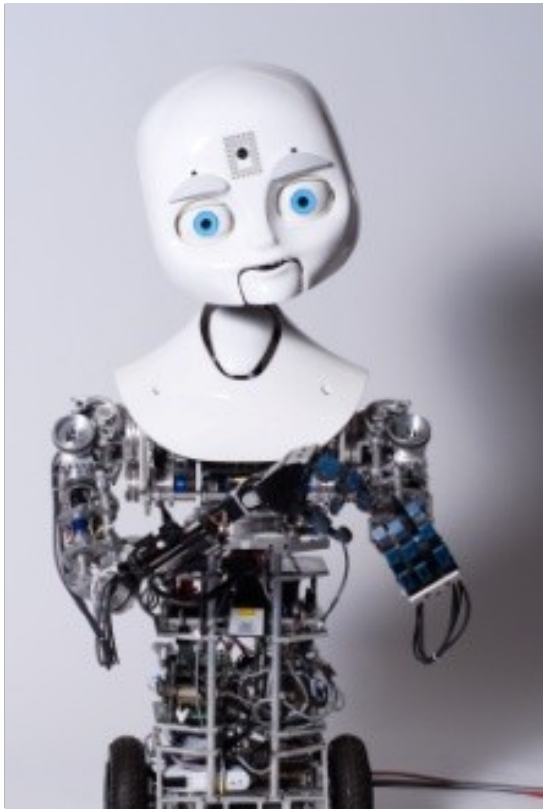
Natural Language and Spatal Reasoning

Stefanie Tellex

MIT Media Lab
Ph.D. Thesis Defense

Where should the robot go?

With your back to the windows, walk straight through the door near the elevators. Continue to walk straight, going through one door until you come to an intersection just past a whiteboard. Turn left, turn right, and enter the second door on your right (sign says "Administrative Assistant").



Show me people walking across the kitchen.

Show me people walking across the kitchen.

Motivation

- What semantic structures can enable a system to understand and use spatial language in realistic situations?
- Applications
  - Information surveillance and reconnaissance.
  - Dialog interface to navigation devices.
  - Supervisory control of robots.

Outline

- Spatial Prepositions
- Spatial Description Clauses
- Direction Understanding
- Spatial Language Video Retrieval
- Conclusion

Related Work

- Cognitive Semantics
  - Talmy (2005), Landau and Jackendoff (1993), Regier and Carlson (2001), Siskind (2001)
- Language and Robots
  - MacMahon et. al (2006), Hsiao et. al (2008), Skubic et. al (2004)
- Video Retrieval
  - Katz et. al (2004), Ivanov and Wren (2005), Fleischman et. al (2006), Naphade et. al (2006)

Spatial Prepositions

Spatial Prepositions in English

about, above, across, after, against, along, alongside, amid(st), among(st), around, at, atop, behind, below, beneath, beside, between, betwixt, beyond, by, down, from, in, inside, into, near, nearby, off, on, onto, opposite, out, outside, over, past, through, throughout, to, toward, under, underneath, up, upon, via, with, within, without, far from, in back of, in between, in front of, in line with, on top of, to the left of, to the right of, to the side of

(from Landau and Jackendoff, 1993)

the, of, and, to, a, in, that, is, was, he, for, it, with, as, his, on, be, at, by, i, this, had, not, are, but, from, or, have, an, they, which, one, were, you, all, her, she, there, would, their, we, him, been, has, when, who, will, no, more, if, out, its, so, up, said, what, about, than, into, them, can, only, other, time, new, some, could, these, two, may, first, then, do, any, like, my, now, over, such, our, man, me, even, most, made, after, also, well, did, many, before, must, years, back, through, much, where, your, way, down, should, because, long, each, just, state, people, those, too, how, Mr., little, good, world, make, very, year, still, see, own, work, men, day, get, here, old, between, both, life, being, under, three, never, know, same, last, another, while, us, off, might, great, states, go, come, since, against, right, came, take, used, himself, few, house, American, use, place, during, high, without, again, home, around, small, however, found, mrs, part, school, thought, went, say, general, once, upon, every, left, war, don't, does, got, united, number, hand, course, water, until, always, away, public, something, fact, less, through, far, put, head, think, called, set, almost, enough, end, took, government, night, yet, system, better, four, nothing, told, eyes, city, going, president, why, days, present, point, didn't, look, find, asked, second, group, later, next, room, social, business, knew, program, give, half, side, face, toward, white, five, let, young, form, given, per, order, large, several, national, important, possible, rather, big, among, case, often, early, john, things, looked, ever, become, best, need, within, felt, along, children, saw, church, light, power, least, family, development, interest, others, open, thing, seemed, want, area, god, members, mind, help, country, service, turned, door, done, law, although, whole, line, problem, sense, certain, different, kind, began, thus, means, matter, perhaps, name, times, york, itself, action, human, above, week, company, free, example, hands, local, show, history, whether, act, either, gave, death, feet, today, across, body, past, quite, taken, anything, field, having, seen, word, car, experience, I'm, money, really, class, words, already, college, information, tell, making, sure, themselves, together, full, air, shall, held, known, period, keep, political, real, miss, probably, century, question, seems, behind, cannot, major, office, brought, special, whose, boy, cost, federal, economic, self, south, problems, heard, six, study, ago, became, moment, run, available, job, street, result, short, west, age, change, position, board, individual, reason,

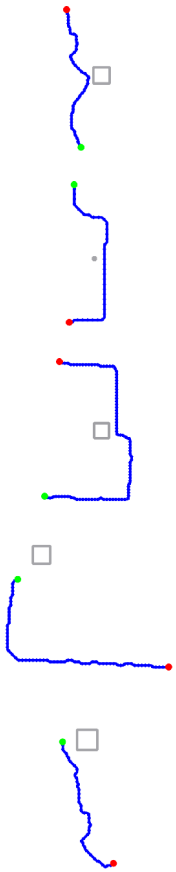
the, of, and, to, a, in, that, is, was, he, for, it, with, as, his, on, be, at, by, i, this, had, not, are, but, from, or, have, an, they, which, one, were, you, all, her, she, there, would, their, we, him, been, has, when, who, will, no, more, if, out, its, so, up, said, what, about, than, into, them, can, only, other, time, new, some, could, these, two, may, first, then, do, any, like, my, now, over, such, our, man, me, even, most, made, after, also, well, did, many, before, must, years, back, through, much, where, your, way, down, should, because, long, each, just, state, people, those, too, how, Mr., little, good, world, make, very, year, still, see, own, work, men, day, get, here, old, between, both, life, being, under, three, never, know, same, last, another, while, us, off, might, great, states, go, come, since, against, right, came, take, used, himself, few, house, American, use, place, during, high, without, again, home, around, small, however, found, mrs, part, school, thought, went, say, general, once, upon, every, left, war, don't, does, got, united, number, hand, course, water, until, always, away, public, something, fact, less, through, far, put, head, think, called, set, almost, enough, end, took, government, night, yet, system, better, four, nothing, told, eyes, city, going, president, why, days, present, point, didn't, look, find, asked, second, group, later, next, room, social, business, knew, program, give, half, side, face, toward, white, five, let, young, form, given, per, order, large, several, national, important, possible, rather, big, among, case, often, early, john, things, looked, ever, become, best, need, within, felt, along, children, saw, church, light, power, least, family, development, interest, others, open, thing, seemed, want, area, god, members, mind, help, country, service, turned, door, done, law, although, whole, line, problem, sense, certain, different, kind, began, thus, means, matter, perhaps, name, times, york, itself, action, human, above, week, company, free, example, hands, local, show, history, whether, act, either, gave, death, feet, today, across, body, past, quite, taken, anything, field, having, seen, word, car, experience, I'm, money, really, class, words, already, college, information, tell, making, sure, themselves, together, full, air, shall, held, known, period, keep, political, real, miss, probably, century, question, seems, behind, cannot, major, office, brought, special, whose, boy, cost, federal, economic, self, south, problems, heard, six, study, ago, became, moment, run, available, job, street, result, short, west, age, change, position, board, individual, reason,

Modeling Spatial Prepositions

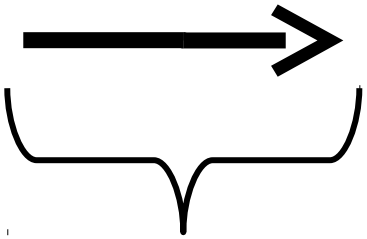
- Functions that take geometric arguments.
- Classifiers for “to,” “across,” “towards,” “through,” “around,” etc.
- Library of features.
- Train and test on labeled examples.

