SOCIAL ROBOT NAVIGATION

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Motivation

- How should robots react around people?
- In hospitals, office buildings, etc.

Motivation

- Typical reaction: treat people as obstacles
  - Don't yield to oncoming people
  - Stop and block people while recalculating paths
  - Collide with people if they move unexpectedly

This is the current state of the art!

(studied by Mutlu and Forlizzi 2008)

Motivation

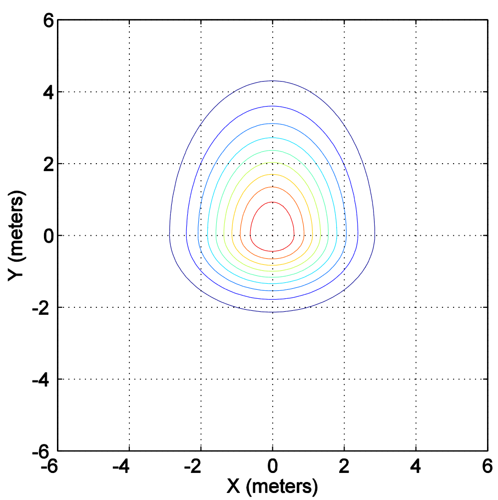
- How do *people* react around people?
- Social conventions
  - Respect personal space
  - Tend to one side of hallways
  - Yield right-of-way
- Common Ground (Clark 1996)
  - Shared knowledge
  - Can this be applied to a social robot?

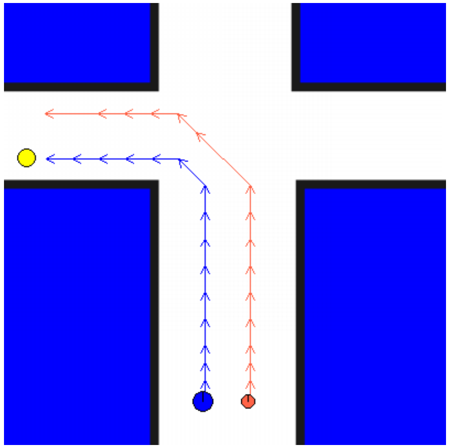
Thesis Statement

Human social conventions for movement can be represented as a set of mathematical cost functions. Robots that navigate according to these cost functions are interpreted by people as being socially correct.

Contributions

1. COMPANION framework
2. Social navigation in hallways
3. Companion robot
4. Joint human-robot social navigation





Outline

- Related Work
- Thesis Contributions
- Limitations and Future Work
- Conclusions

Outline

- **Related Work**
  - Human navigation
  - Robot navigation
  - Social robots
- Thesis Contributions
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- Conclusions

Related Work: Human Navigation

- Social conventions of walking around others
  - Use of personal space (Hall 1966 and many others)
  - Passing on a particular side (Whyte 1988; Bitgood and Dukes 2006)
- Culturally shared conventions
  - Common ground (Clark 1996)
  - Helps predict what others will do (Frith and Frith 2006)
- Efficiency
  - Minimize energy expenditure (Sparrow and Newell 1998)
  - Minimize joint effort in collaborative tasks (Clark and Brennan 1991)

Related work: Robot Navigation

- Local obstacle avoidance
  - Many examples, e.g.:
    - Artificial Potential Fields (Khatib 1986)
    - Vector Histograms (Borenstein and Koren 1989)
    - Curvature Velocity Method (Simmons 1996)
  - Do not account for human social conventions
  - Do not account for global goals
- Global planning
  - Random planners: RRTs (LaValle 1998)
  - Heuristic search: A* (Hart et al. 1968)
    - Re-planners: D* (Stentz 1994), GAA* (Sun et al 2008)

Related Work: Social Robots

- Specific tasks (non-generalizeable)
  - Passing people (Olivera and Simmons 2002; Pacchierotti et al. 2005)
  - Standing in line (Nakauchi and Simmons 2000)
  - Approaching groups of people (Althaus et al. 2004)
  - Giving museum tours (Burgard et al. 1999; Thrun et al. 1999)
- General navigation
  - Change velocity near people (Shi et al. 2008)
  - Respect “human comfort” (Sisbot et al. 2007)

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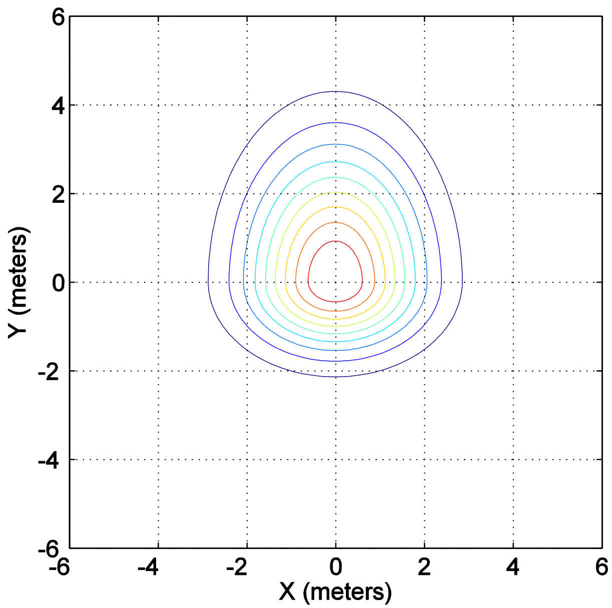


COMPANION Framework

Constraint-**O**ptimizing

Method for

Person-**A**cceptable

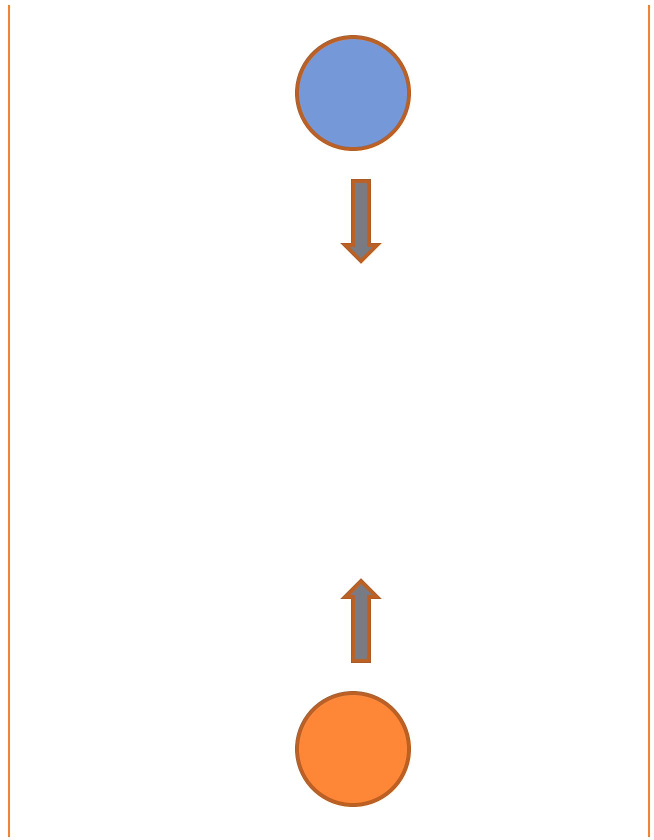
Navigat**ION**

COMPANION Framework

1. Socially optimal global planning, not just locally reactive behaviors
2. Social behaviors represented as mathematical cost functions

