 302, 1176 (2003)

Europe - 2000



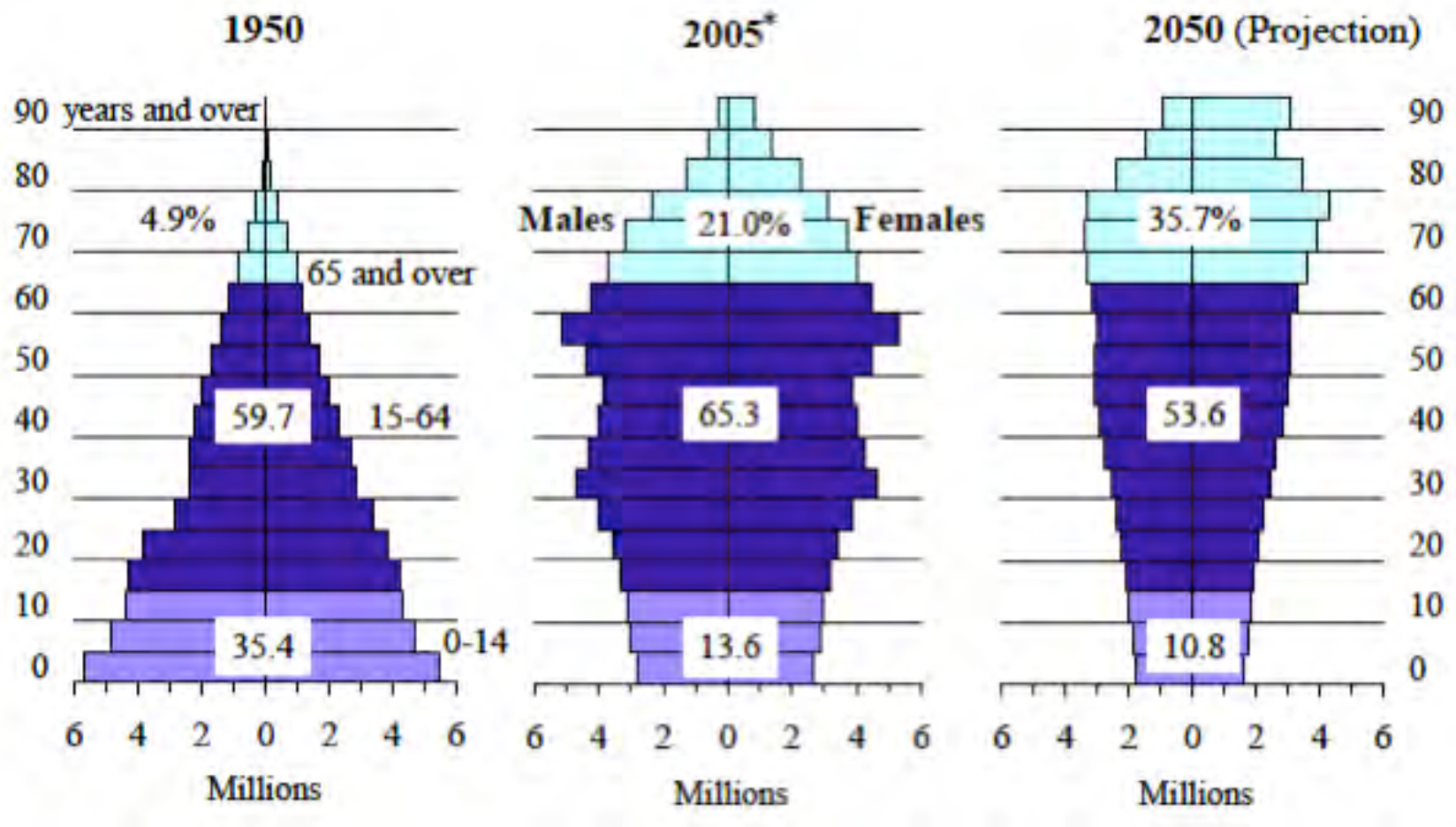
JE Cohen, Science 302, 1176 (2003)

Europe - 2050

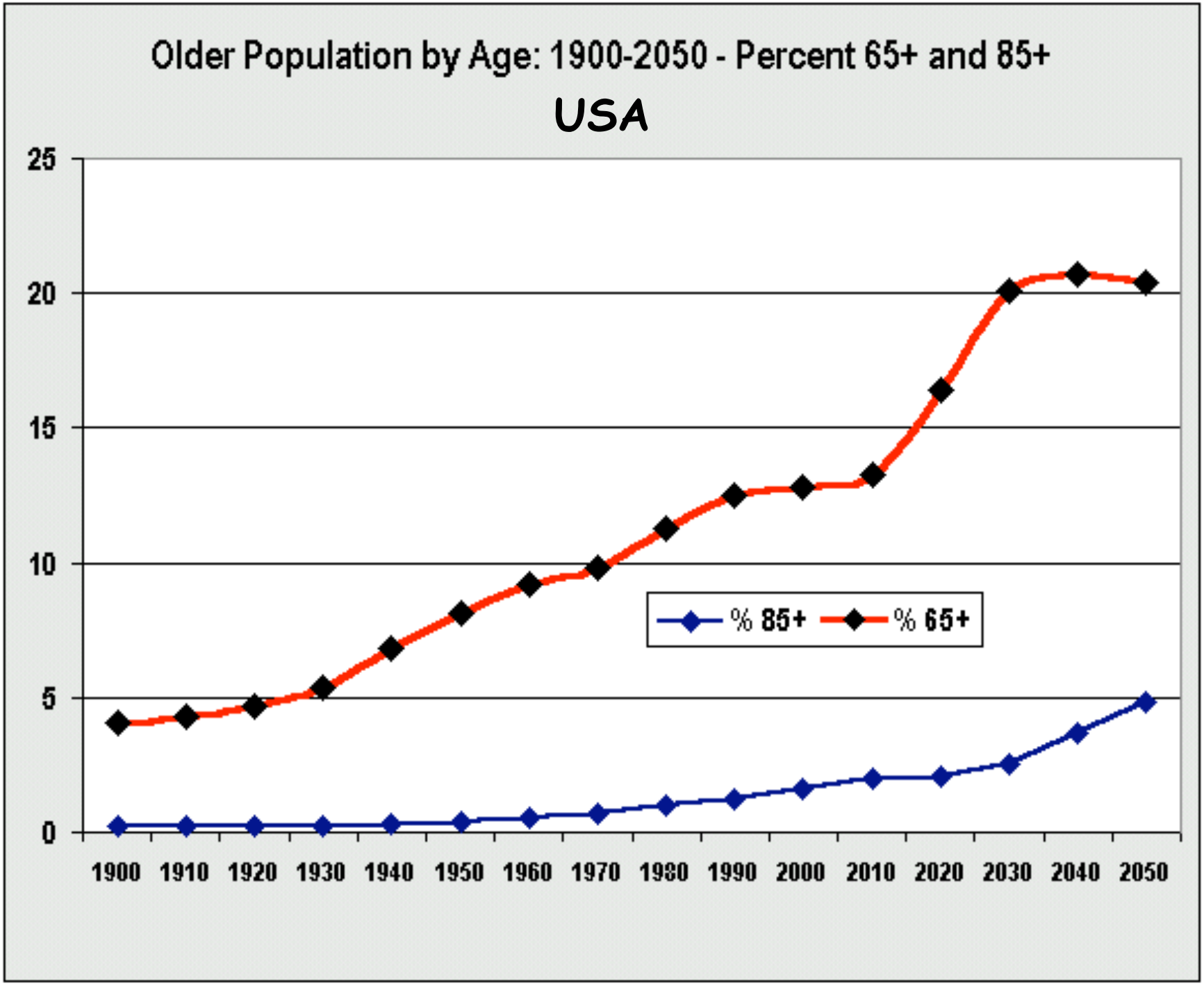


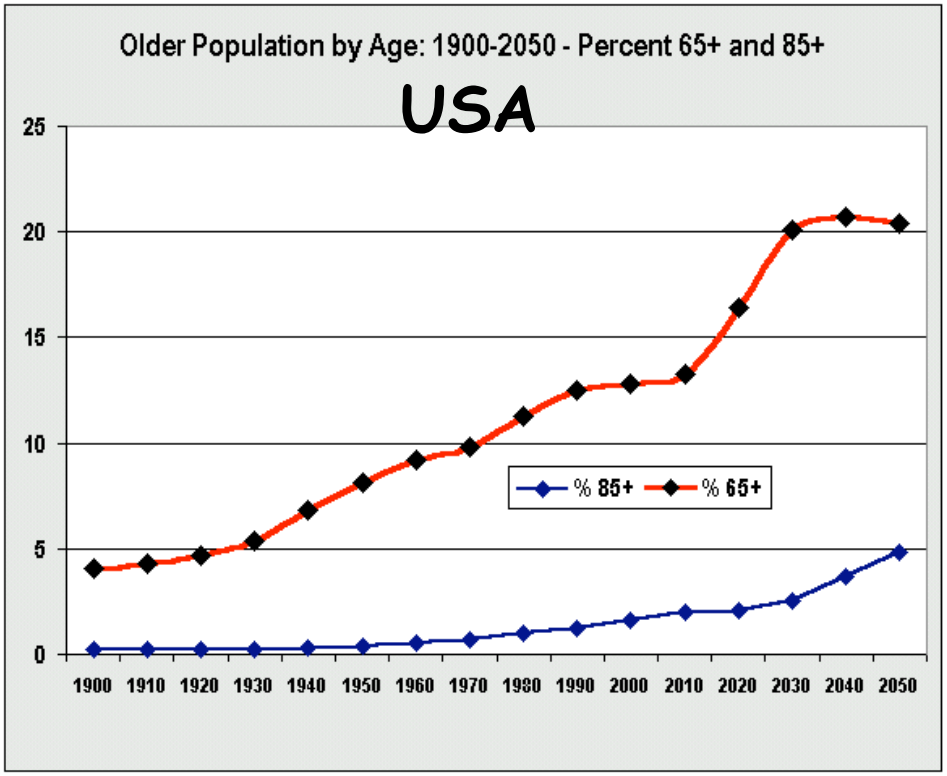
JE Cohen, Science 302, 1176 (2003)