Learning Spatial Prepositions

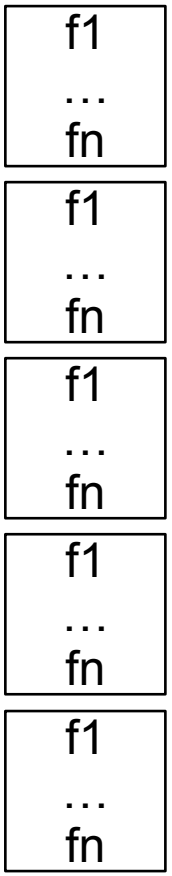
Examples of *past*



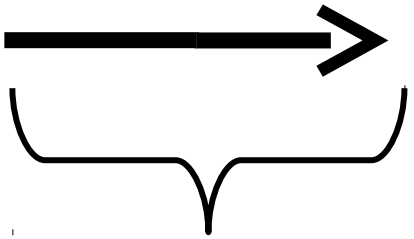
Features



e.g., the minimum distance between the robot and the landmark



Probability of *past*

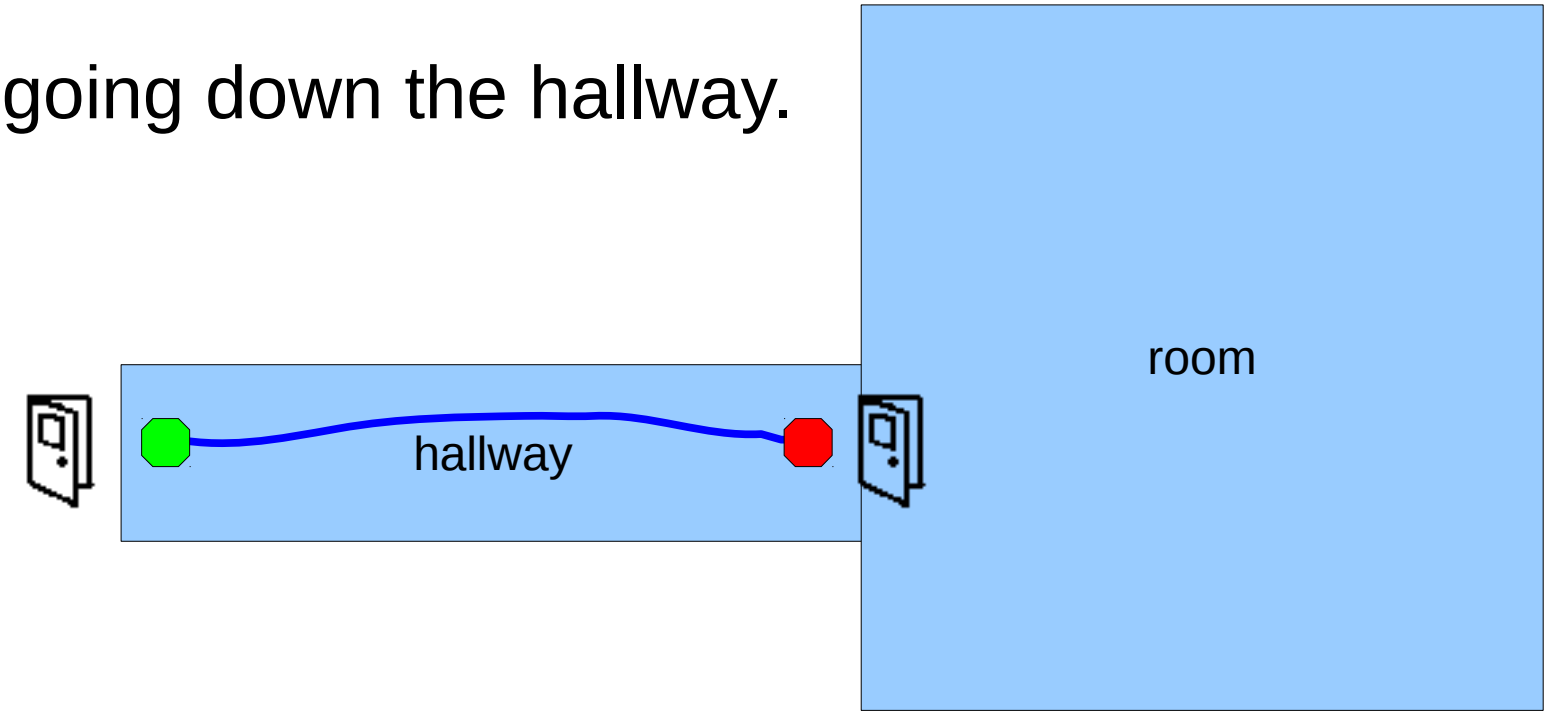


e.g., naïve Bayes, decision tree, SVM

Across Video

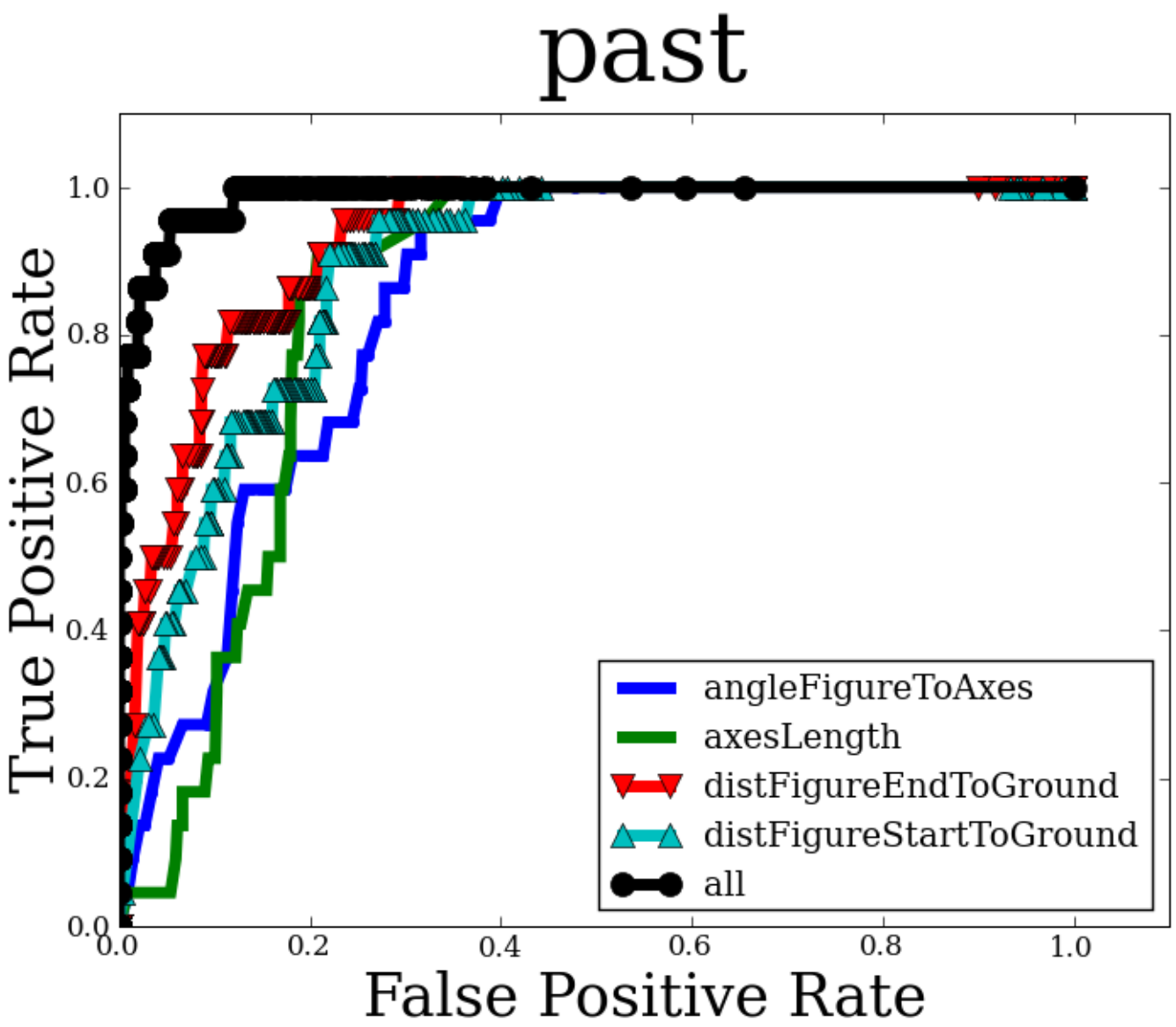
Corpus of Examples of Spatial Relations

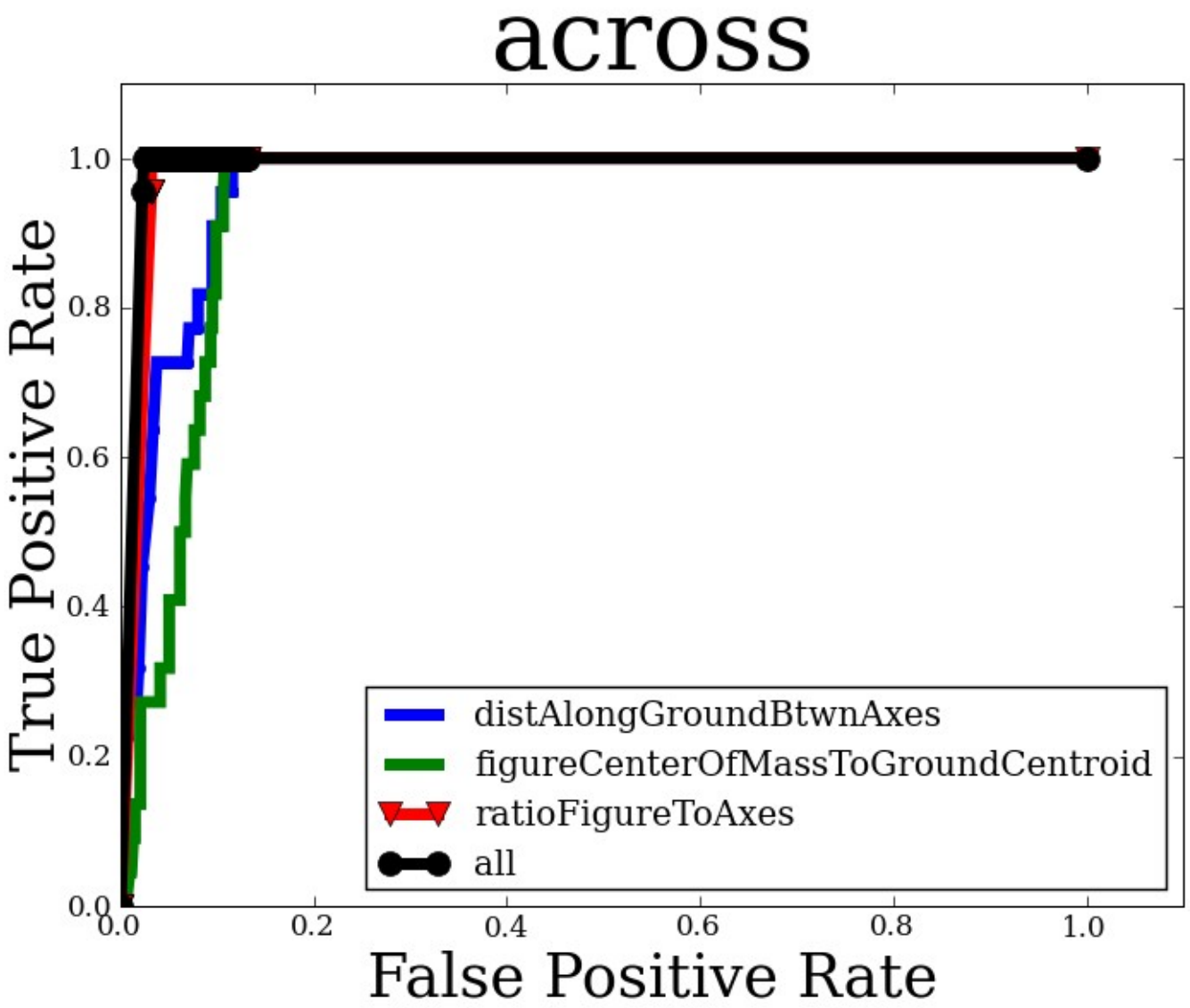
Draw a path going down the hallway.



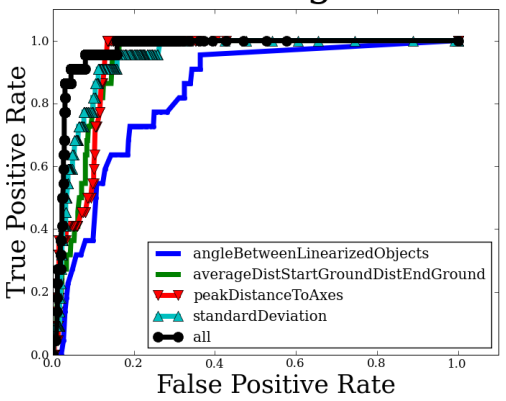
Training Classifiers for Spatial Prepositions

- Binary classifiers.
- Positive examples of “across” are negative examples of “to.”
  - Some exceptions (e.g., “to” and “towards.”)

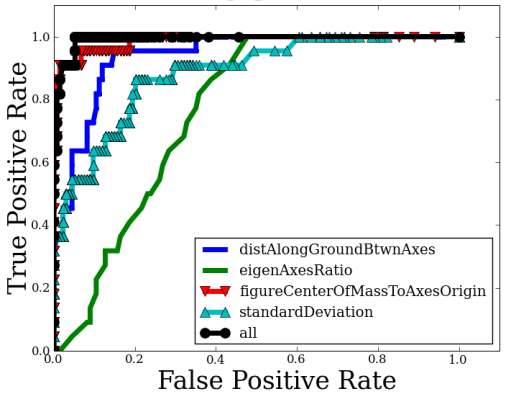

past
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
angleFigureToAxes
axesLength
distFigureEndToGround
distFigureStartToGround
all


across
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
distAlongGroundBtwnAxes
figureCenterOfMassToGroundCentroid
ratioFigureToAxes
all