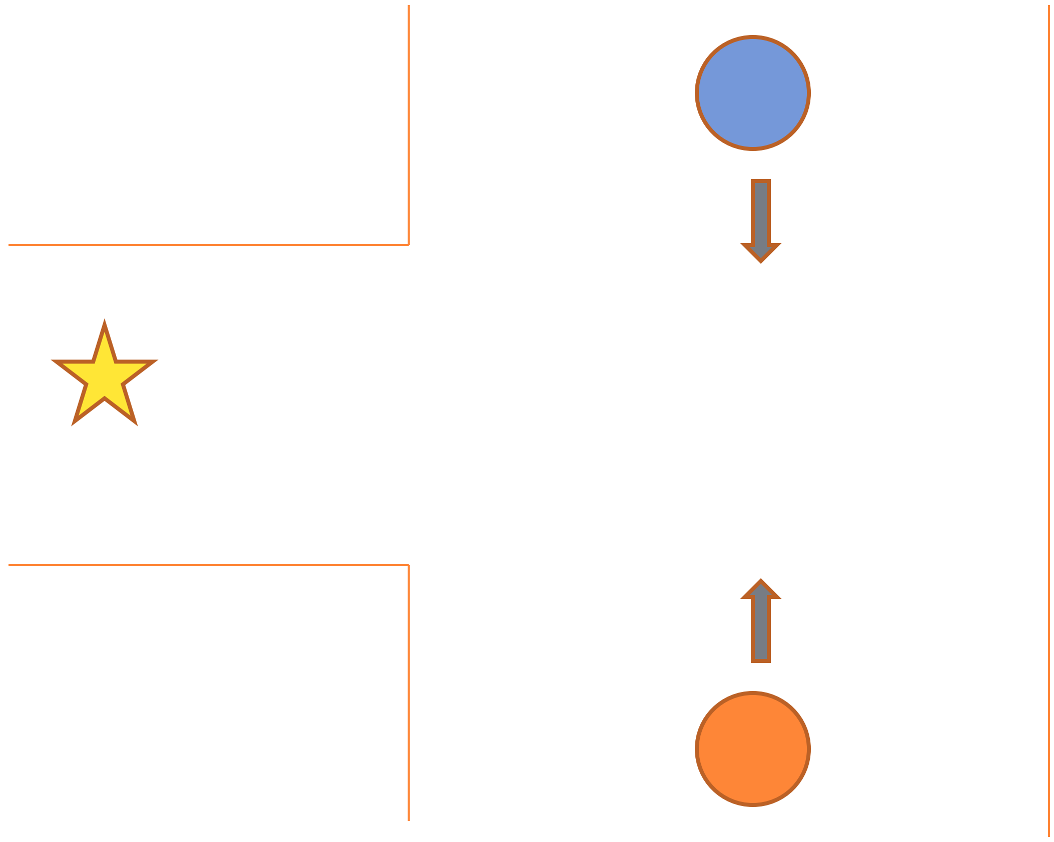
COMPANION: Global Planning

- Why global planning?



COMPANION: Global Planning

- Why global planning?



COMPANION: Global Planning

- What is global?
  - Short-term
    - Between two offices on the same floor
    - From an office to an elevator
    - 10-20 meters
  - Goal is real-time search
    - React to new sensor data
    - Continuously generating new plans

COMPANION: Global Planning

- Heuristic planning (A*)
  - Optimal paths
  - Arbitrary cost function: distance plus other constraints

$$\text{cost}(s_1, s_2, a) = \sum_i w_i \cdot c_i(s_1, s_2, a)$$

COMPANION: Constraints

- Constraint: limit the allowable range of a variable
  - Hard constraint: absolute limit
  - Soft constraint: cost to passing a limit
- Objective function
  - "Cost"
  - Can be *optimized* (maximized or minimized)
- Mathematical equivalence between soft constraints and objectives

COMPANION: Constraints

1. Minimize Distance
2. Static Obstacle Avoidance
3. Obstacle Buffer
4. People Avoidance
5. Personal Space
6. Robot “Personal” Space
7. Pass on the Right
8. Default Velocity
9. Face Direction of Travel
10. Inertia

COMPANION: Constraints

1. **Minimize Distance**
2. Static Obstacle Avoidance
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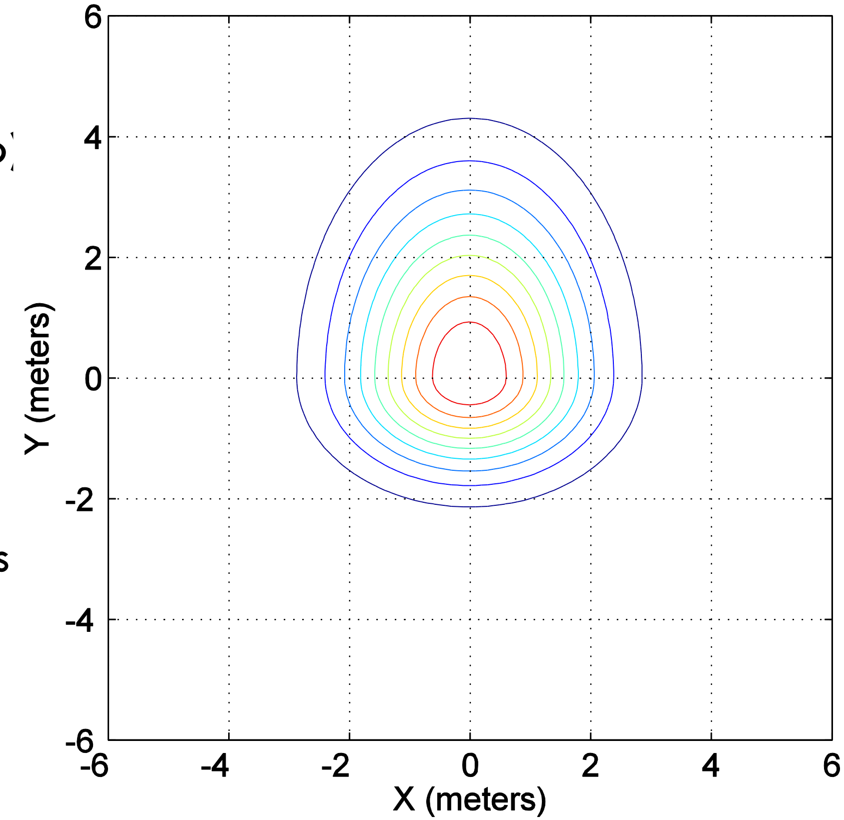
COMPANION: Distance

- Task-related: get to a goal
- Social aspect
  - Minimize energy expenditure (Sparrow and Newell 1998; Bitgood and Dukes 2006)
  - Take shortcuts when possible (Whyte 1988)
- Cost is Euclidian distance

$$c_{\text{distance}}(s_1, s_2, a) = \sqrt{(s_2.x - s_1.x)^2 + (s_2.y - s_1.y)^2}$$

COMPANION: Personal Space

- "Bubble" of space that people try to keep around themselves and others (Hall 1966)
- Changes based on walking speed (Gérin-Lajoie et al. 2005)
- People keep the same space around robots (Nakauchi and Simmons 2000; Walters et al. 2005)
- We model as a combination of two Gaussian functions



COMPANION: Face Travel

- Ability to side-step obstacles
  - Not all robots can do this!
  - Need *holonomic* robot
- Do not walk sideways for an extended period
  - Looks awkward (social)
  - Kinematically expensive (task-related)
- Cost relative to distance traveled sideways

$$c_{\text{facing}}(s_1, s_2, a) = a.t \, | a.v_y \, |$$

COMPANION: Weighting Constraints

- How to combine constraints?
  - Weighted linear combination

$$\mathrm{cost}(s_1, s_2, a) = \sum_i w_i \cdot c_i(s_1, s_2, a)$$

- Range of social behavior
  - Wide variation in human behavior
  - Different weights yield different "personalities"

COMPANION: Weighting Constraints

Constraint Name	Weight
Minimize Distance	1
Static Obstacle Avoidance	on
Obstacle Buffer	1
People Avoidance	on
Personal Space	2
Robot “Personal” Space	3
Pass on the Right	2
Default Velocity	2
Face Direction of Travel	2
Inertia	2

COMPANION: Implementation

- CARMEN framework (robot control and simulation)
- A* search on 8-connected grid
- Represent people in the state space
- Various techniques for improving search speed
- Laser-based person-tracking system