Japan: 1950 to 2050

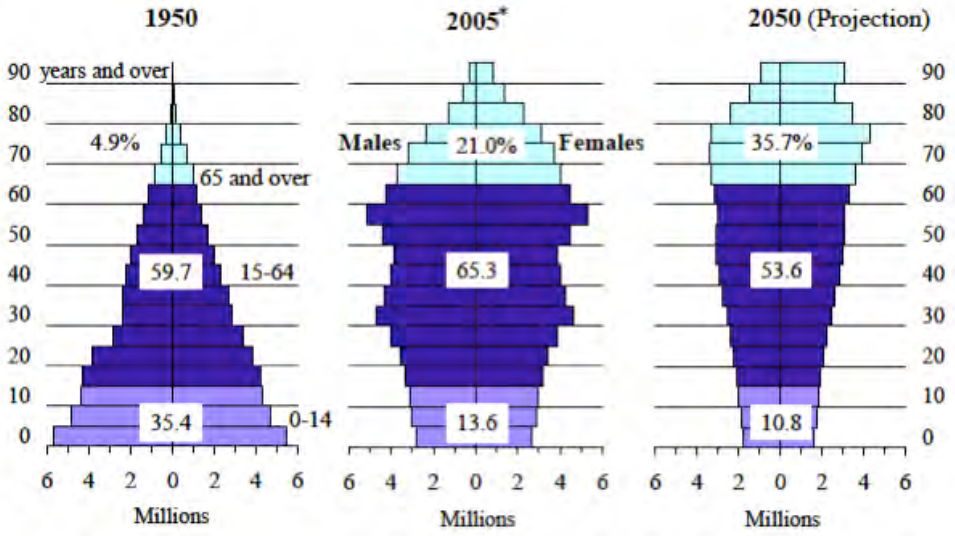


Statistics Bureau, Japan Ministry of Health, Labor, and Welfare

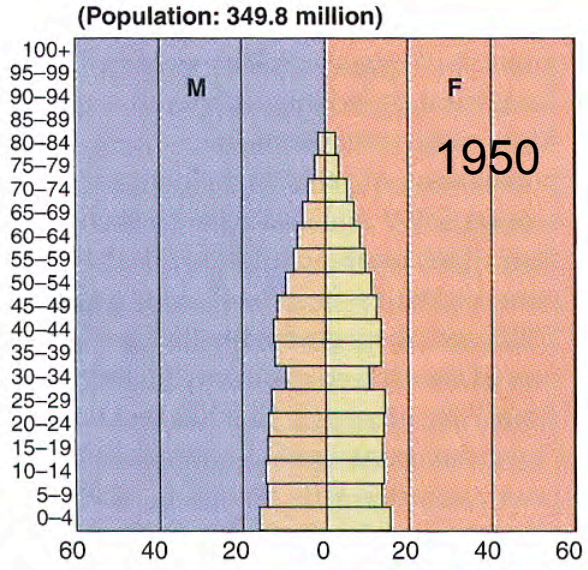

Older Population by Age: 1900-2050 - Percent 65+ and 85+
USA
25
20
15
10
5
0
% 85+
% 65+
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050

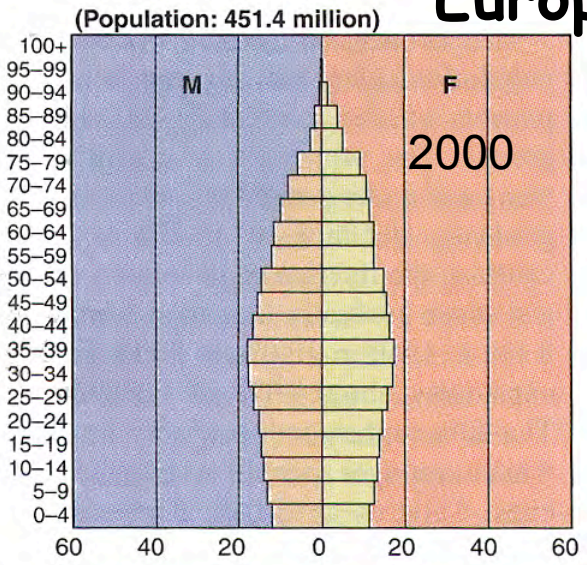


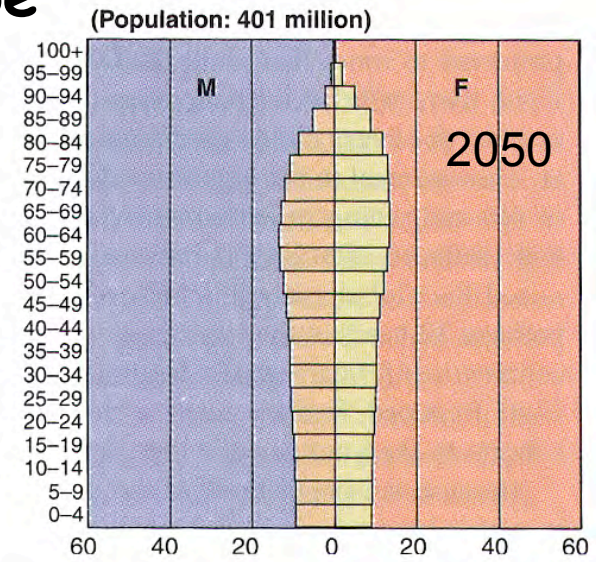
Japan



Europe







IDG News, Dec 6, 2007

At a Tokyo news conference held to unveil the two new robots, Toyota also showed its Robina robot, which made its first public appearance in the middle of this year. The Robina is designed for face-to-face communication with humans. In that role, the robot served as a guide at the Toyota Kaikan Exhibition Hall in Toyota City in August this year.

The robot can automatically navigate a route through obstacles and, by holding a pen in one hand and a piece of card in the other, sign its signature on the card.

Toyota is one of many Japanese companies actively investigating robotics and the areas that go hand-in-hand with the technology, such as artificial intelligence. While violin playing and autograph signing may appear to be nothing more than whimsical tricks they require a high level of mechanical and electrical control and are the kind of tasks that engineers need to perfect before they take the next step towards human assistance.

Japan's rapidly aging society is providing the push behind all these projects.

Immigration Backlash

- Both a legal and an illegal issue
- Some industries are suffering due to loss of illegal immigrants (e.g., OK, CO, CA)
- Some places are suffering due to legal immigrants getting too rich (e.g., lack of Polish workers in UK and Germany)

- Some work just has to take place in-situ, and not even immigrants want to work there

Robots to rule at Rio Tinto

Ben Woodhead | January 18, 2008

RESOURCES giant Rio Tinto will replace humans with robots in its Western Australian mining operations over the next two years as it rolls out a fleet of automated vehicles including trucks, trains and drilling rigs.

Rio Tinto chief Tom Albanese wants the resources giant to be global leaders in fully integrated, automated operations

The work is part of Rio Tinto's 'mine of the future' program, which has been underway for close to a decade and aims to radically transform mining by automating processes throughout the supply chain.

"We're aiming to be the global leaders in fully integrated, automated operations," Rio Tinto chief executive Tom Albanese said today as the miner unveiled its plans for robotic mining over the next two years.

"It will allow for more efficient operations and directly confront the escalating costs associated with basing employees at remote sites, giving us a competitive advantage as an employer along the way."

A number of new technologies including autonomous drilling rigs, trucks and trains will be deployed in Rio Tinto's Iron Ore division in Western Australia's Pilbara region over the next two years.

The vehicles will be part of a two-year trial of autonomous technology and the company hopes to install robotic gear at other iron ore mines from 2010.

Printed May 17, 2008 02:11am AEST

Crew shortage hits subs

Cameron Stewart | *March 10, 2008*

ONLY half of Australia's submarine fleet can be sent to war, because of a critical shortage of qualified submariners.

The crisis has left the Royal Australian Navy with only three full crews for its six Collins-class submarines, severely undermining the effectiveness of one of the nation's most vital and expensive defence assets.

"It's becoming a ghost fleet," said one submariner, who asked not to be named. "We are losing our crews - it feels like the Mary Celeste."

The Defence Department maintains that despite the "significant shortfall" in submarine crews, it still has enough to "meet operational requirements" for the submarines.

But Defence does not say if these operational tasks have been reduced in line with declining crew numbers.

Defence sources say the exodus of submariners - mostly to better-paid jobs in Western Australia's booming mining sector - has been stemmed in recent months, raising hopes that the worst may be over.

However, there is no sign of any recovery in crew numbers from current historical lows.

Globalization Backlash

- Worries about product quality when built in unregulated environments
- Increasing costs in China and India
- Cost of transportation
- Anger at perceived loss of jobs
- Worry about loss of local capability

- Can robots increase the productivity of manual workers?