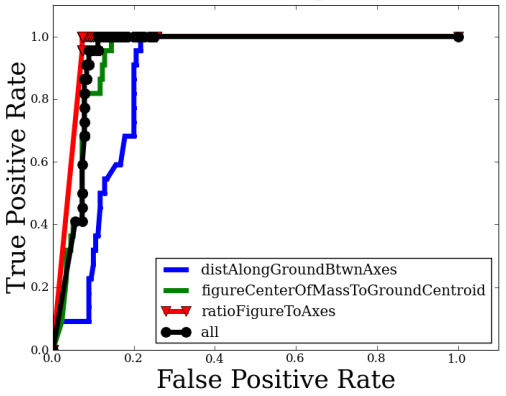
along



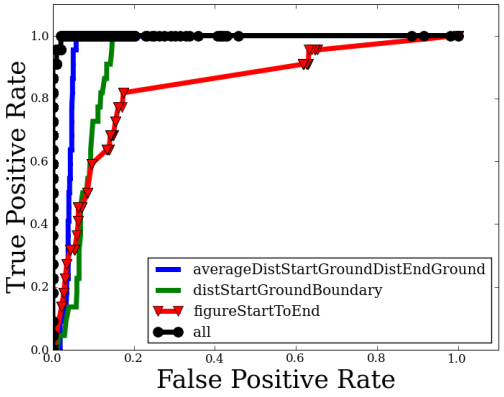
down



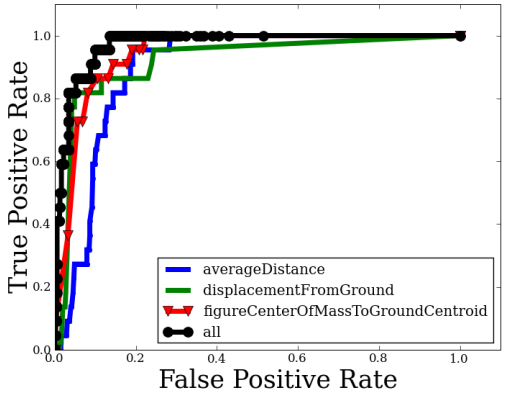
through



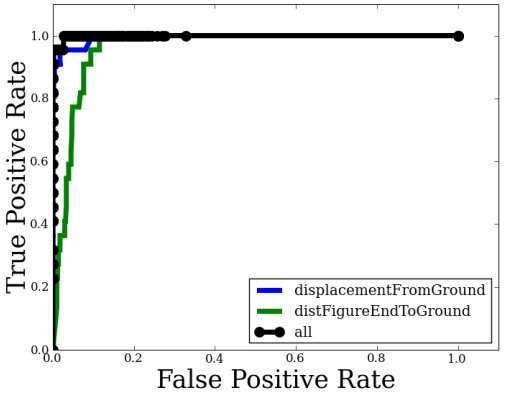
around



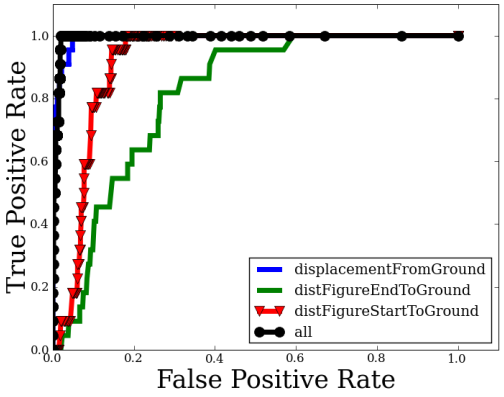
out



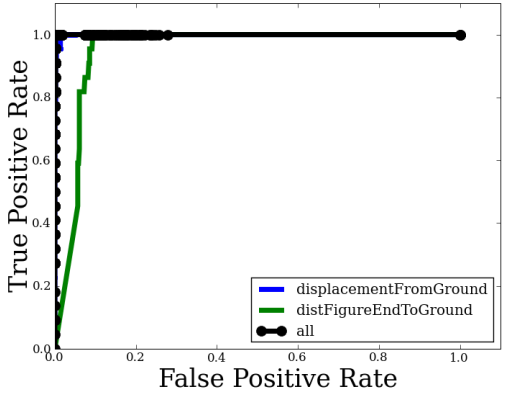