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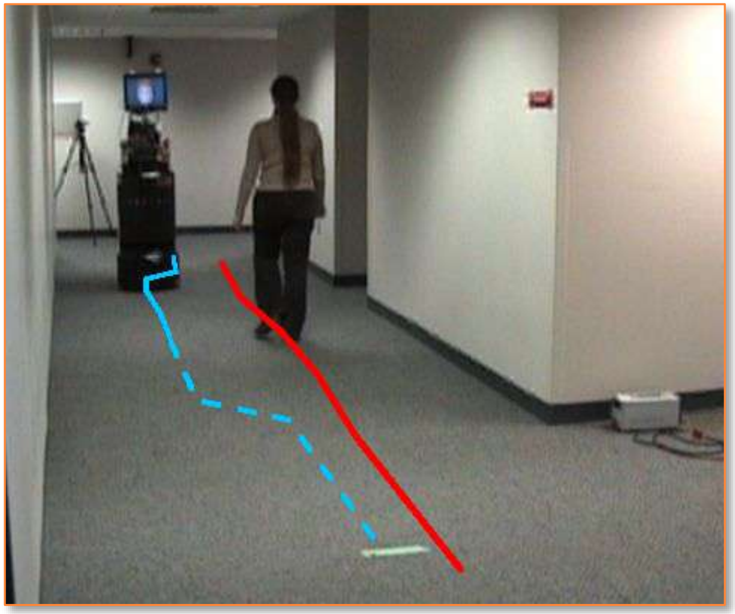
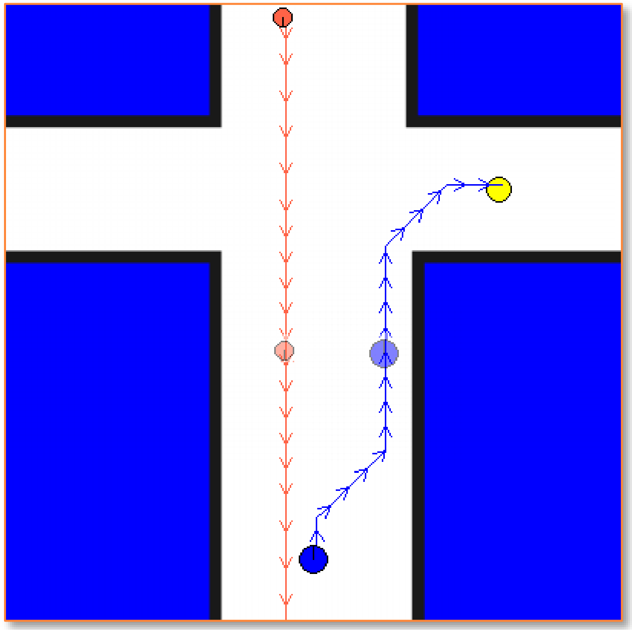
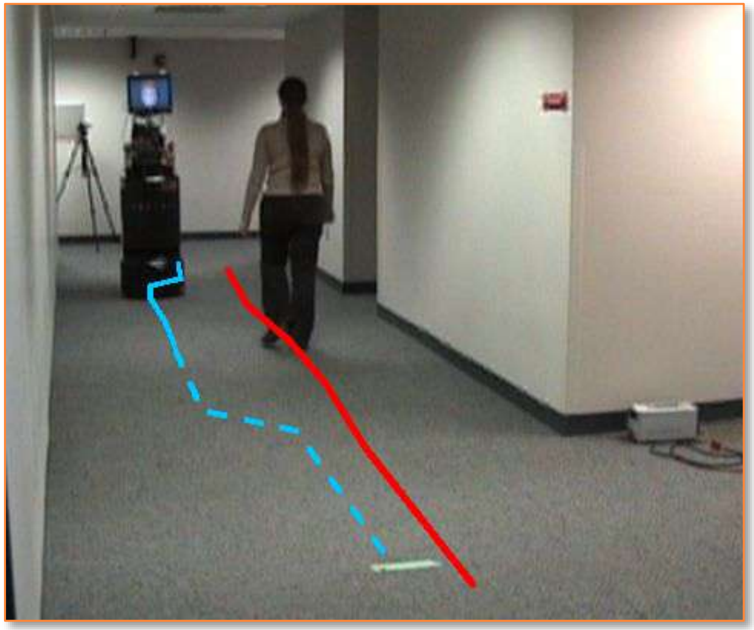


Hallway Interactions

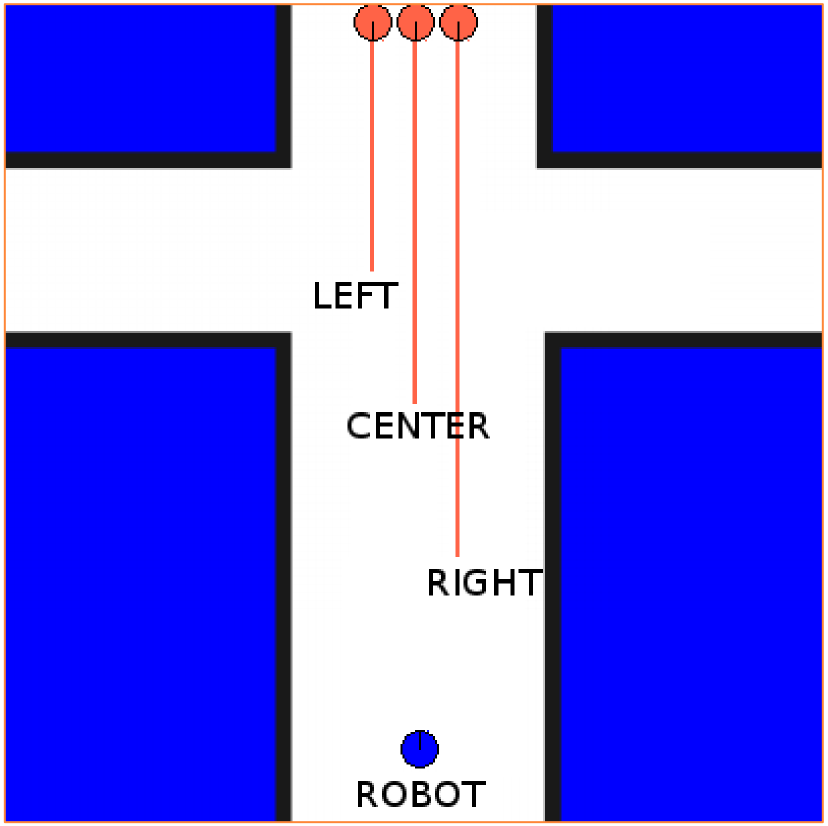
- Simulations
  - Static paths
  - Navigation
- User study
  - Human reactions
  - Grace





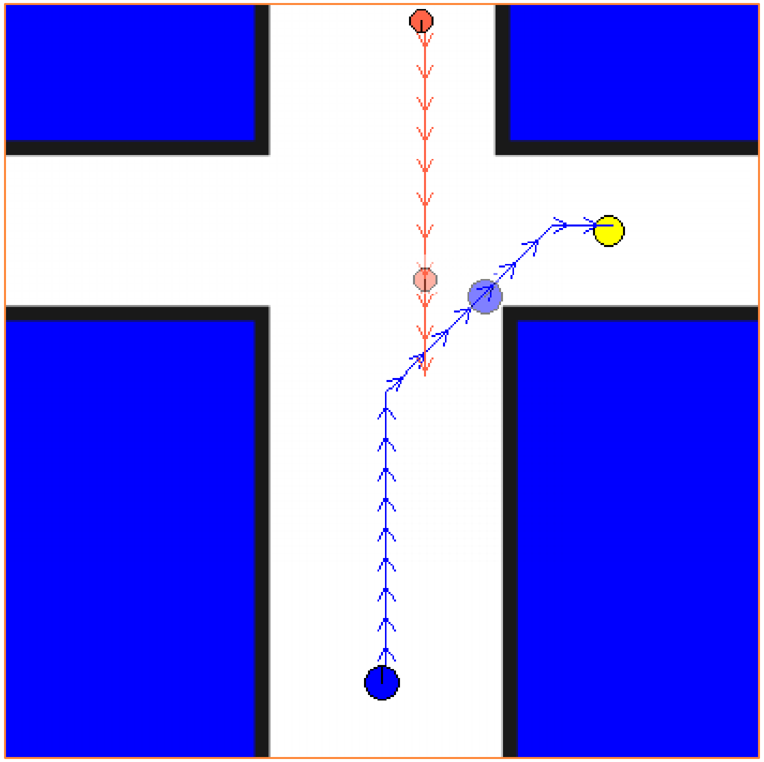
Hallway: Simulations

- Simple environment
- One person
  - 3 possible locations
  - 3 possible speeds
- 3 possible goals
  - Left turn
  - Right turn
  - Straight