But, Also Need Research…

- Visual object recognition capabilities of a two year old child

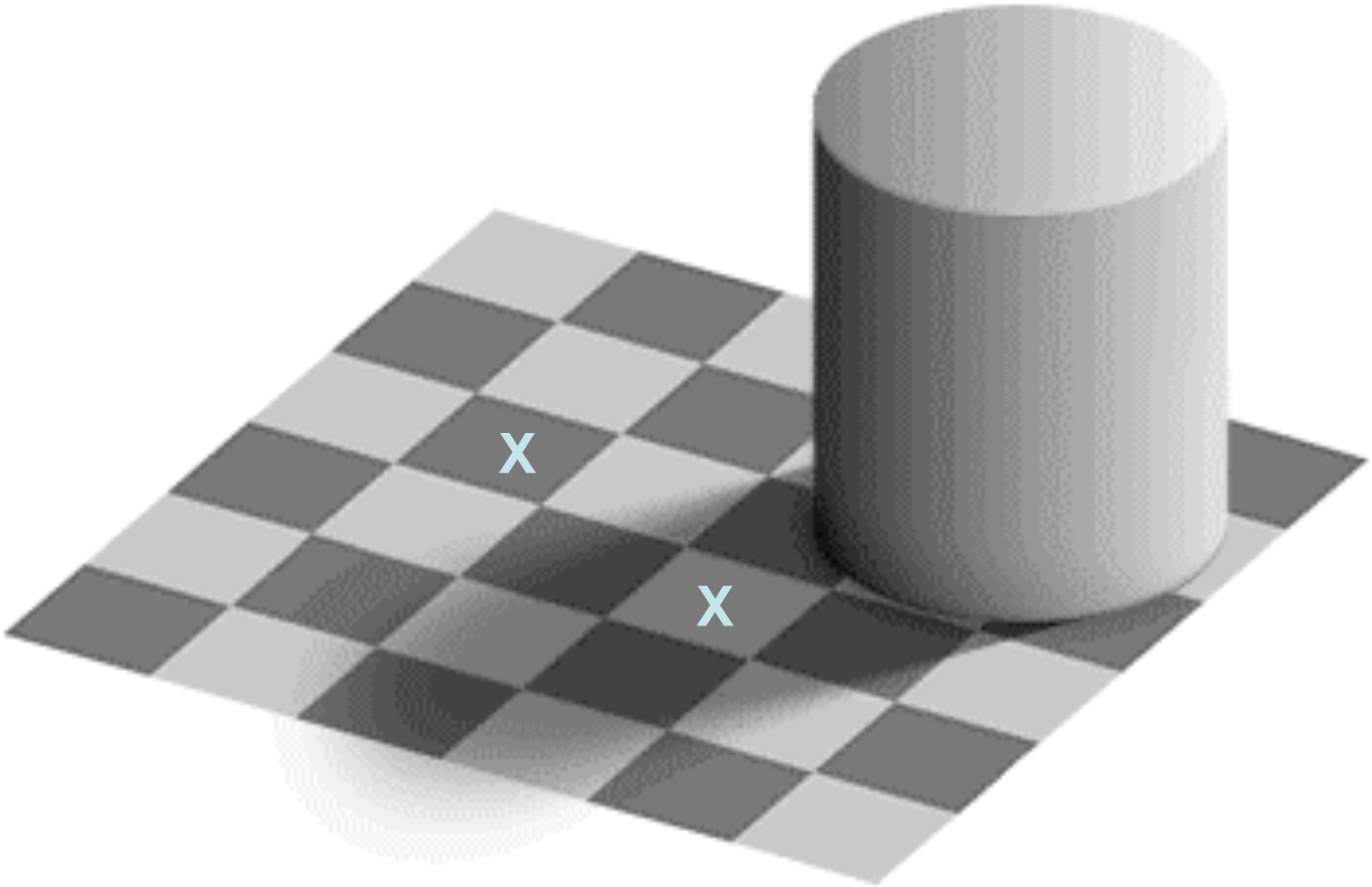
Human Vision Is Sophisticated

Courtesy of Ted Adelson

Human Vision Is Sophisticated

Courtesy of Ted Adelson

Human Vision Is Sophisticated



Courtesy of Ted Adelson

Solving Vision Once And For All

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PROJECT MAC

Artificial Intelligence Group
Vision Memo. No. 100.

July 7, 1966

THE SUMMER VISION PROJECT

Seymour Papert

The summer vision project is an attempt to use our summer workers effectively in the construction of a significant part of a visual system. The particular task was chosen partly because it can be segmented into sub-problems which will allow individuals to work independently and yet participate in the construction of a system complex enough to be a real landmark in the development of "pattern recognition".

The basic structure is fixed for the first phase of work extending to some point in July. Everyone is invited to contribute to the discussion of the second phase. Sussman is coordinator of "Vision Project" meetings and should be consulted by anyone who wishes to participate.

Goals - General

The primary goal of the project is to construct a system of programs which will divide a vidisector picture into regions such as

likely objects

likely background areas

chaos.

We shall call this part of its operation FIGURE-GROUND analysis.

It will be impossible to do this without considerable analysis of shape and surface properties, so FIGURE-GROUND analysis is really inseparable in practice from the second goal which is REGION DESCRIPTION.

The final goal is OBJECT IDENTIFICATION which will actually name objects by matching them with a vocabulary of known objects.

Subgoal for July

Analysis of scenes consisting of non-overlapping objects from the following set:

balls

bricks with faces of the same or different colors or textures

cylinders.

Each face will be of uniform and distinct color and/or texture.

Background will be homogeneous.

Does not generalize like this…

Extensions for August

The first priority will be to handle objects of the same sort but with complex surfaces and backgrounds, e.g. cigarette pack with writing and bands of different color, or a cylindrical battery.

Then extend class of objects to objects like tools, cups, etc.

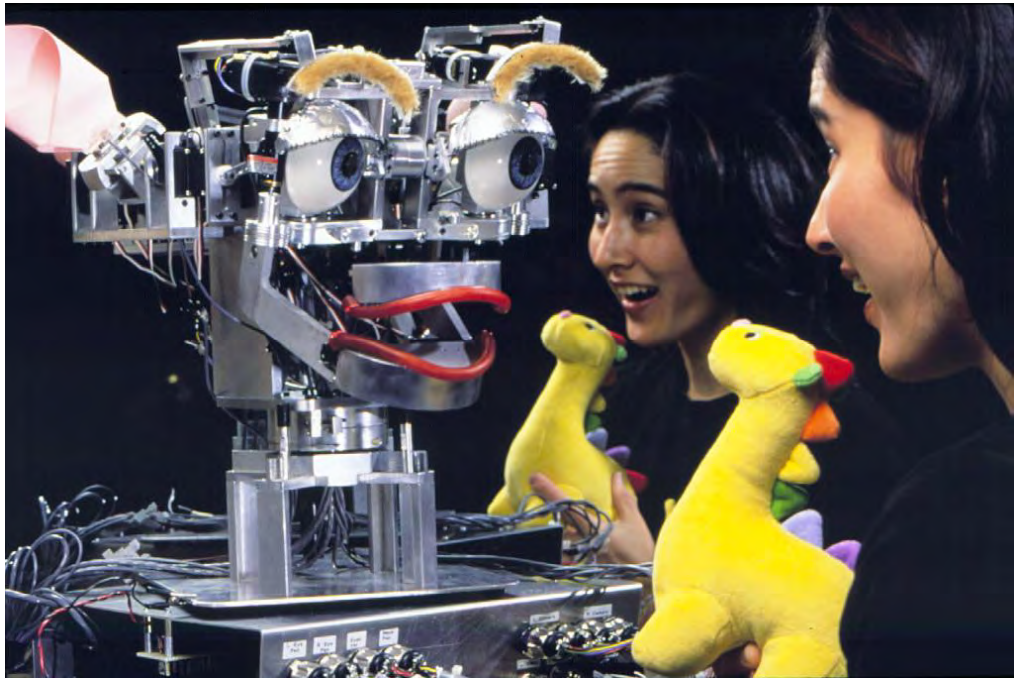
More Failure, Brooks, 1981

But, Also Need Research…

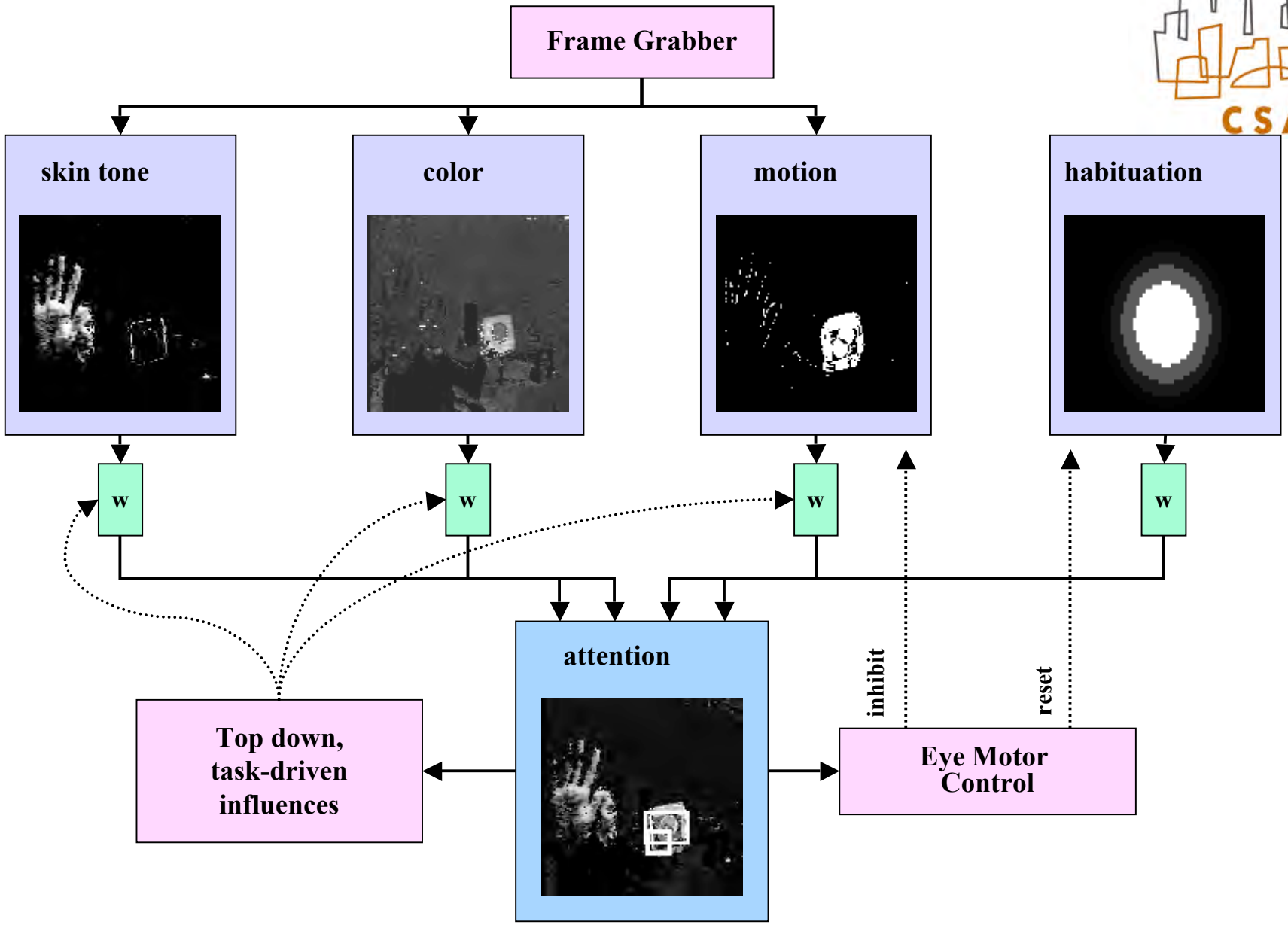
- Visual object recognition capabilities of a two year old child
- Language capabilities of a four year old child
- Manual dexterity of a six year old child
- Social sophistication of an eight year old child