towards



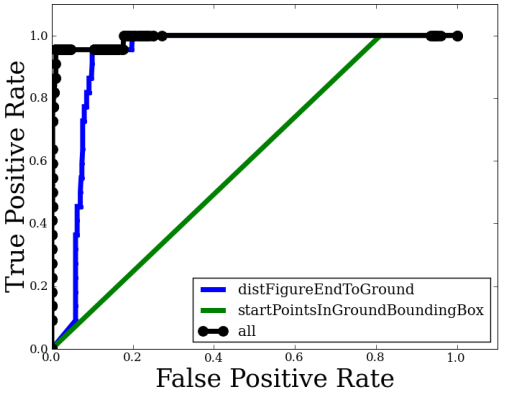
away from



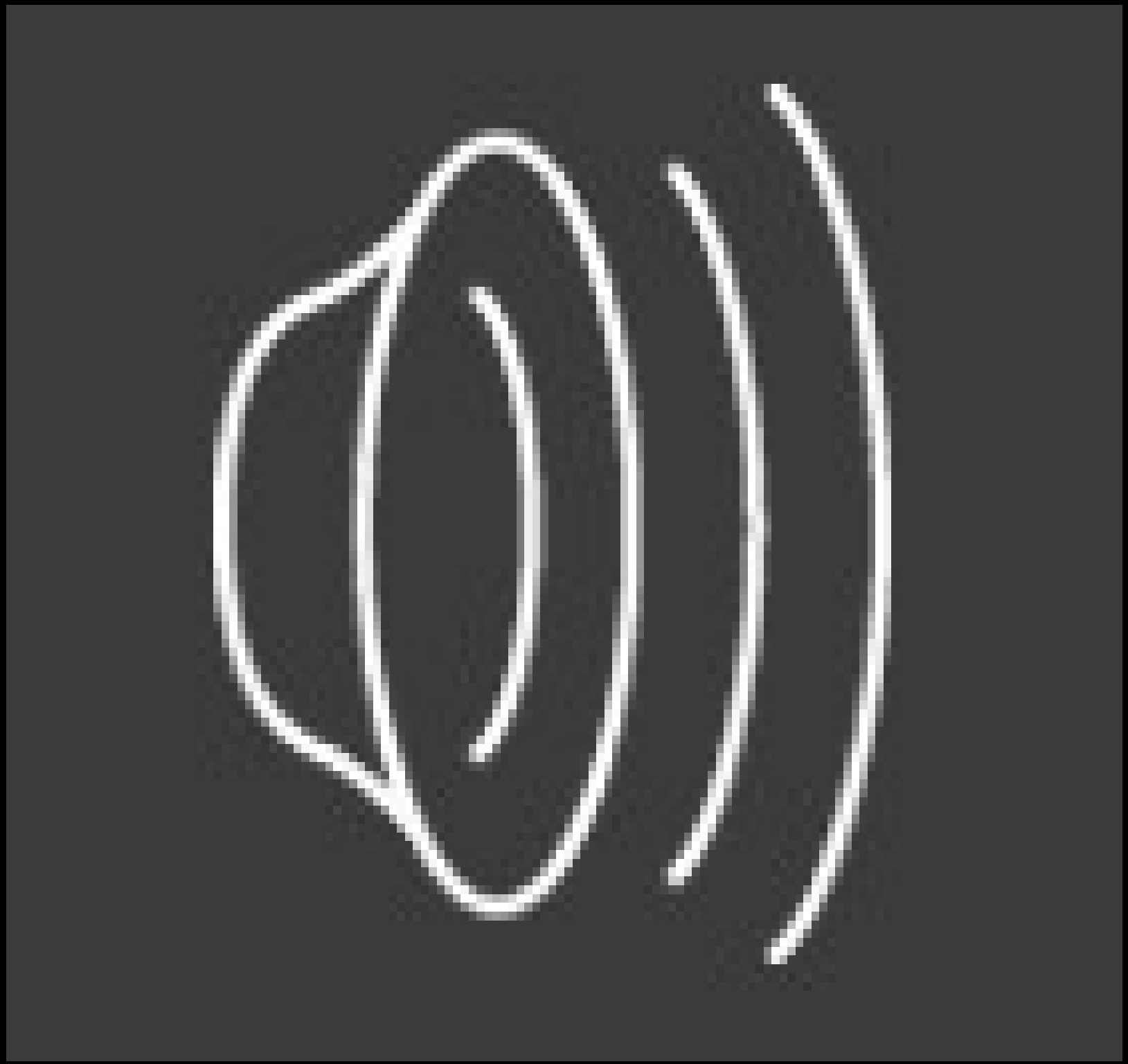
to



until



Phrase-based Video Retrieval

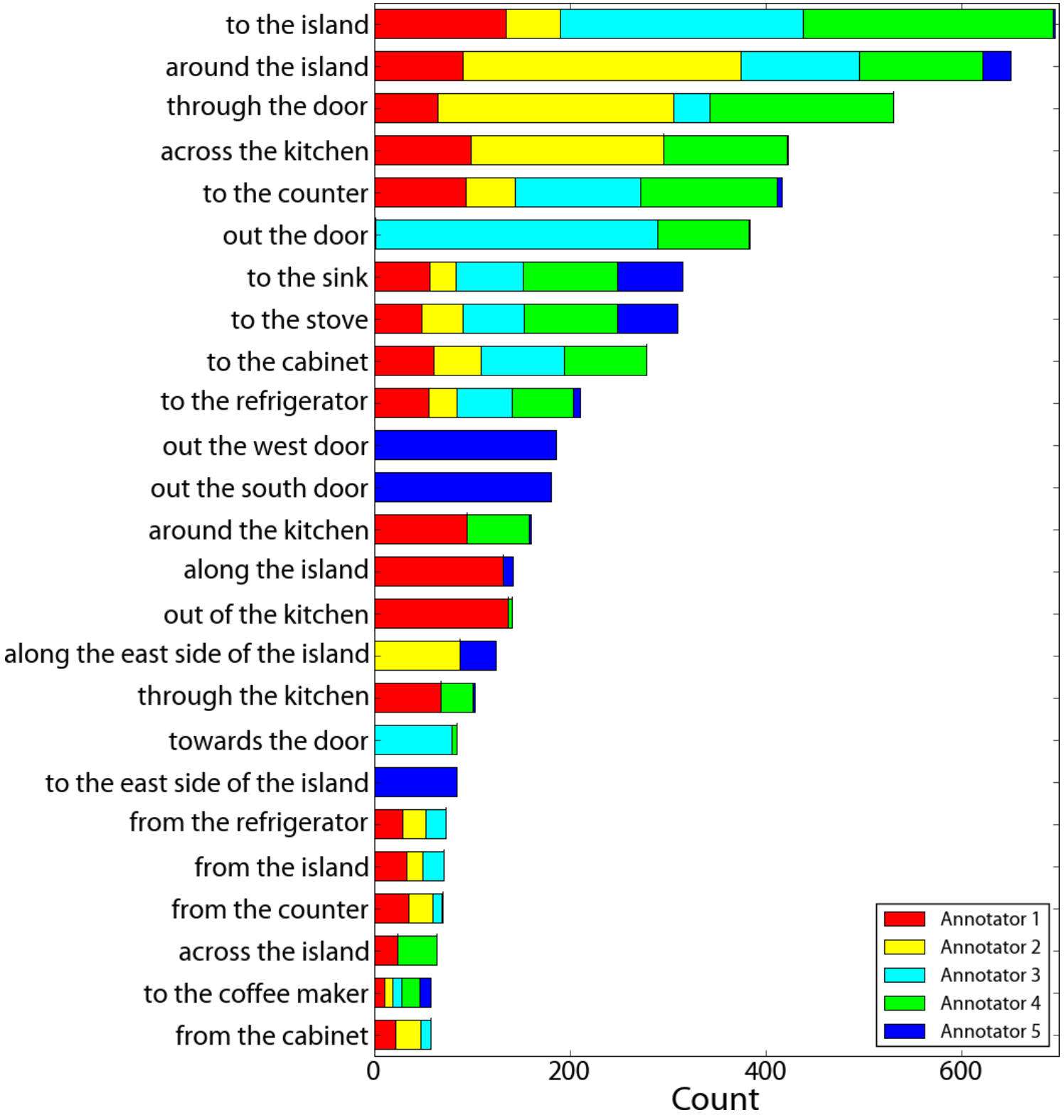


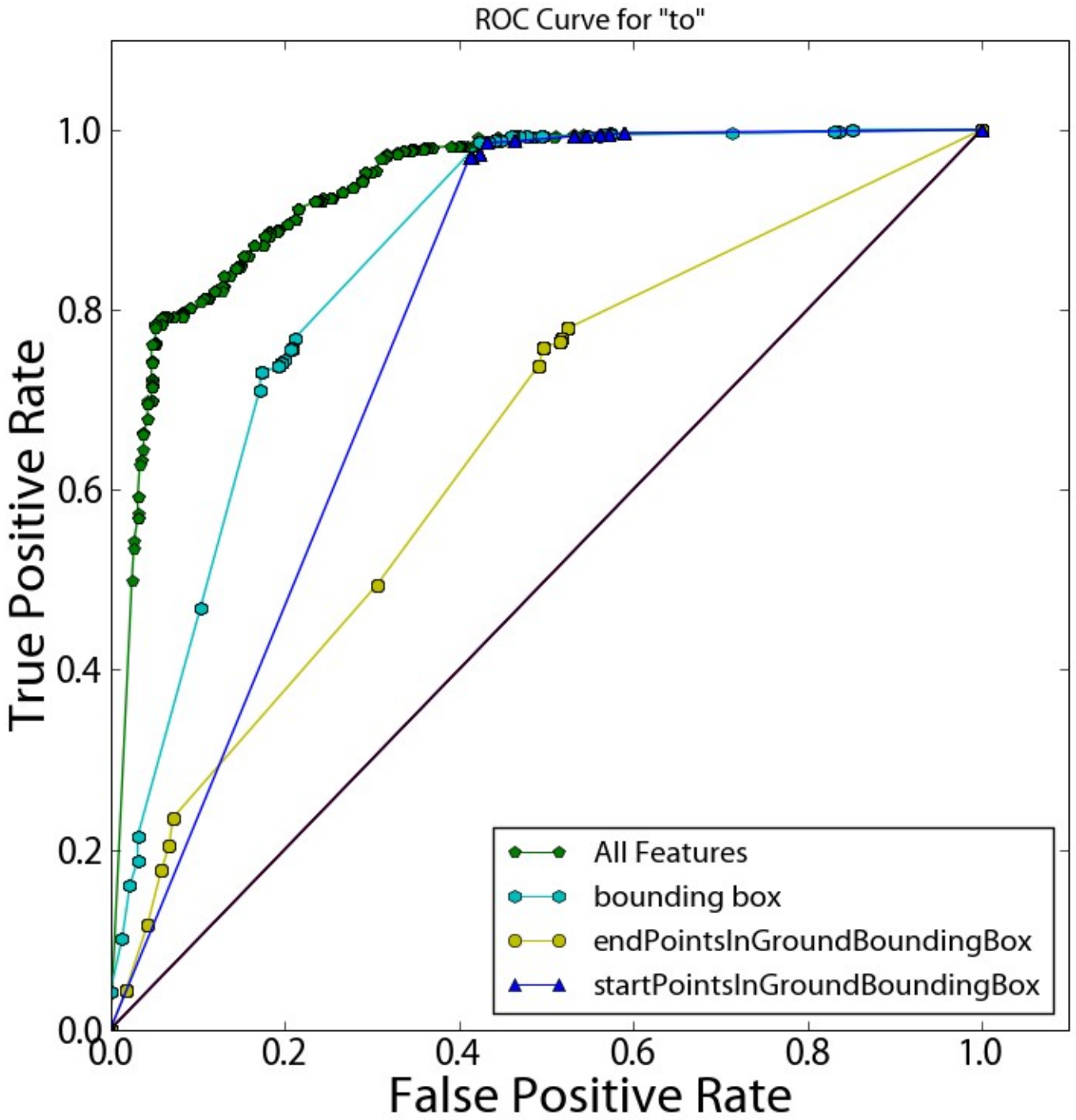
Annotation Task

Complete the sentence:
“The person is going...”