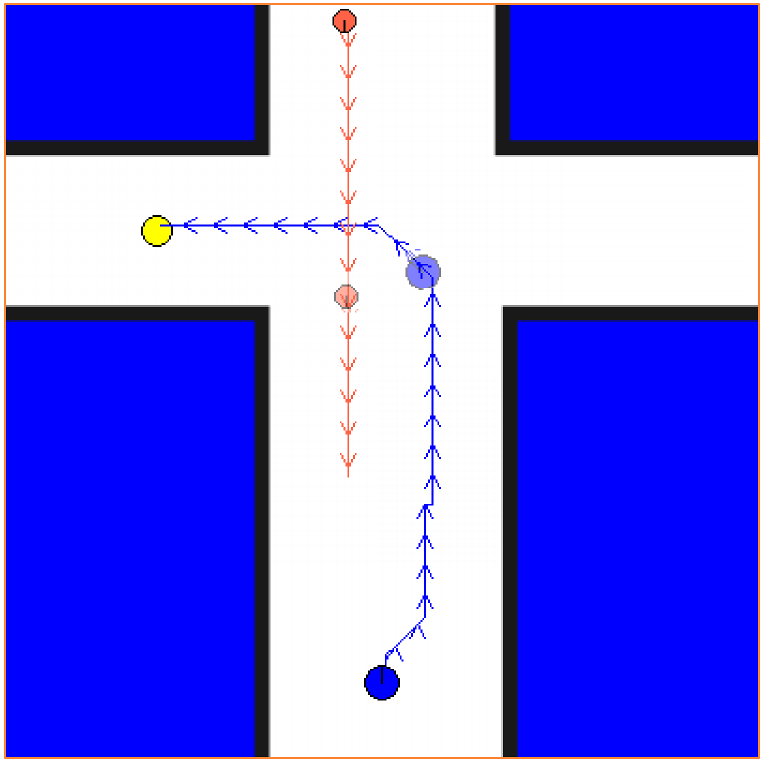


Hallway: Simulations

Right turn, person on right

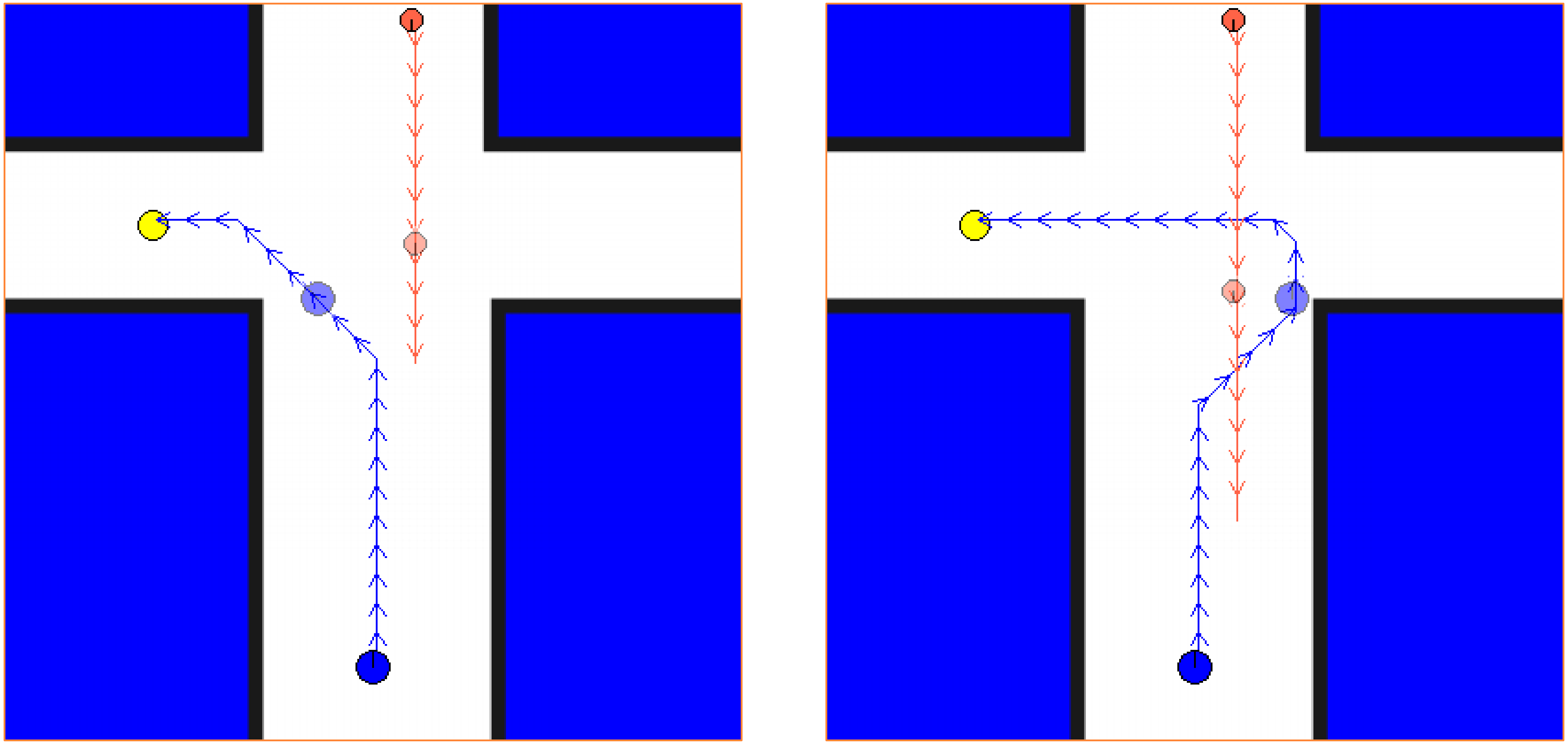


Left turn, person on left

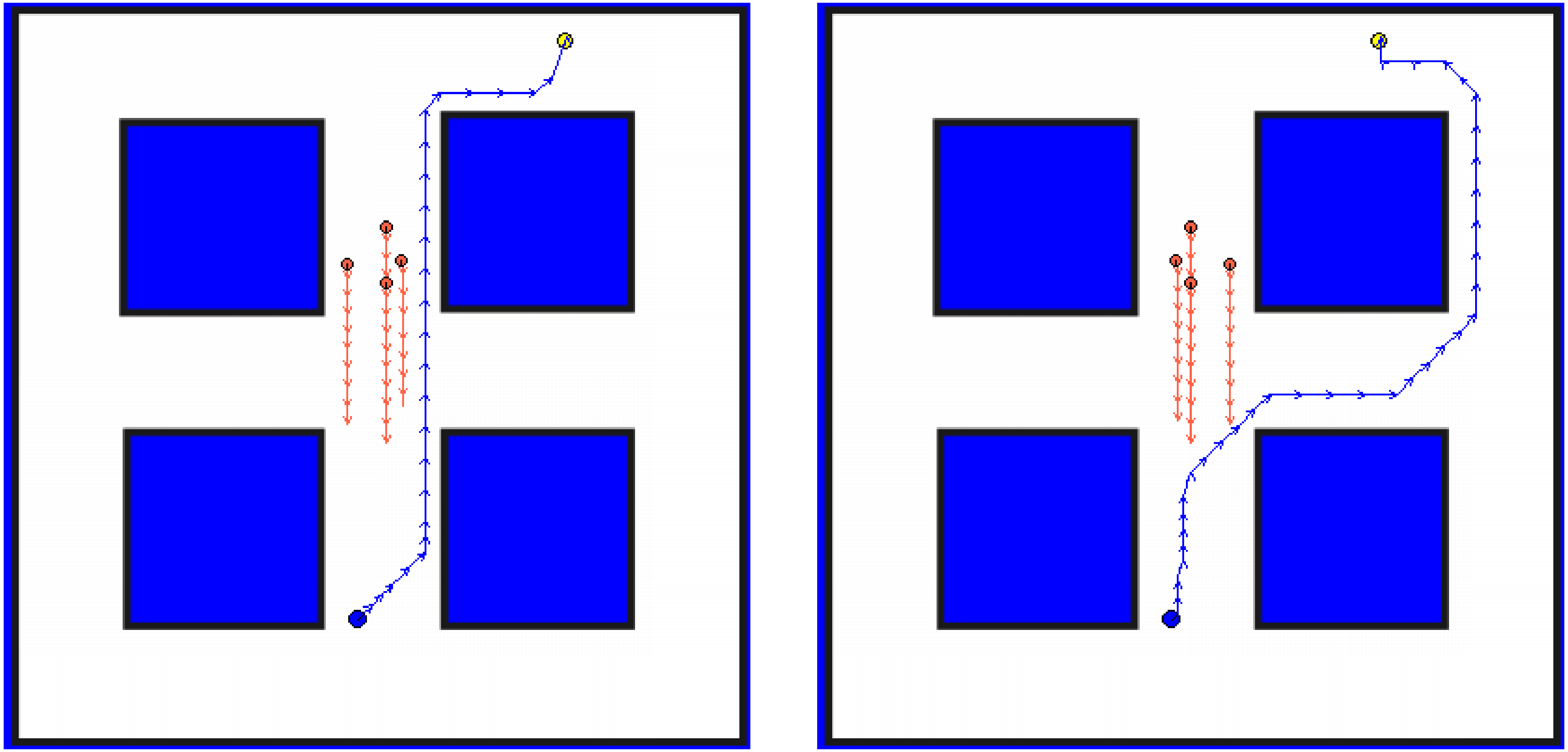


Hallway: Simulations

- What happens with different constraint weights?