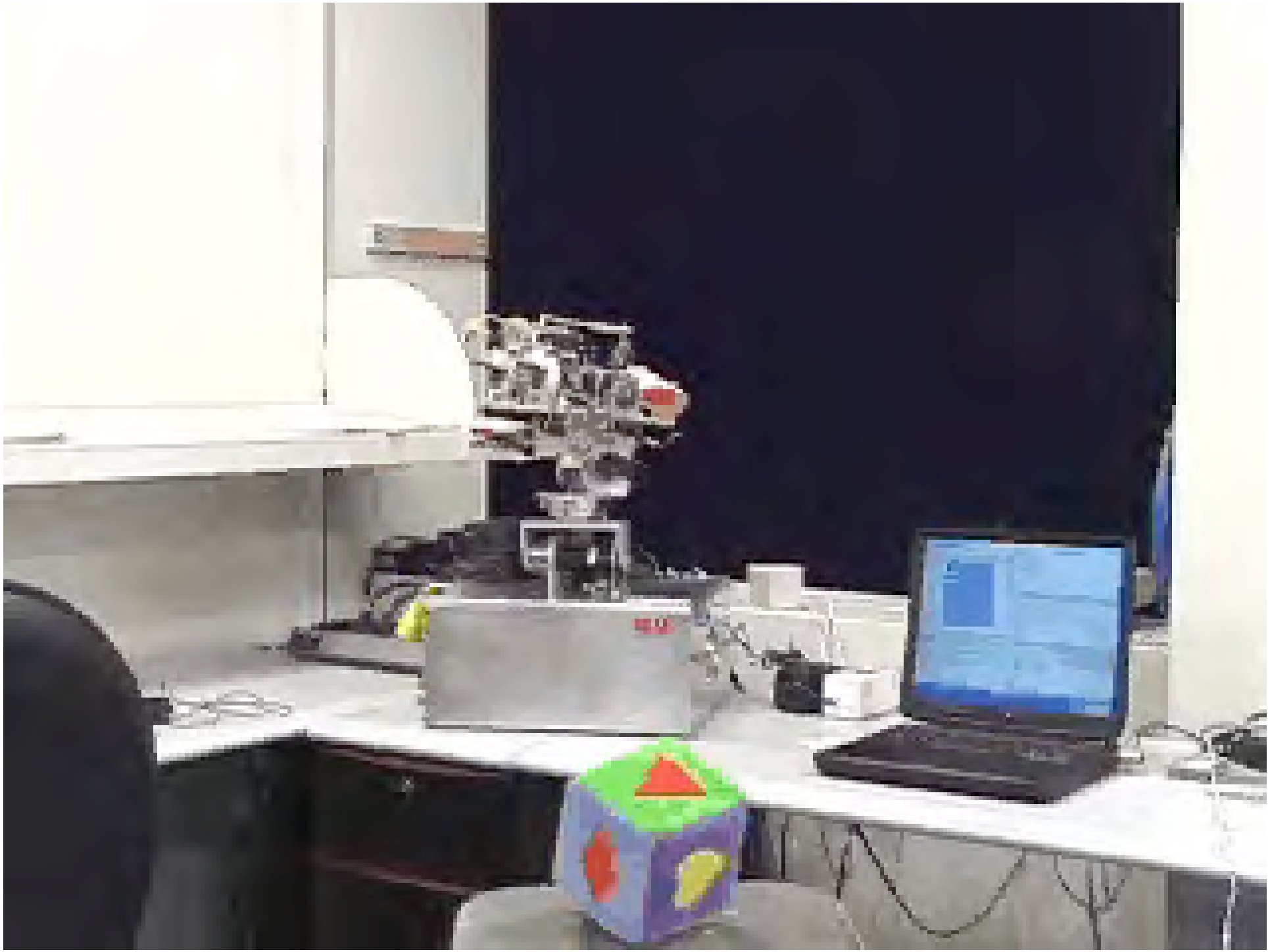
Two examples from my (now former) students