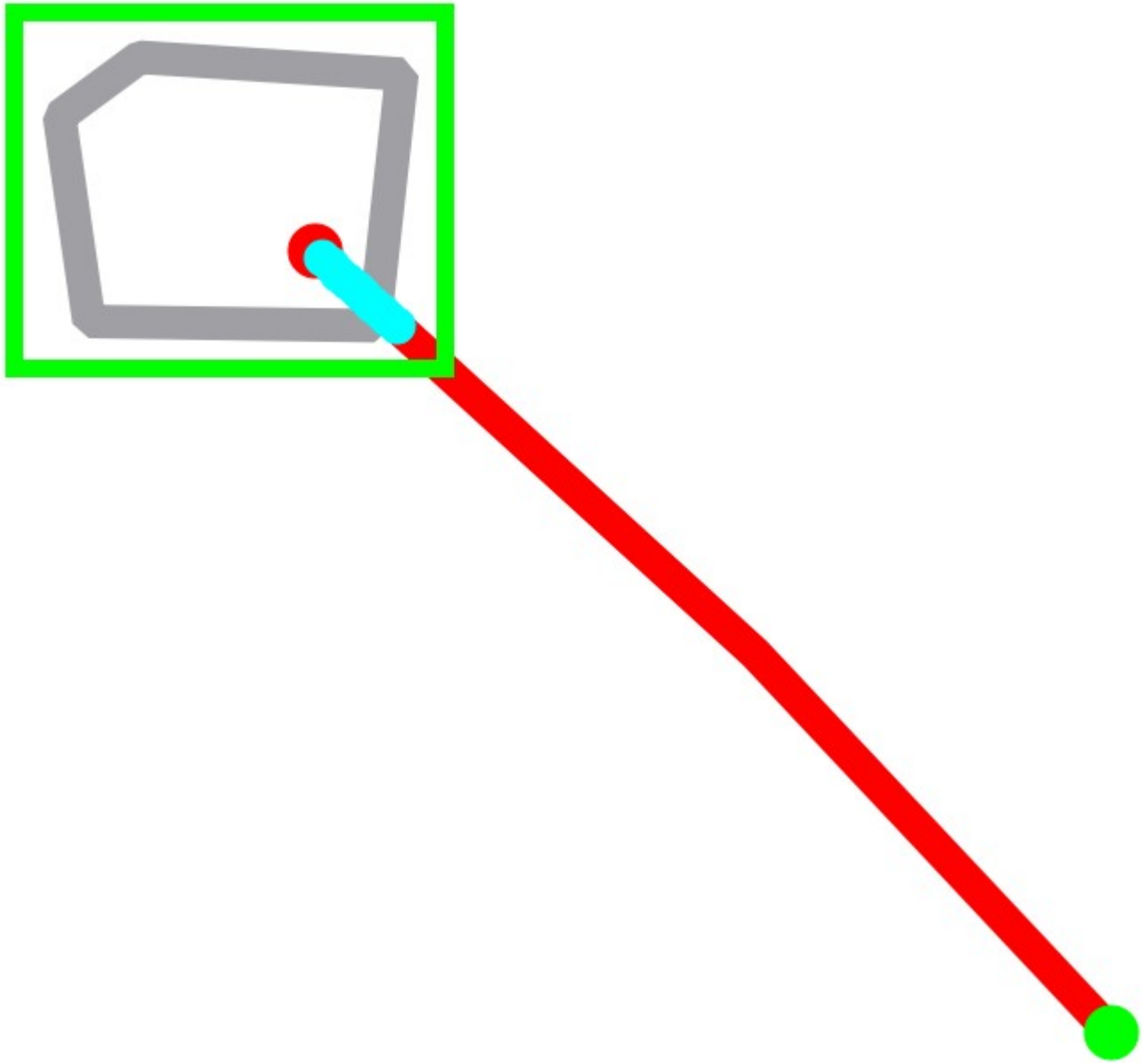
Corpus

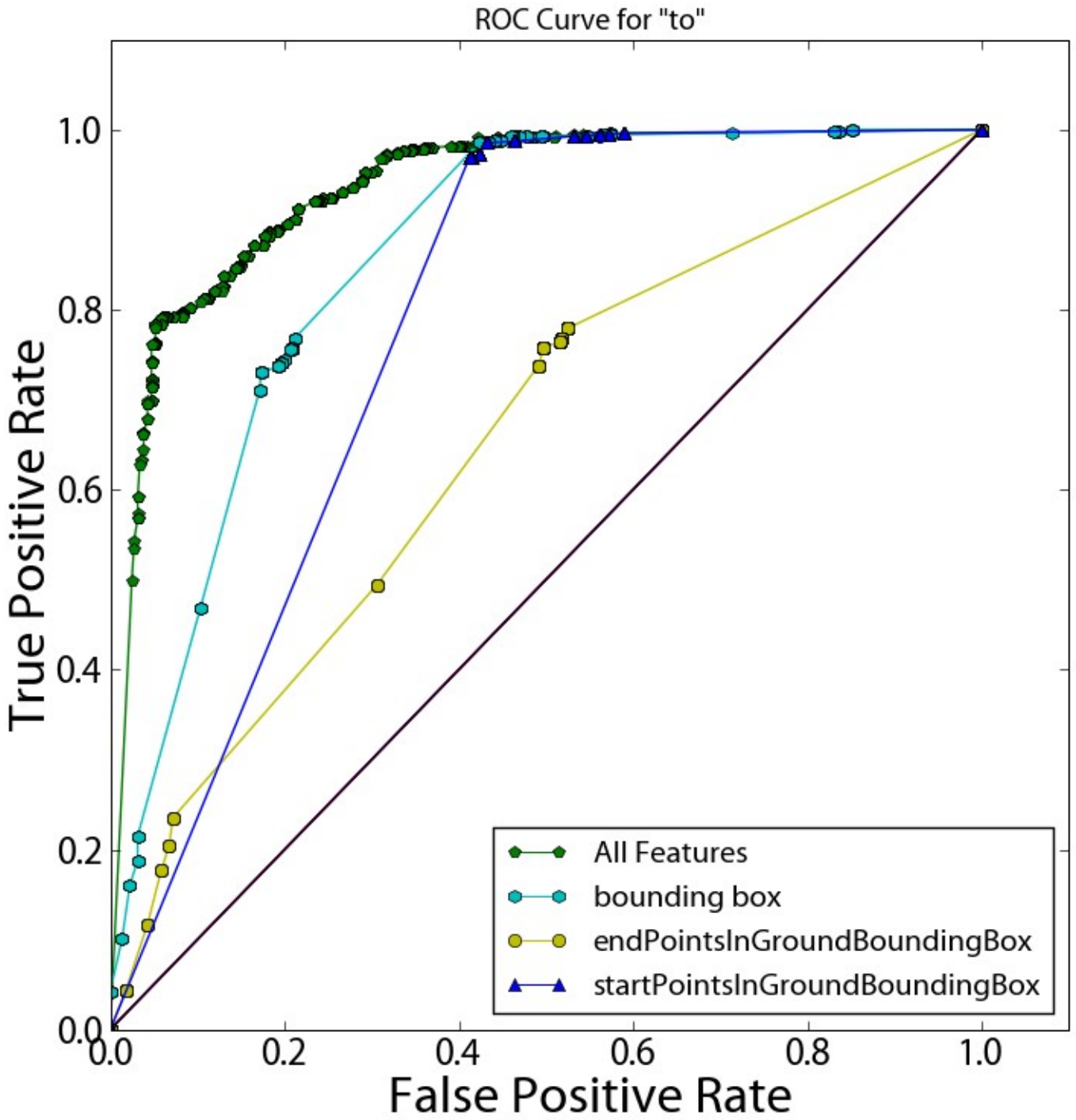
to the counter.
along the east side of the island.
from the refrigerator.
to the cabinet.
across the kitchen.


to the island
around the island
through the door
across the kitchen
to the counter
out the door
to the sink
to the stove
to the cabinet
to the refrigerator
out the west door
out the south door
around the kitchen
along the island
out of the kitchen
along the east side of the island
through the kitchen
towards the door
to the east side of the island
from the refrigerator
from the island
from the counter
across the island
to the coffee maker
from the cabinet
Annotator 1
Annotator 2
Annotator 3
Annotator 4
Annotator 5
0
200
400
600
Count


ROC Curve for "to"
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
All Features
bounding box
endPointsInGroundBoundingBox
startPointsInGroundBoundingBox

endPointsInGroundBoundingBox




ROC Curve for "to"
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
All Features
bounding box
endPointsInGroundBoundingBox
startPointsInGroundBoundingBox

“to the sink”

“to the sink”

Full model: 0.99
Bounding boxes: 0.76

“to the sink”

“to the sink”

Full model: 0.10
Bounding boxes: 0.63

Results

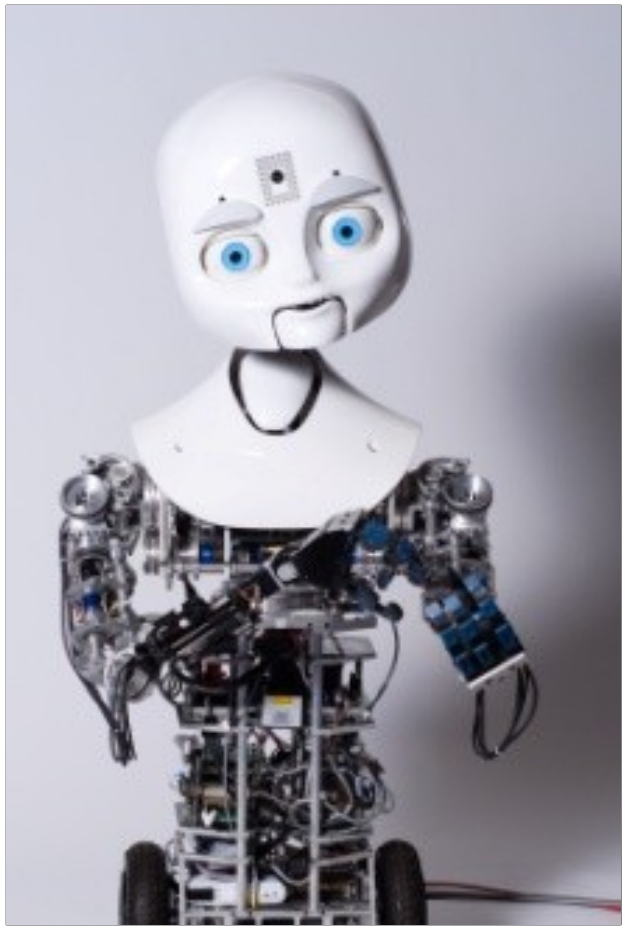
- Library of features for spatial prepositions.
- Models for eleven prepositions.
- Phrase-based video retrieval system.