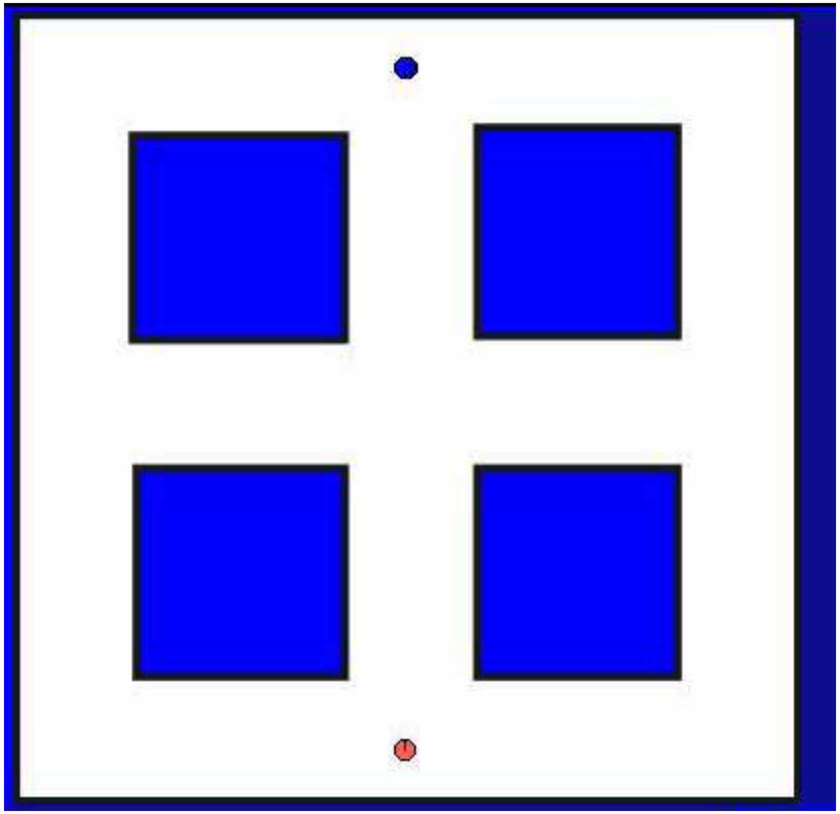


Hallway: Simulations

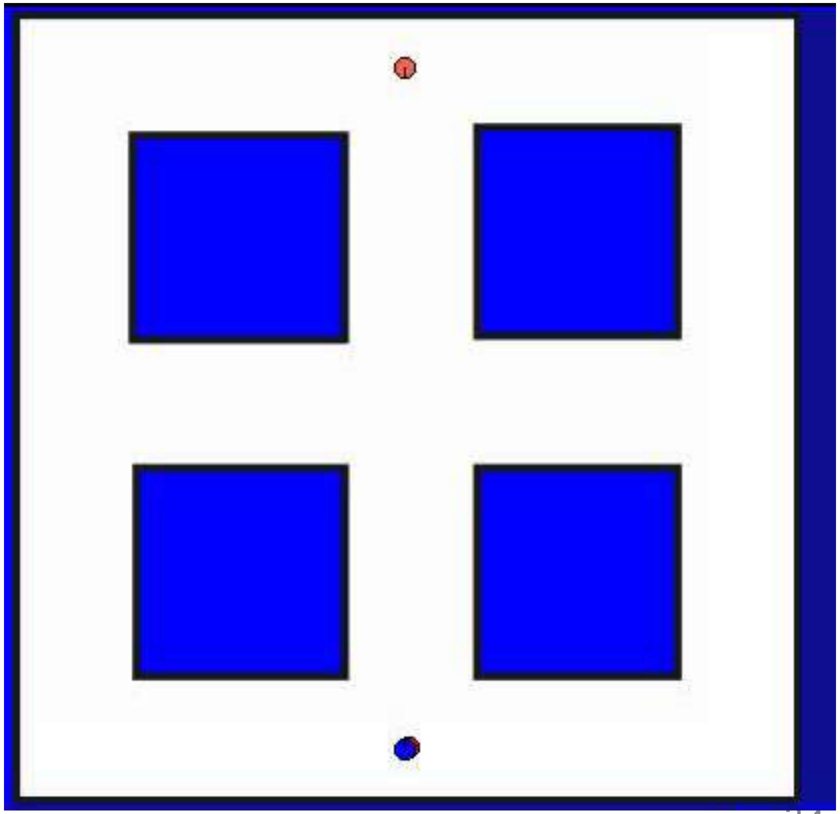


Hallway: Simulations

Top robot point-of-view



Bottom robot point-of-view



Hallway Study

- Is the robot's behavior socially appropriate?
- Robot used in study: Grace
- Tested "social" versus "non-social"
  - "Social": all defined constraints
  - "Non-social": same framework, but removed purely social conventions

Hallway Study: Constraints

Constraint Name	“Social”	“Non-Social”
Minimize Distance	1	1
Static Obstacle Avoidance	on	on
Obstacle Buffer	1	1
People Avoidance	on	on
Personal Space	**2**	**0**
Robot “Personal” Space	**3**	**0**
Pass on the Right	**2**	**0**
Default Velocity	1	1
Face Direction of Travel	**0**	**0**
Inertia	1	1

Hallway Study: Procedure

- 27 participants
- Within-subjects design
- Surveys
  - Affect (PANAS, SAM)
  - General robot behavior (5 questions)
  - Robot movement (4 questions)
  - Free-response comments