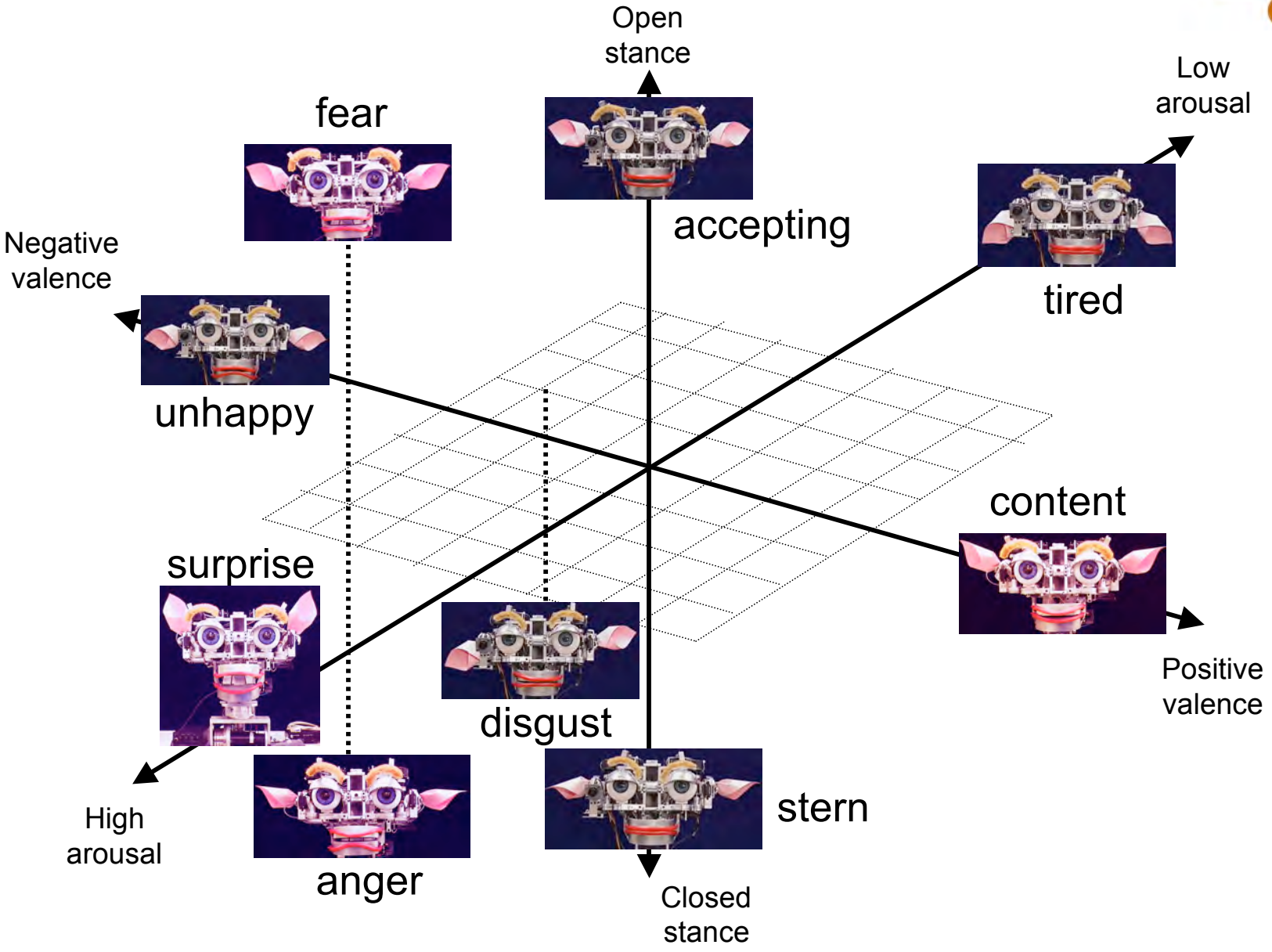
Kismet, 2000

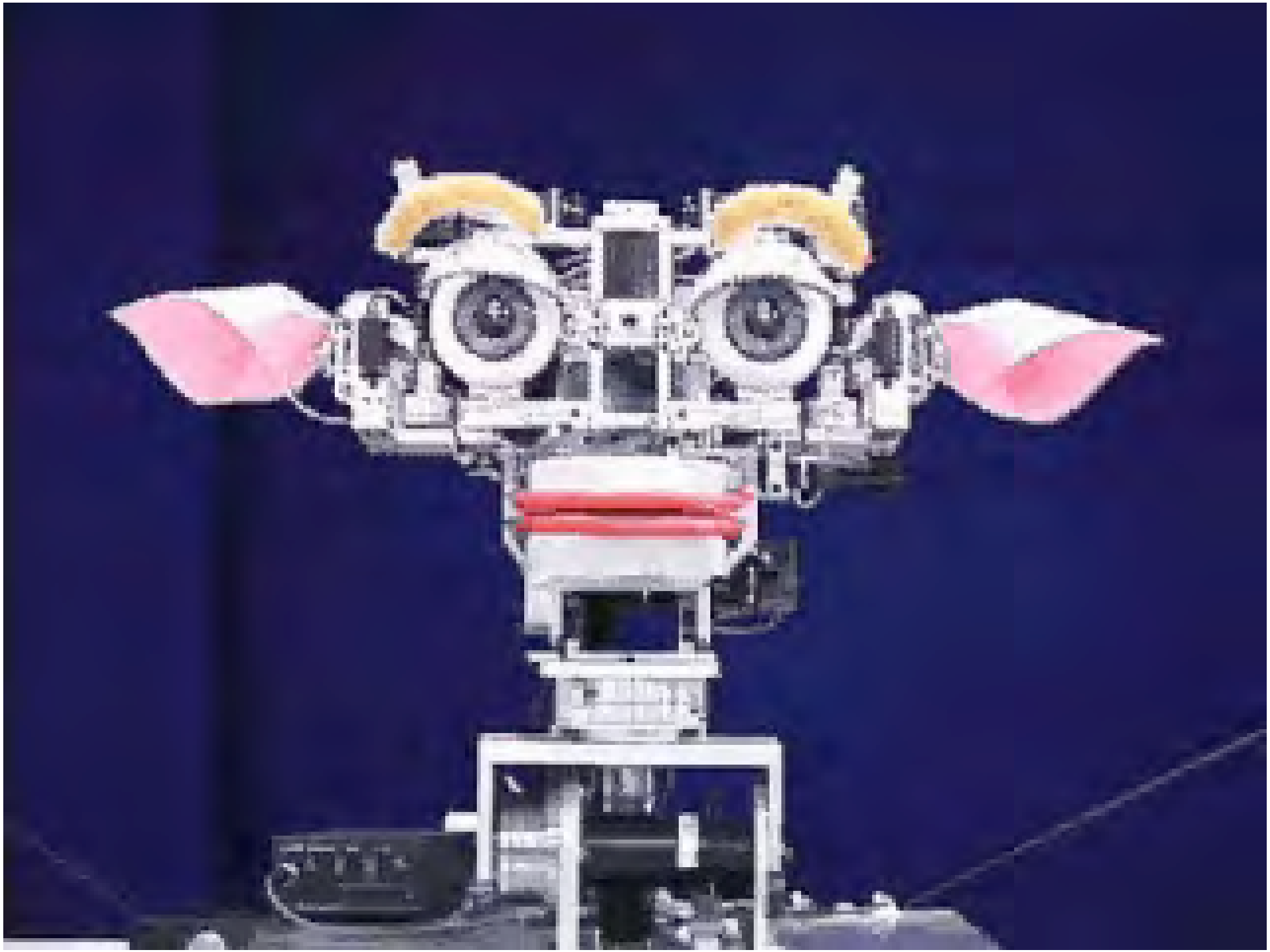


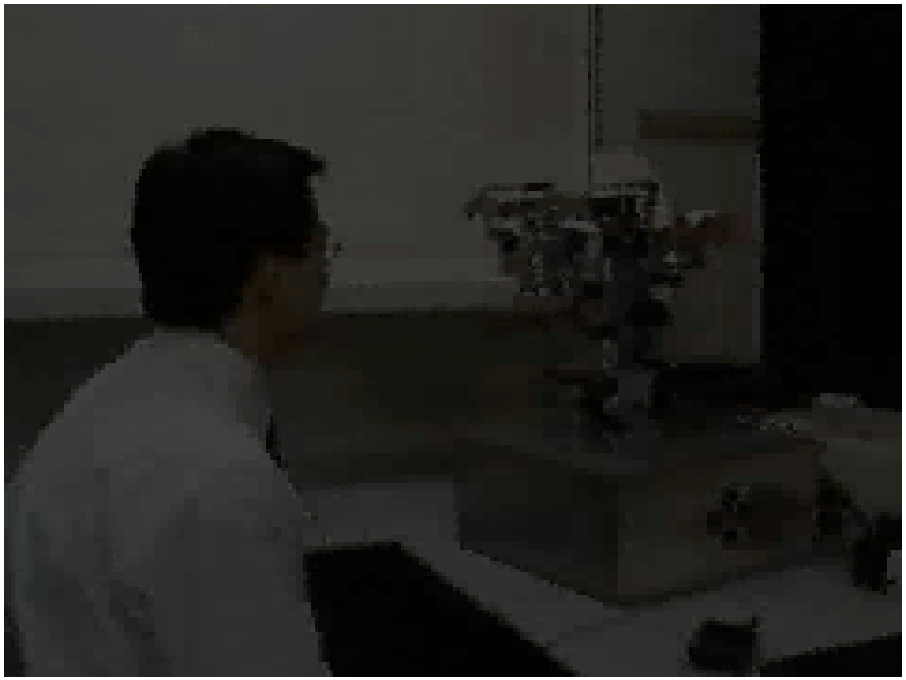
Cynthia Breazeal

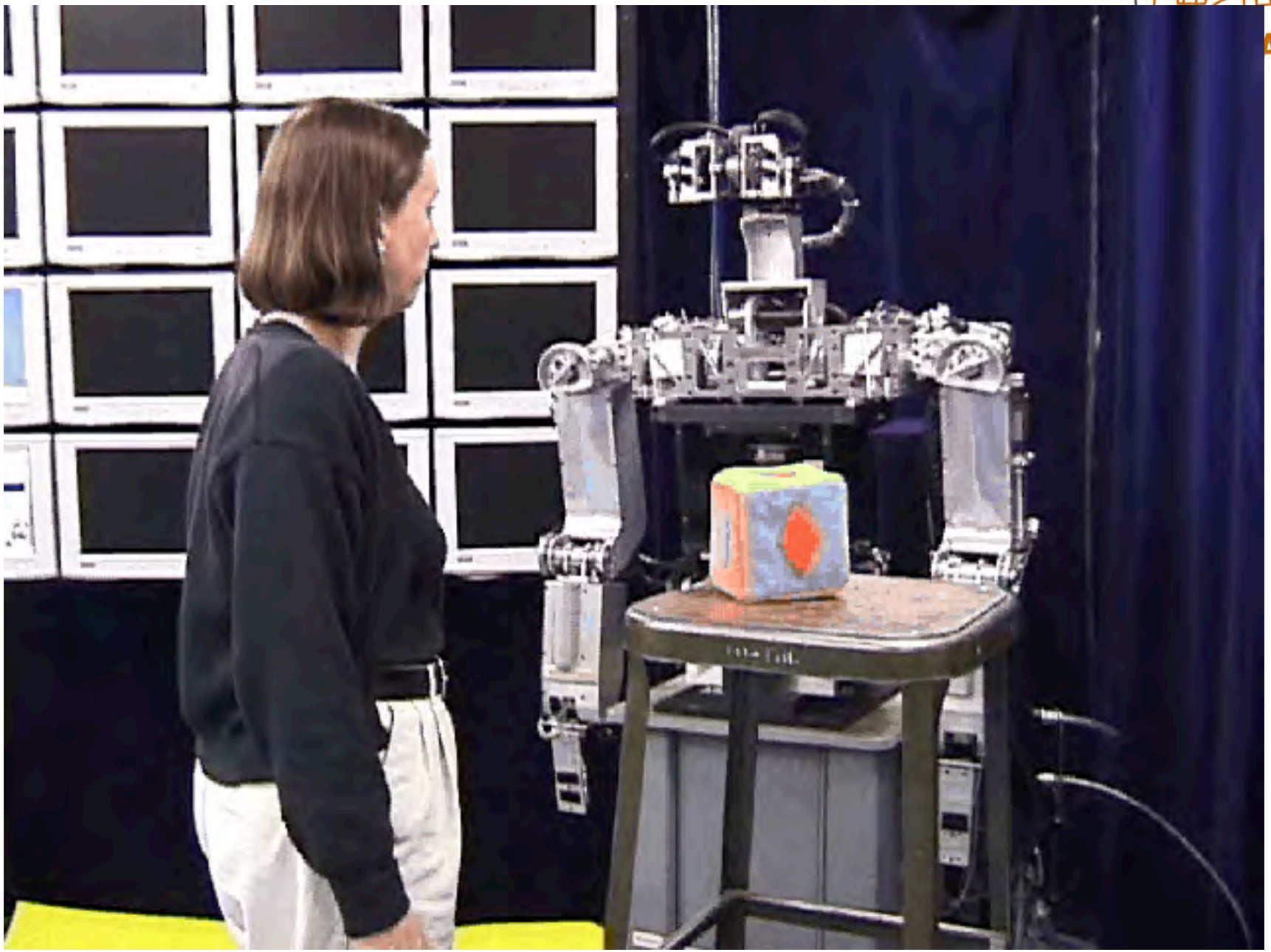

Frame Grabber
skin tone
color
motion
habituation
w
w
w
w
attention
inhibit
reset
Top down,
task-driven
influences
Eye Motor
Control