Outline

- Spatial Prepositions
- **Spatial Description Clauses**
- Direction Understanding
- Spatial Language Video Retrieval
- Conclusion

Two Different Domains

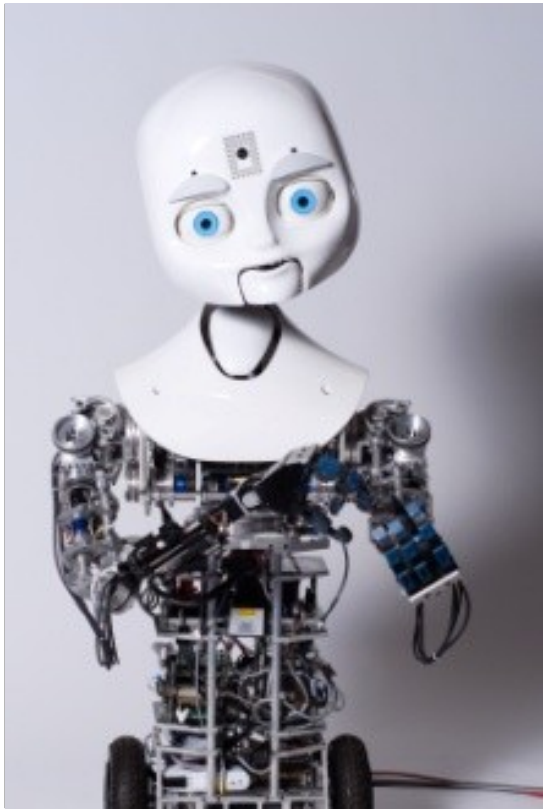
- Direction Understanding



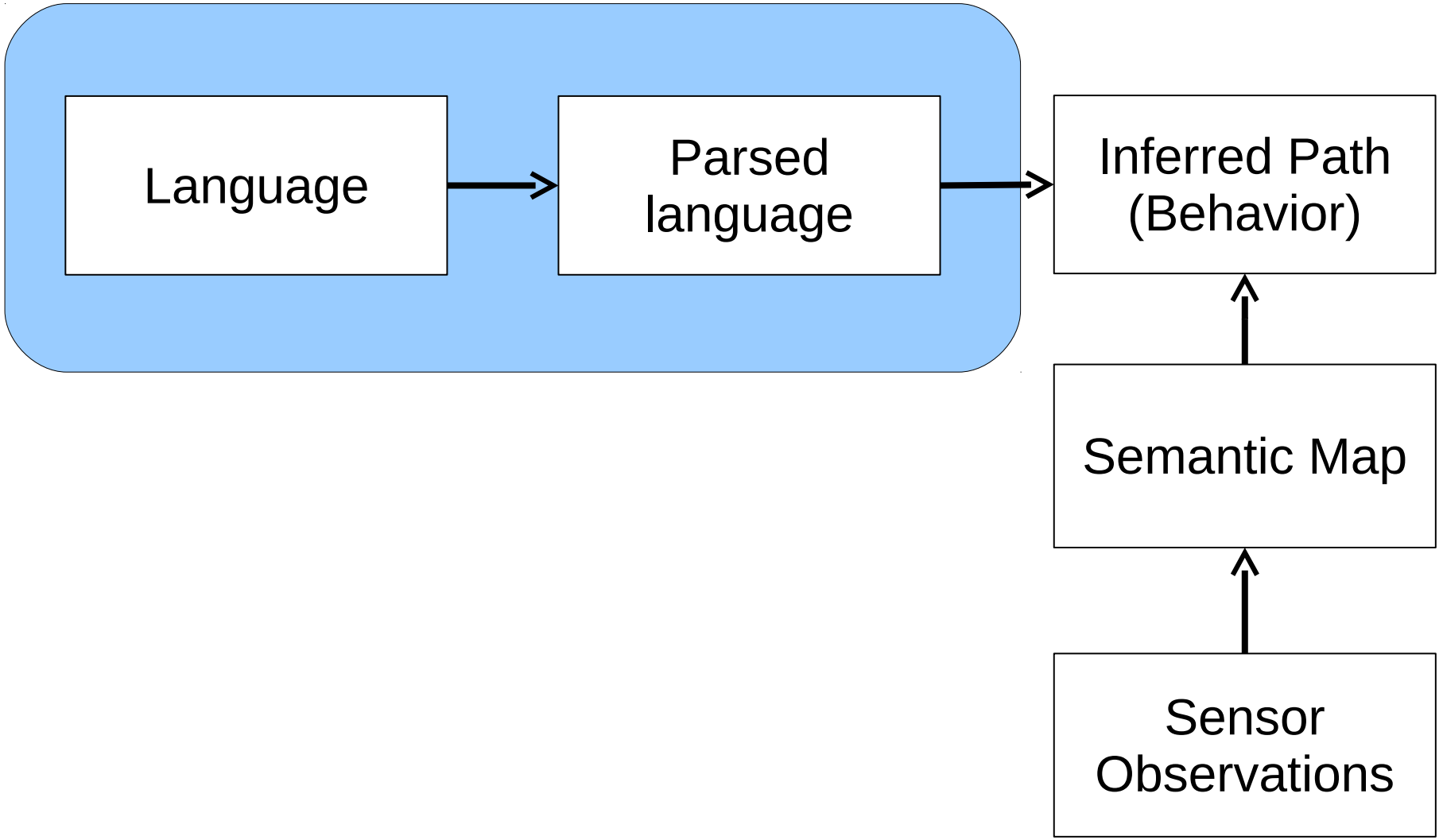
- Video Retrieval

Where should the robot go?

With your back to the windows, walk straight through the door near the elevators. Continue to walk straight, going through one door until you come to an intersection just past a whiteboard. Turn left, turn right, and enter the second door on your right (sign says "Administrative Assistant").



System


Language
Parsed language
Inferred Path (Behavior)
Semantic Map
Sensor Observations

Structure of Natural Language Directions

- Sequential

Sequential

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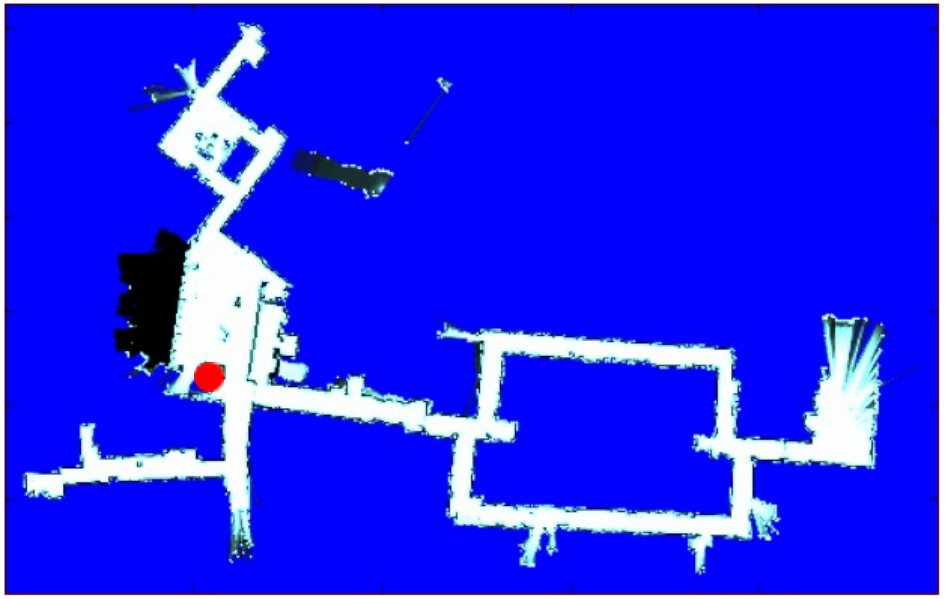