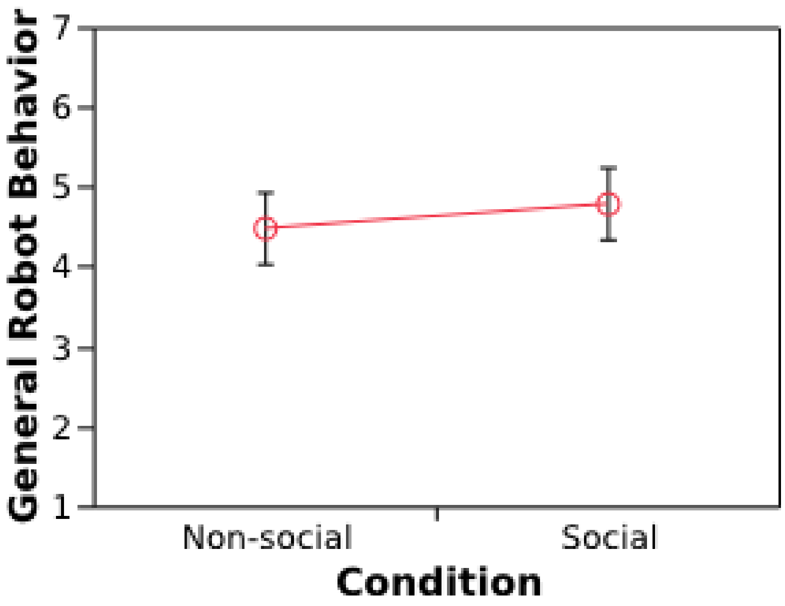
Hallway Study: Non-Social Example

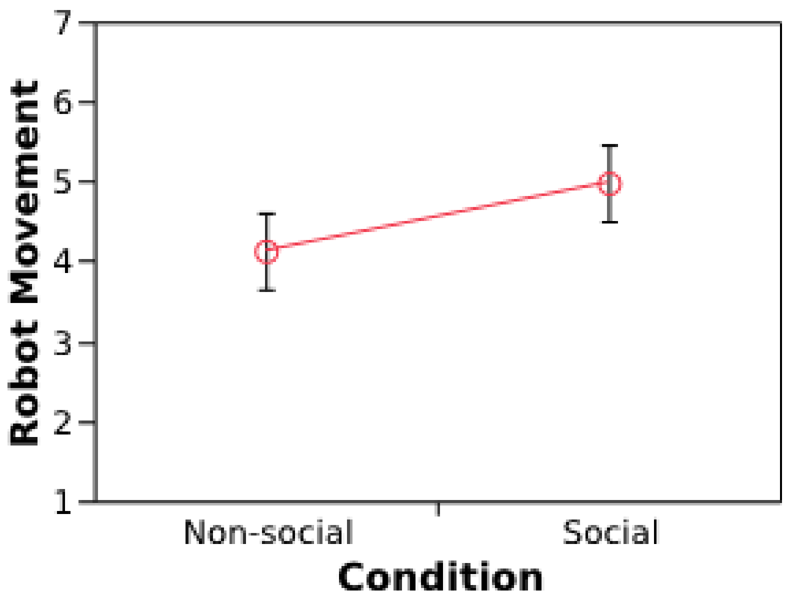
Hallway Study: Social Example

Hallway Study: Results

General Behavior: $p > 0.1$

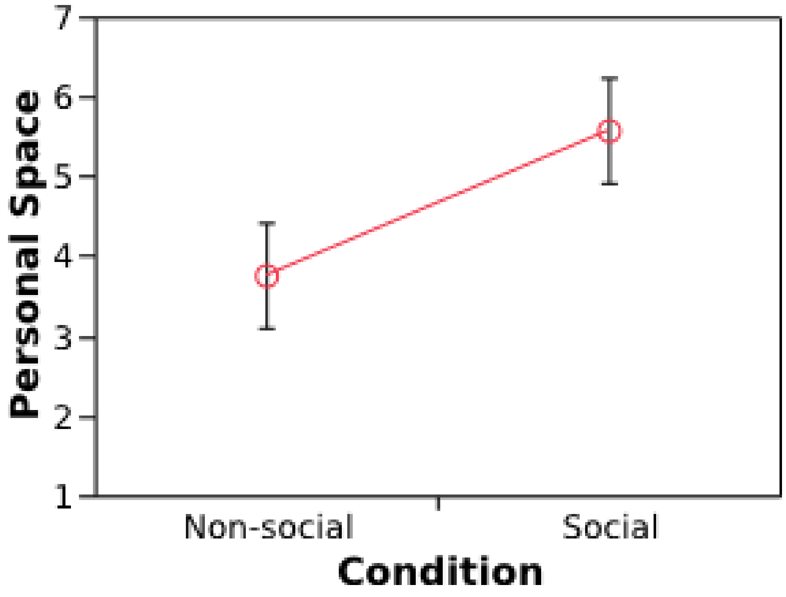
Robot Movement: $p = 0.015$ *



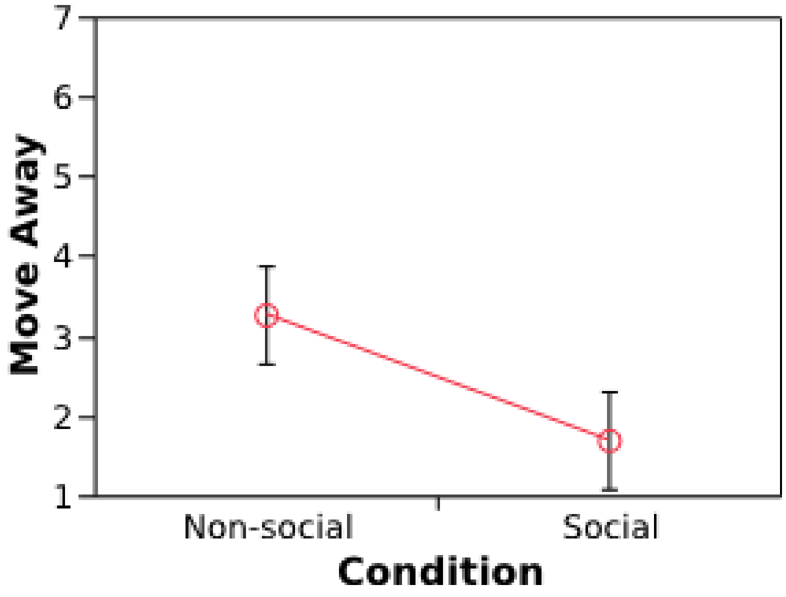


Hallway Study: Results

Personal Space: p = 0.0003 *



Move Away: p = 0.0006 *



Hallway Study: “Non-Social” Comments

- “I didn’t feel that the robot gave me enough space to walk on my side of the hallway.”
- “The robot came much closer to me than humans usually do.”
- “Robot acted like I would expect a slightly hostile/proud human (male?) to act regarding personal space—coming close to making me move without actually running into me.”

Hallway Study: “Social” Comments

- “It was really cool how it got out of *my* way.”
- “It felt like the robot went very close to the wall… which a human wouldn’t do as much (except maybe a very polite human…)”
- “I felt that the robot obeyed social conventions by getting out of my way and passing me on the right. However, it seemed to turn away from me quite suddenly, which was very slightly jarring.”

Hallway Study: “Social” Comments

- “It was really cool how **it got out of *my* way**.”
- “It felt like the robot went very close to the wall… which a human wouldn’t do as much (except maybe a **very polite** human…)”
- “I felt that the robot **obeyed social conventions** by getting out of my way and passing me on the right. However, it seemed to turn away from me quite suddenly, which was very slightly jarring.”

Hallway Study: "Social" Comments

- "It was really cool how it got out of *my* way."
- "It felt like the robot went **very close to the wall**… which a human wouldn't do as much (except maybe a very polite human…)"
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Hallway Study: Discussion

- "Jarring" behavior
  - Robot *turns away* to yield
  - Non-holonomic behavior
- "Social" condition rated higher on social movement scale
  - Better respected personal space
  - Required less avoidance movements from people
- No difference on other social scales
  - Same robot both times
- Even "non-social" behavior was not *anti*-social!
  - Different personalities

Hallways: Summary

- Simulation results
  - COMPANION framework
  - Flexible application of social conventions
- User study
  - Robot behaviors are interpreted according to human social norms
  - Ascribed personalities: “overly polite” versus “hostile”

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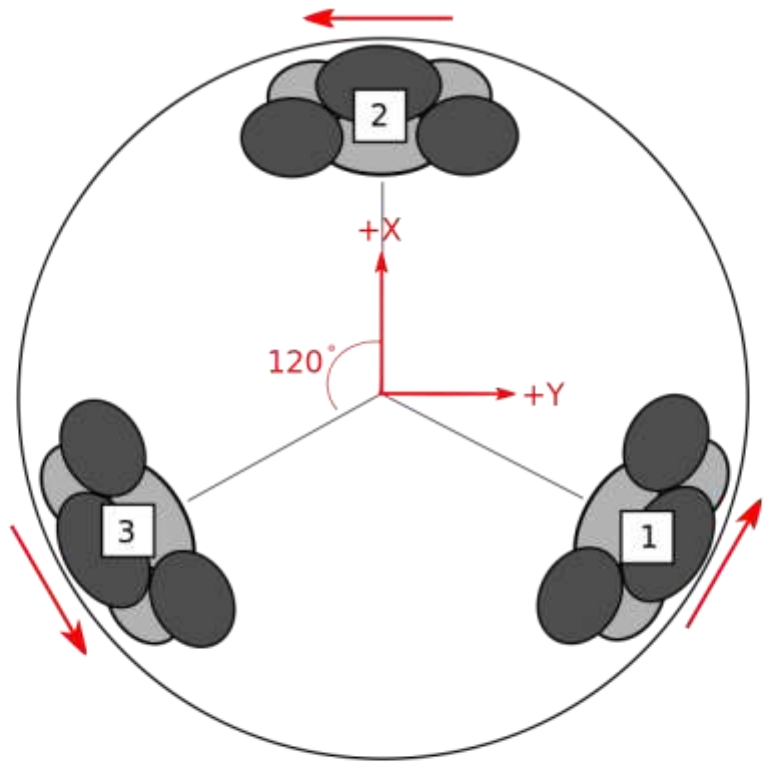
Companion Robot: Motivation

- Research goal: social navigation around people
- Ability to side-step obstacles
  - Holonomic capability
  - Necessary for social behavior
- "Friendly" appearance
  - Grace is ~6' tall!