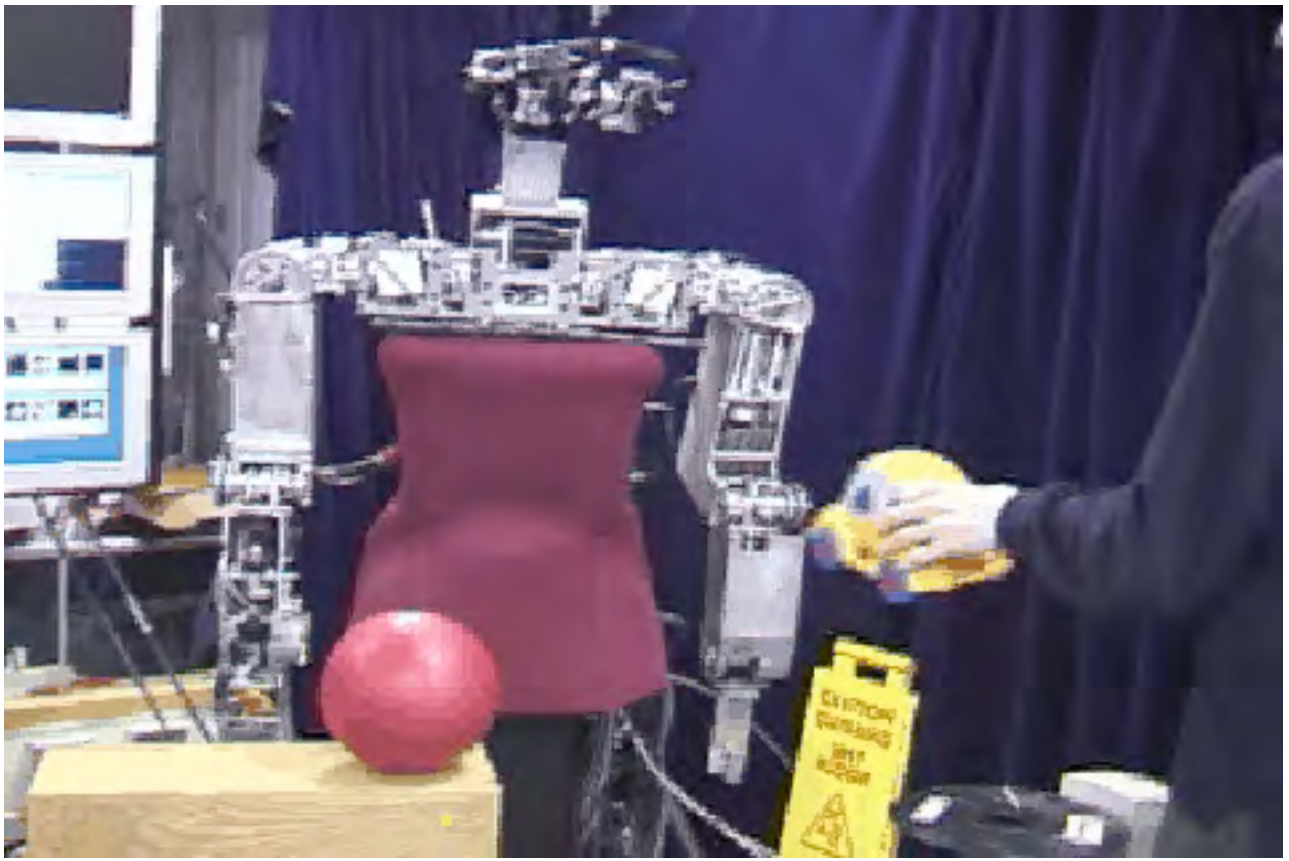


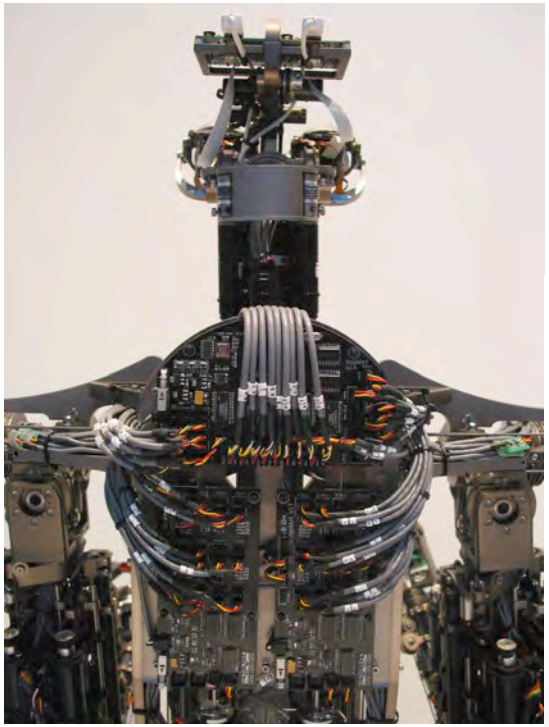

Open
stance
fear
accepting
Low
arousal
Negative
valence
tired
unhappy
content
surprise
disgust
Positive
valence
High
arousal
anger
stern
Closed
stance



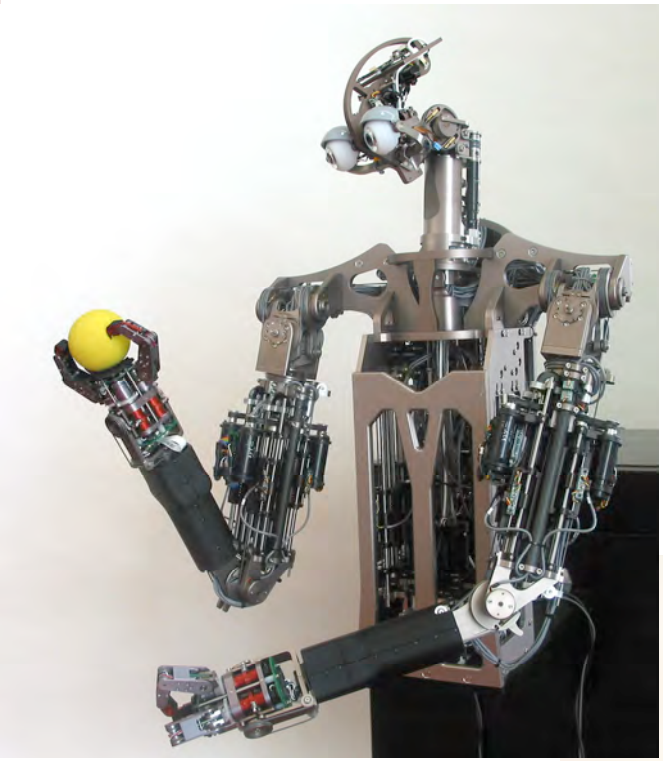


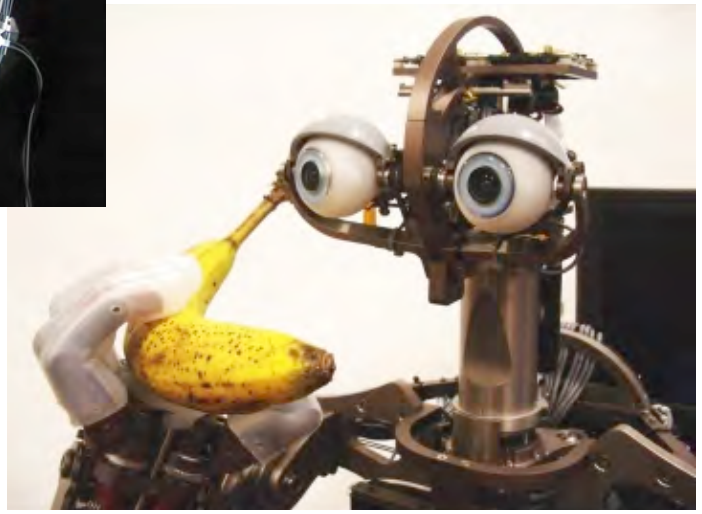




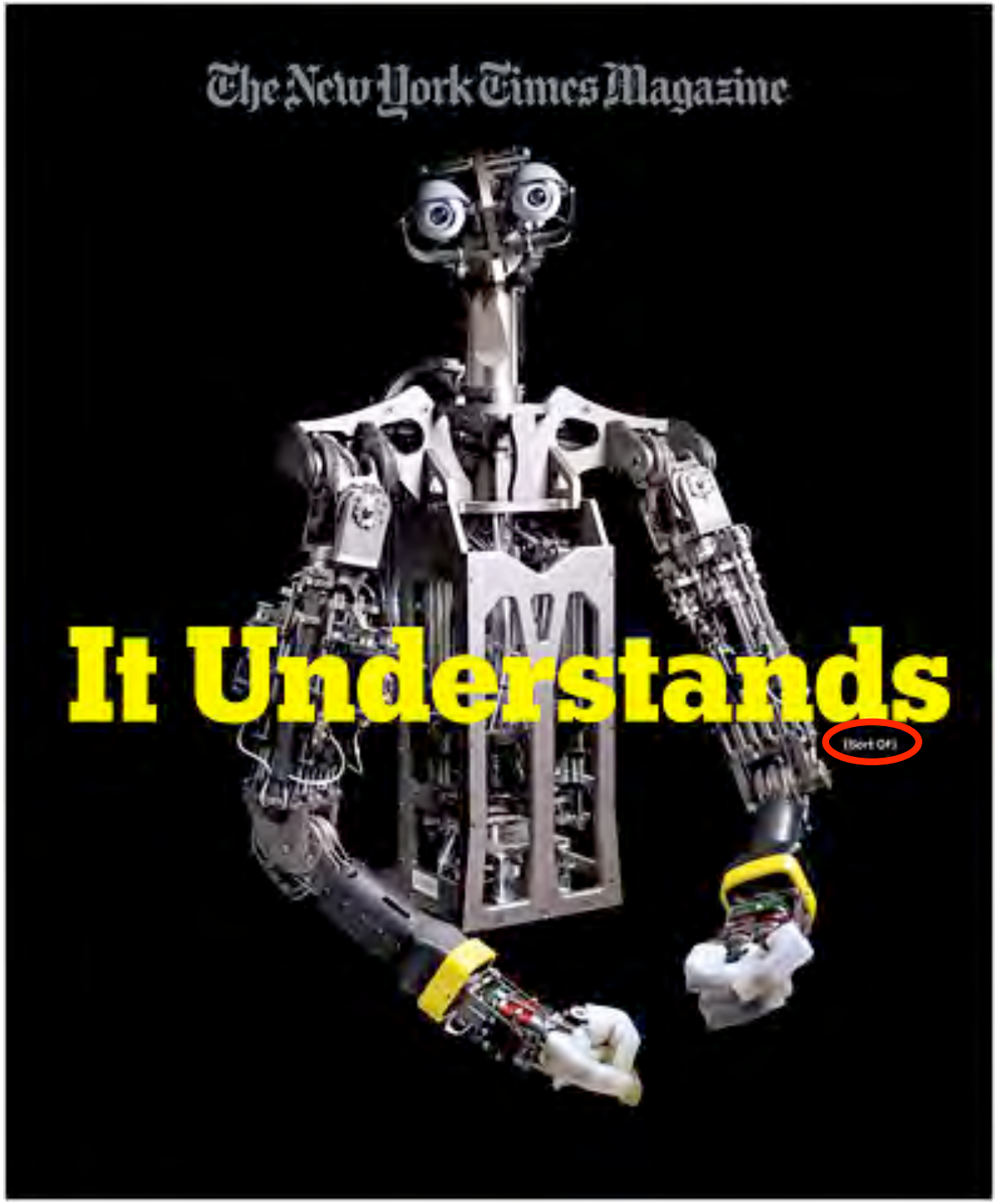


Domo, 2007



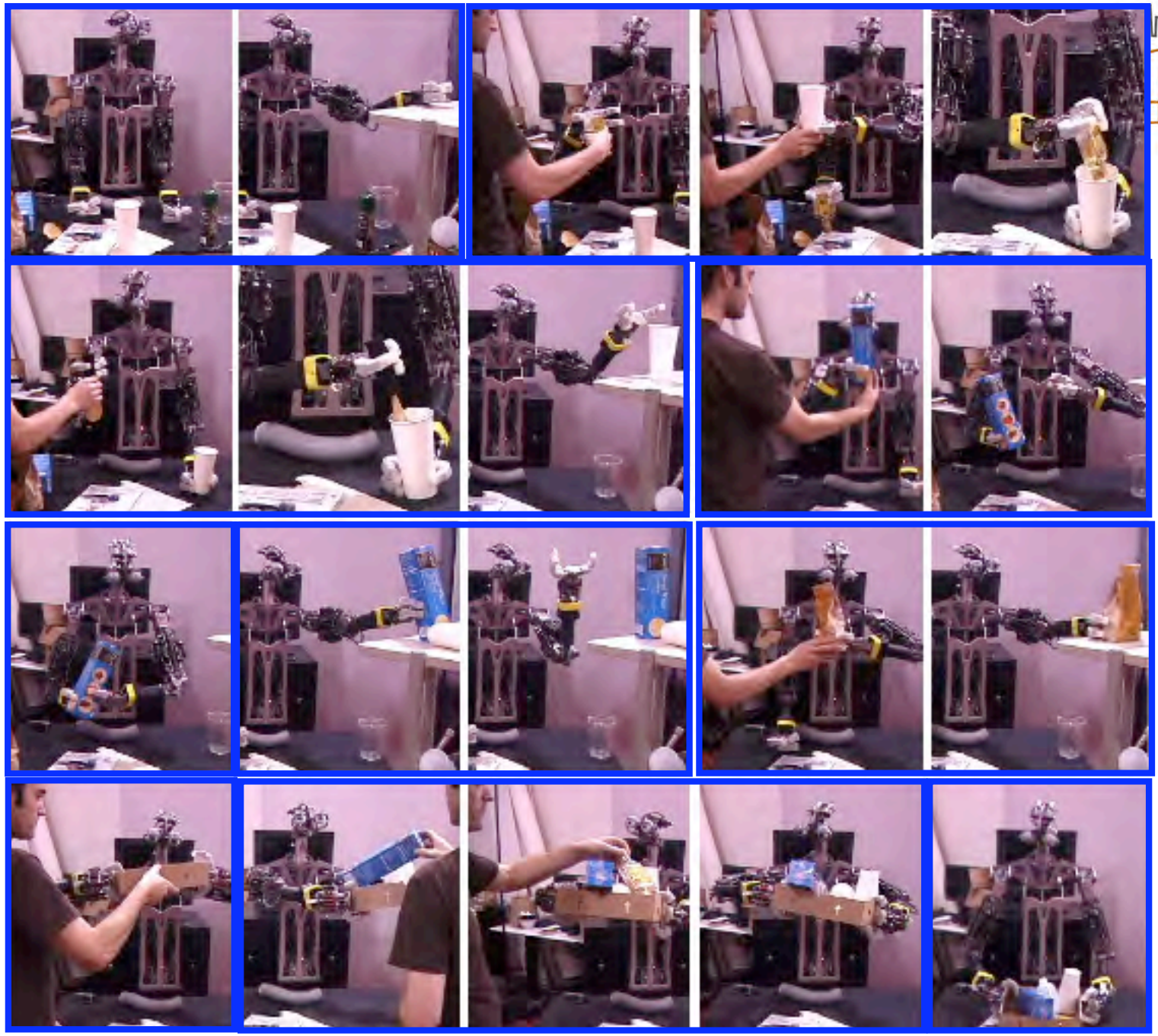


Aaron Edsinger



CSAIL

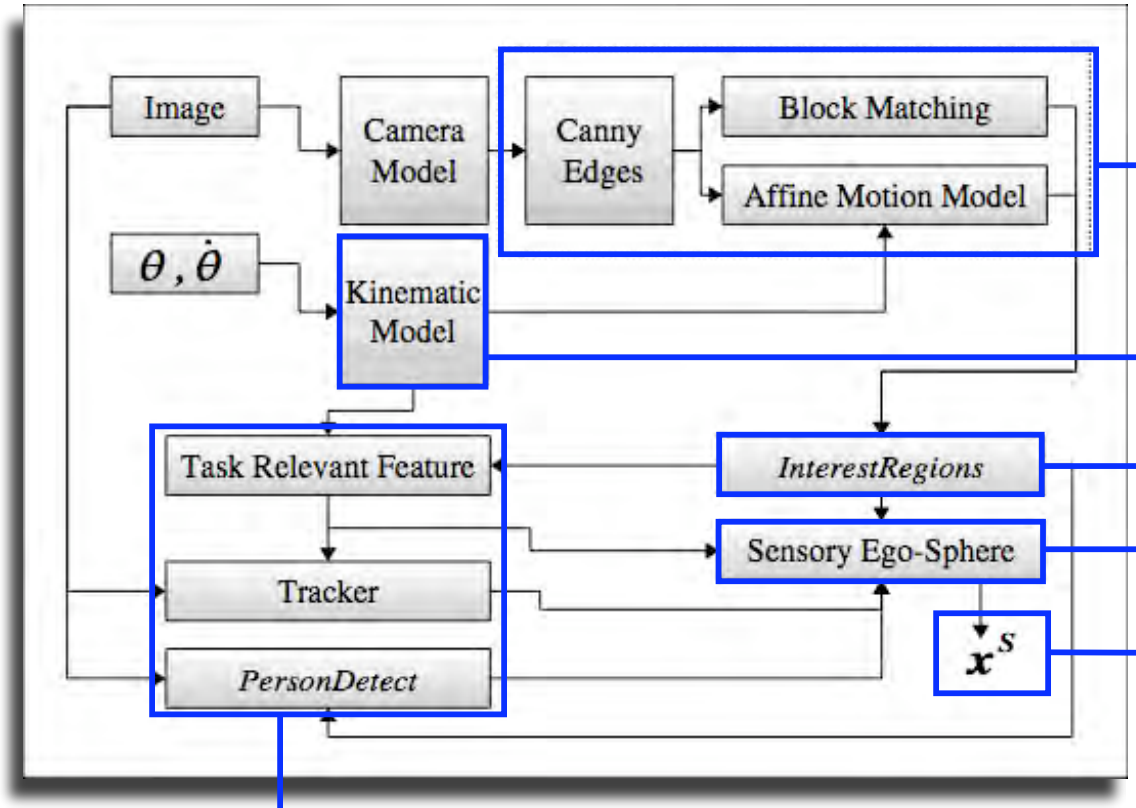
Awareness of Forces (Int. and Ext.)