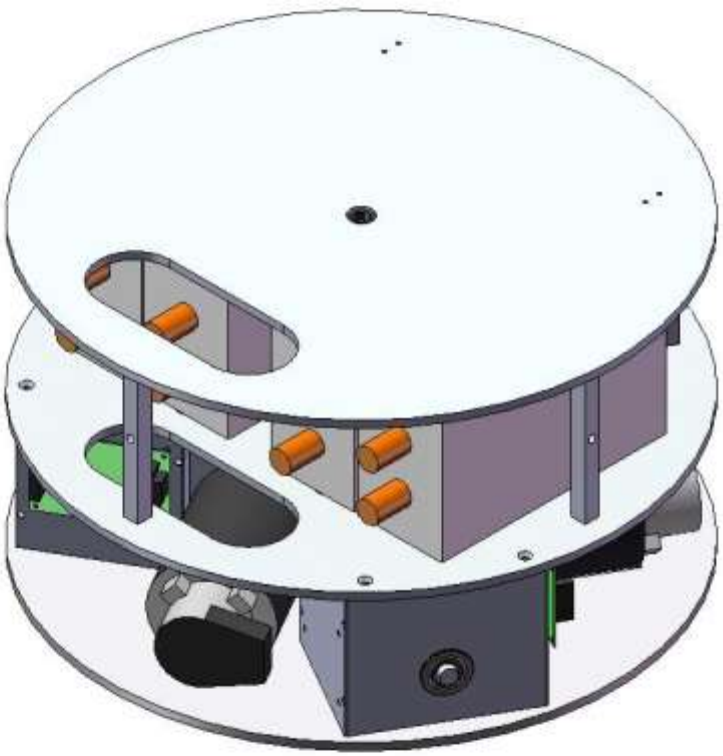
Companion Robot: Base

- Holonomic: can move sideways instantaneously
- Designed primarily by Brian Kirby (staff)
- Capabilities
  - ~2.0m/s maximum velocity
  - 3-6 hours battery life
  - Continuous acceleration
  - 360-degree laser coverage

Companion Robot: Base

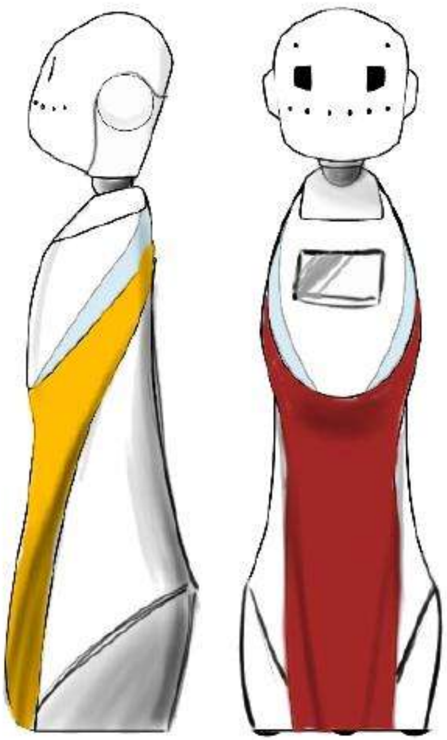


Companion Robot: Base

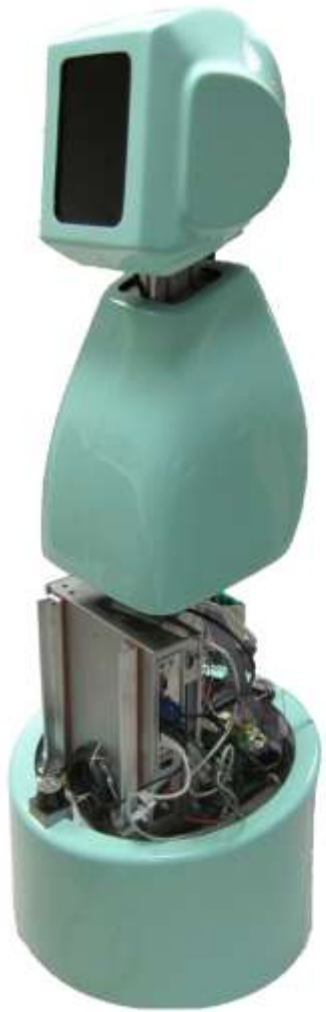


Companion Robot: Shell

- Design criteria:
  - Organic shape; not a “trash can”
  - Tall enough to travel with people, but not intimidating
  - Not suggestive of skills beyond capabilities
  - Have a face
  - Provide orientation with distinct front, back, and sides
- Iterative design process
  - Scott Smith, Josh Finkle, Erik Glaser



Companion Robot: Final



Companion Robot: Final

Companion Robot: Status

- Still in progress
- Shell: need to identify suitable fabric for covering
- Base: joystick control (almost)
  - Motor controllers must be better tuned
  - Higher-level control: need holonomic localization

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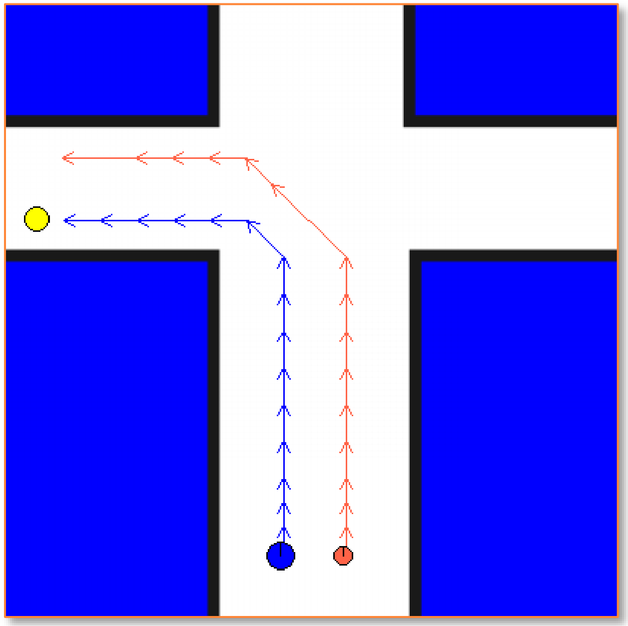


Joint Social Navigation: Motivation

- What is joint planning and navigation?
  - Joint tasks for a person and a robot
  - Robot must stay coordinated with person
- Task of side-by-side travel
  - Nursing home assistant: escort residents socially
  - Smart shopping cart: stays in sight

Joint Social Navigation: Motivation

- Current robotic escorting systems require people to follow behind the robot
- No regard for social conventions
- Not how people walk together