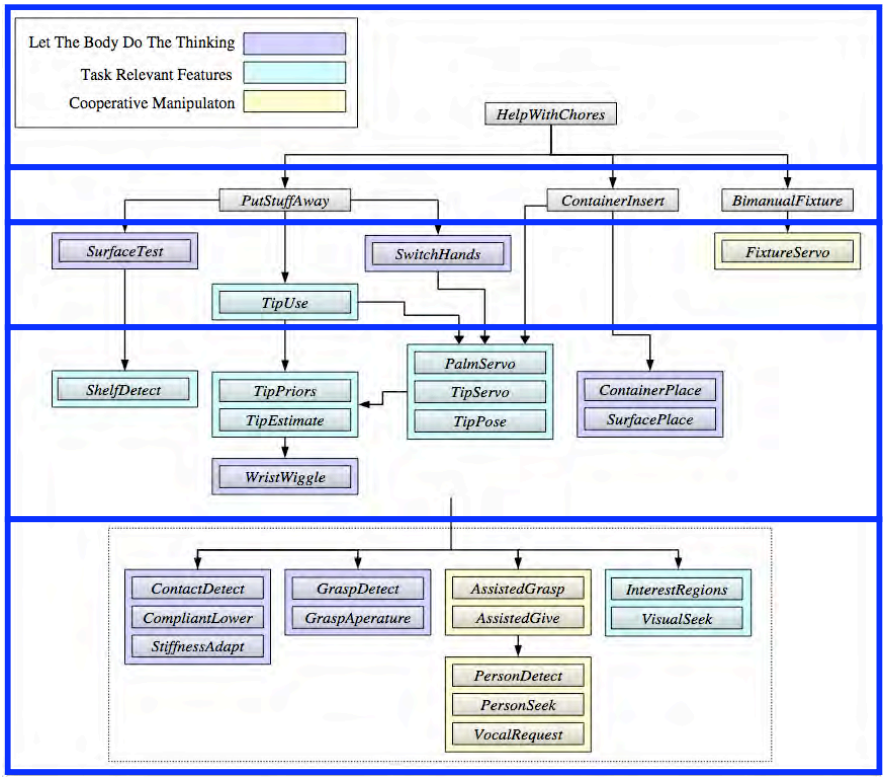
CSAIL

Visual attention system

Consolidate perceptual streams into a single spotlight of attention



Behavior Modules



Single, integrated system

Integrated tasks

Manual skills

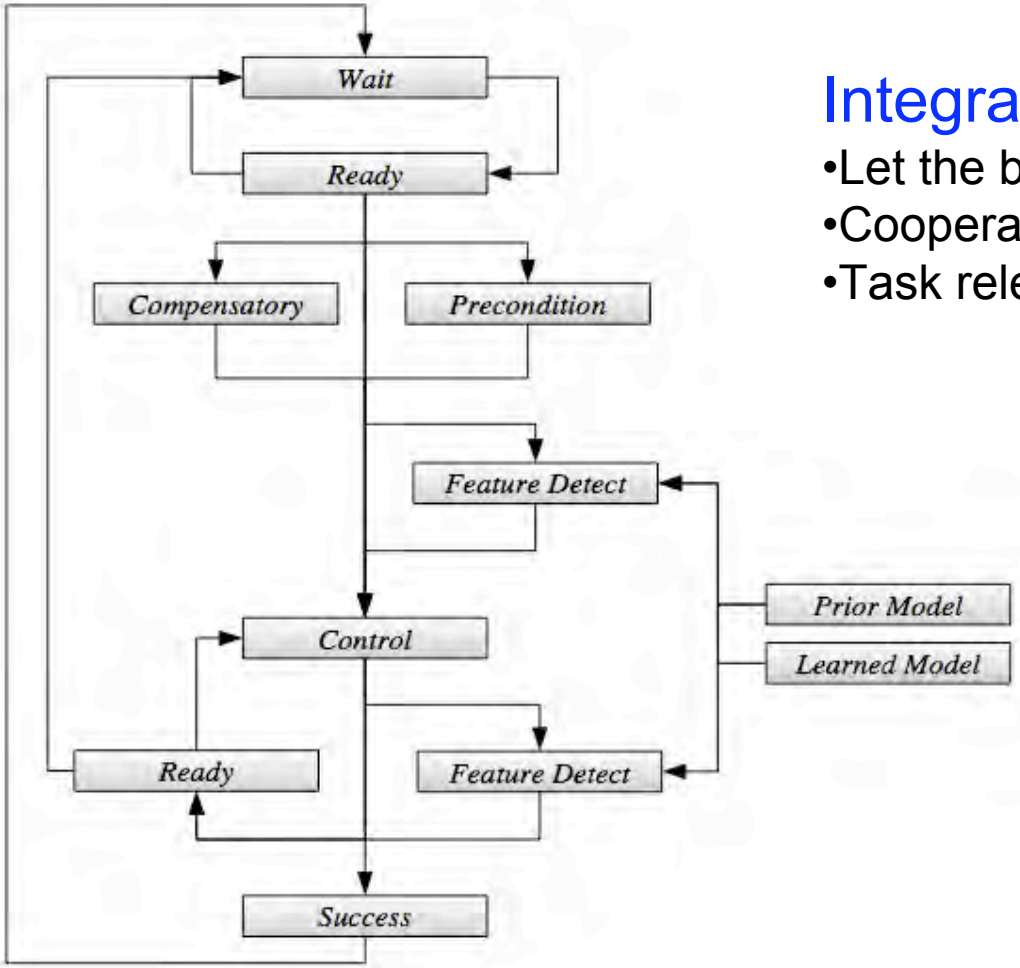
Task relevant features
Compensatory actions

Detectors and motor primitives

Main Process

125 Threads, 40 Wires, 35 FSAs, 10 Arbitrators

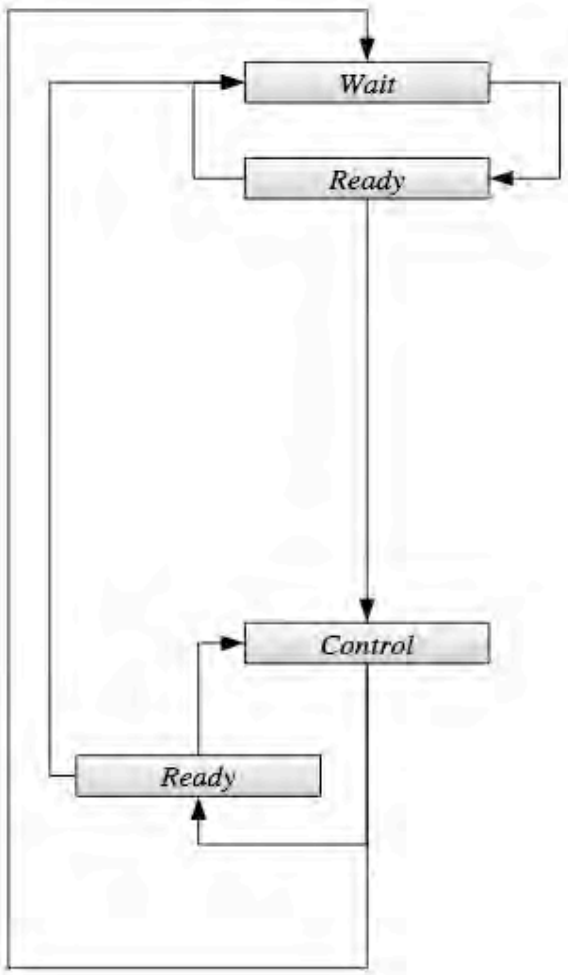
Manual skill algorithm



Integration

- Let the body do the thinking
- Cooperative manipulation
- Task relevant features

Manual skill algorithm

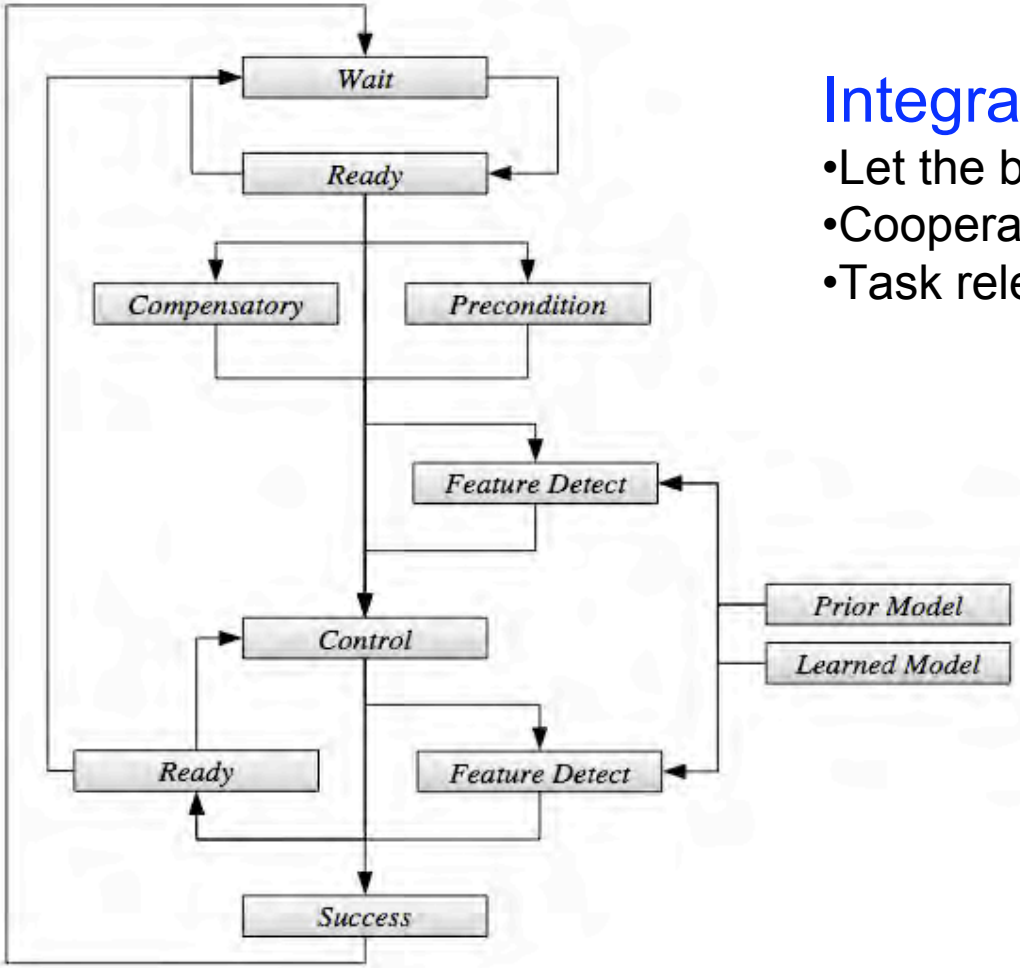


Integration

- Let the body do the thinking
- Cooperative manipulation
- Task relevant features

Basic control loop

Manual skill algorithm



Integration

- Let the body do the thinking
- Cooperative manipulation
- Task relevant features

My Messages:

- A new class of robots just gotten here
- Defense and home cleaning robots are at the vanguard of a transformation of human society
- There are lots of technologies that are enablers
- There is going to be strong pull from many future user communities
- Robots will infuse into all aspects of our lives