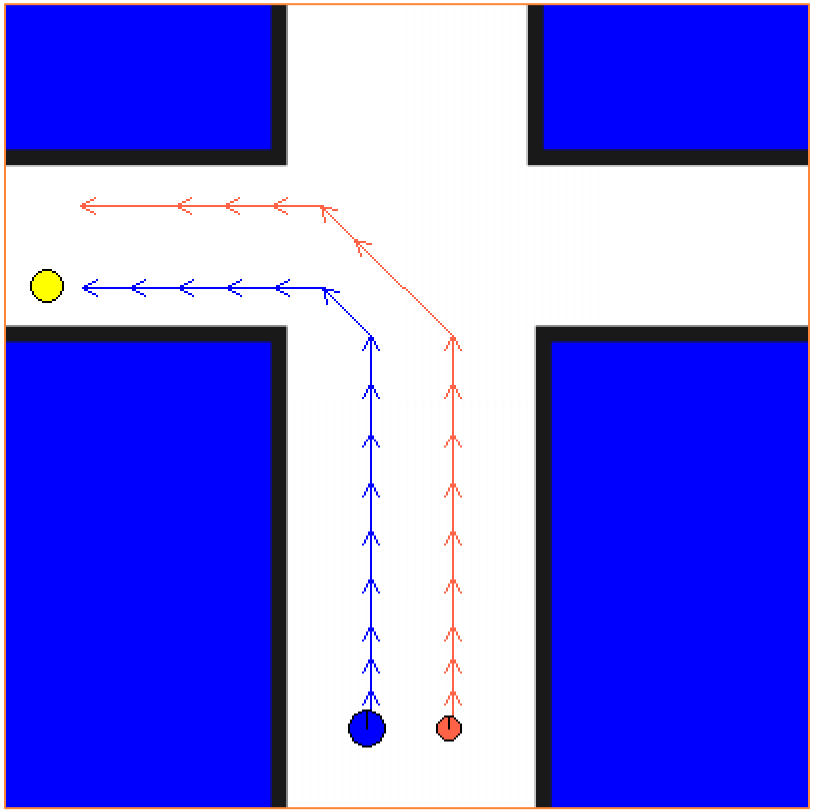
Joint Social Navigation: Approach

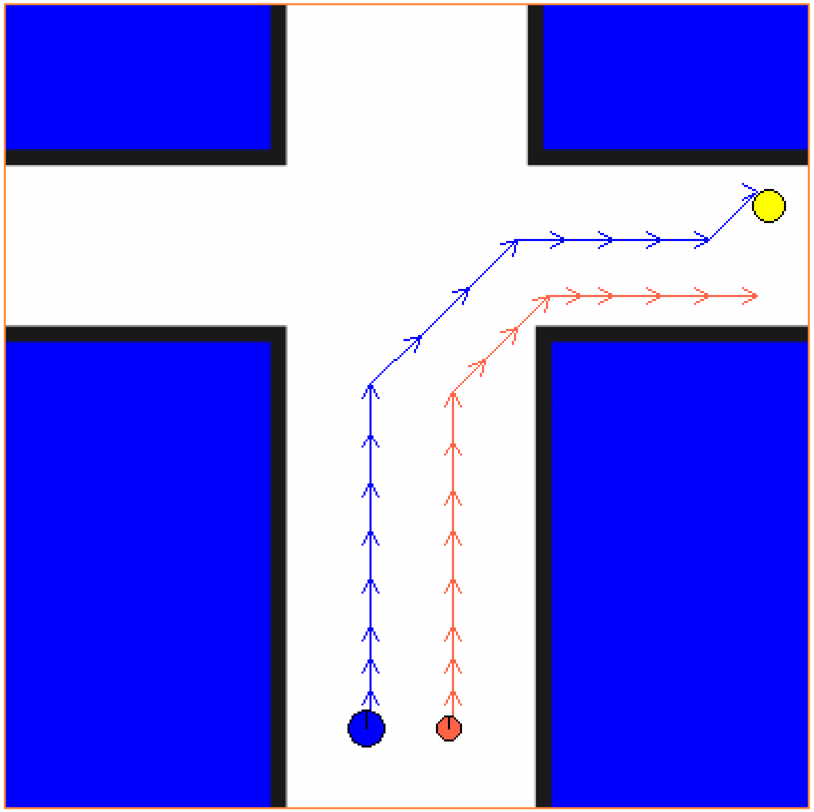
- Extension to COMPANION framework
  - Plan for a person to travel with the robot
  - Common ground: robot can assume person will follow cues
- **Joint Goals**
  - Desired final world state, including goals for both the robot and the person
- **Joint Actions**
  - Action to be taken by a robot plus action to be taken by a person, over the same length of time
- **Joint Constraints**
  - Minimize joint cost for the robot and the person

Joint Social Navigation: Side-by-side

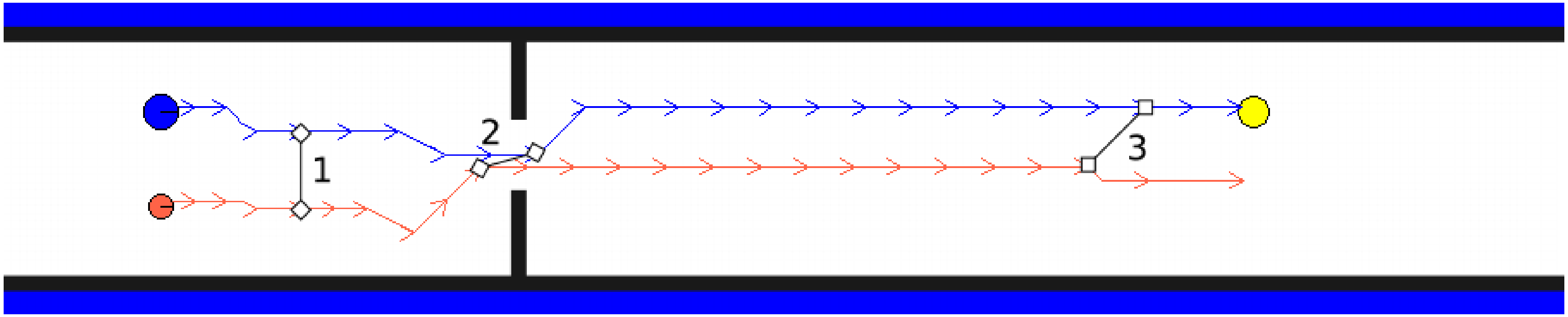
- Constrain the relative position of robot and person
- Two additional constraints:
  - **Walk with a person**: keep a particular distance
  - **Side-by-side**: keep a particular angle
- Balance weights with **Personal Space**

Joint Navigation: Examples





Joint Navigation: Examples



Joint Planning: Summary

- Extension to the COMPANION framework
  - Joint goals
  - Joint actions
  - Joint constraints
- Side-by-side escorting task
  - Walk with a person constraint (distance)
  - Side-by-side constraint (angle)
- Still not real-time
  - Huge state space to search

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Limitations

- Real-time planning
  - Currently only achieved at expense of optimality
  - Possible improvements:
    - Parallelization
    - Other planners
    - Moore's Law
- Person tracking
  - Poor performance from current laser-based system
  - Improve with multi-sensor approach

Future Work

- Additional on-robot experiments
  - More scenarios
  - Companion versus Grace
- Learning constraint weights
- Adding additional social conventions
  - Verbal/non-verbal cues
  - Gender, age, etc.
- Conventions for other cultures
- Additional tasks
  - Side-by-side following (rather than leading)
  - Standing in line
  - Elevator etiquette

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Conclusion

Human social conventions for movement can be represented as mathematical cost functions, and robots that navigate according to these cost functions are interpreted by people as being socially correct.

Conclusion: Contributions

- COMPANION framework
  - 10 key social and task-related conventions
  - Socially optimal global planning
- Hallway navigation tasks
  - Many results in simulation
  - User study on the robot Grace
- Companion robot
  - Holonomic base
  - Designed for human-robot interaction studies
- Joint planning
  - Extension to COMPANION framework
  - Simulation results for side-by-side escorting task

Conclusion: Summary

- Need for robots to follow human social norms
- COMPANION framework produces social behavior
- Foundation for future human-robot social interaction research

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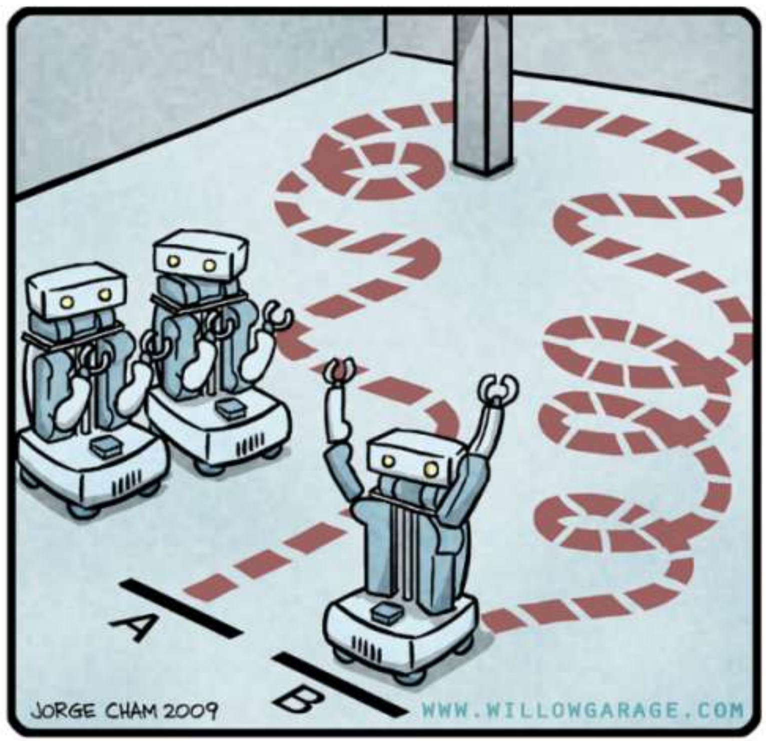
Thanks!

R.O.B.O.T. Comics



"HIS PATH-PLANNING MAY BE SUB-OPTIMAL, BUT IT'S GOT FLAIR."