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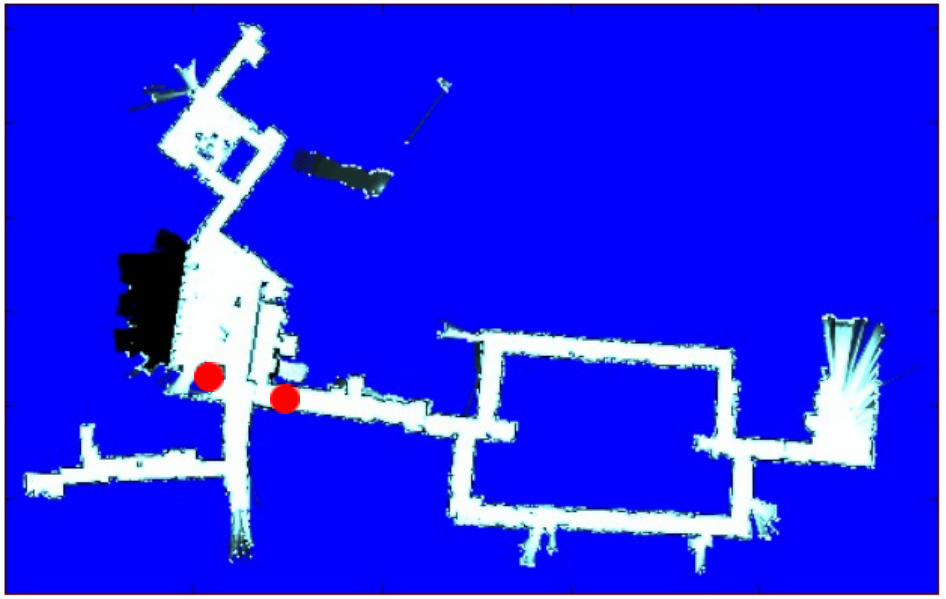

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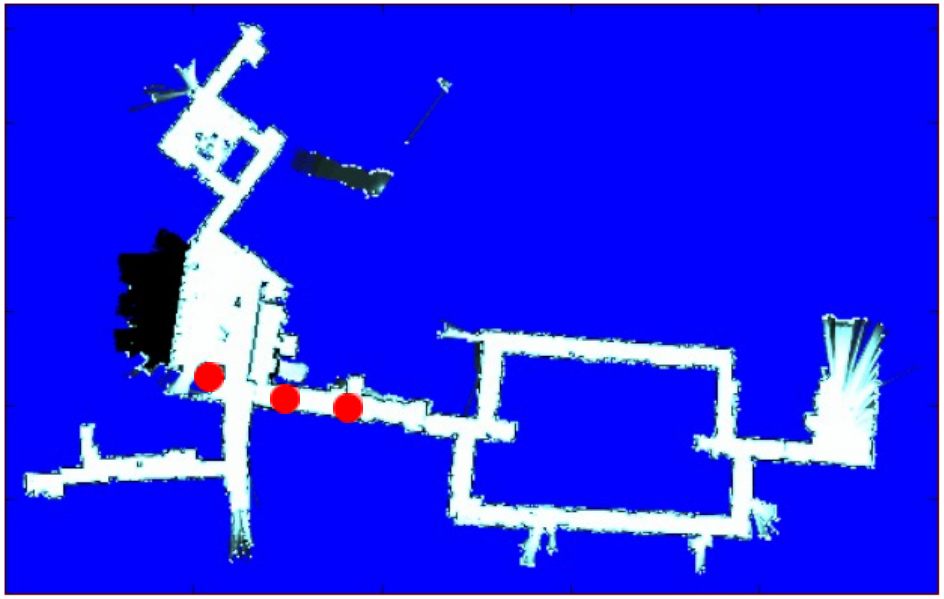

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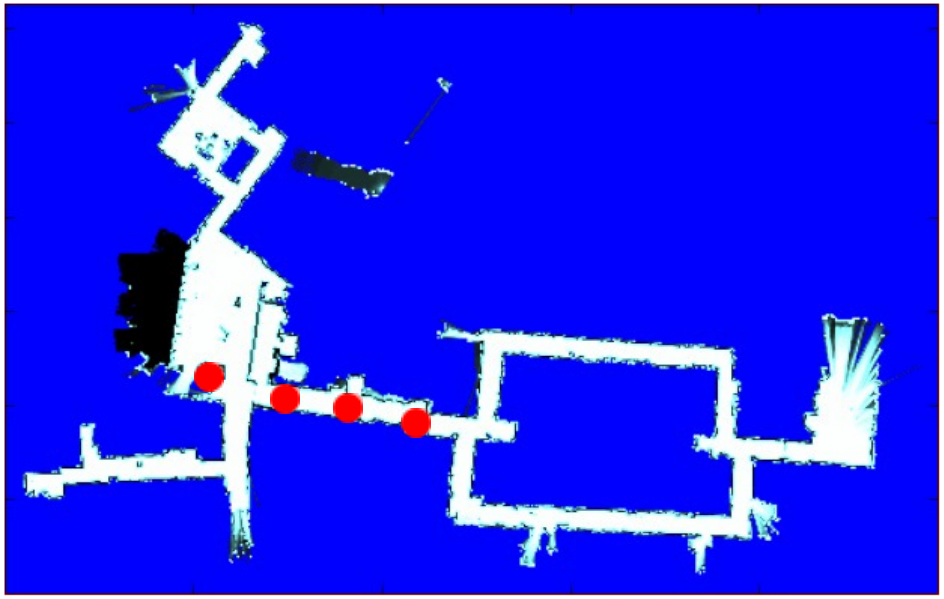

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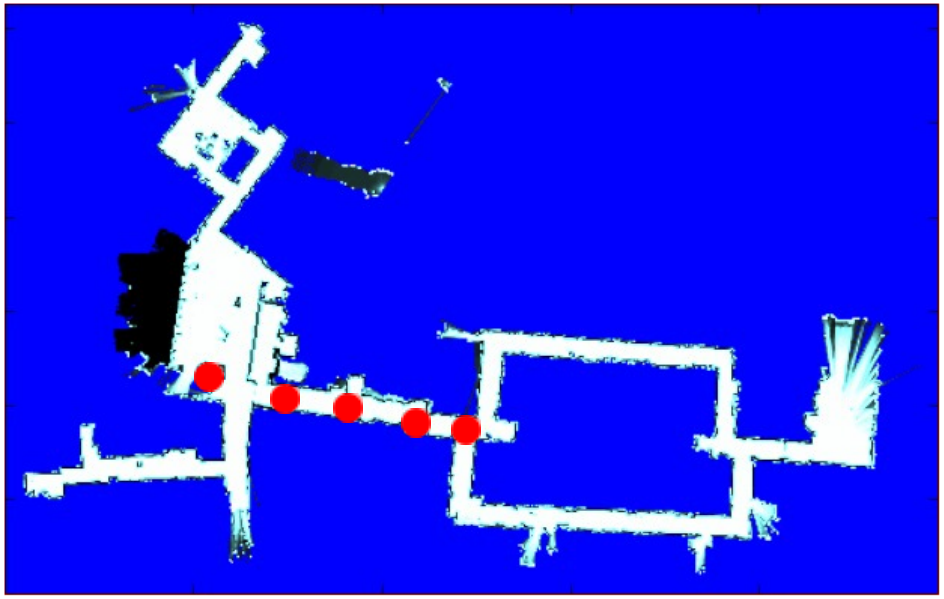

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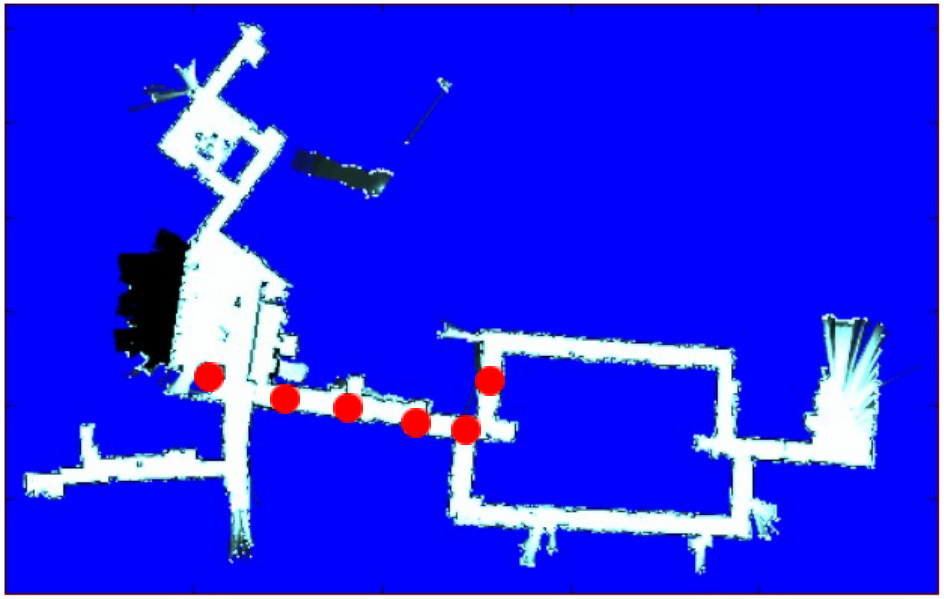

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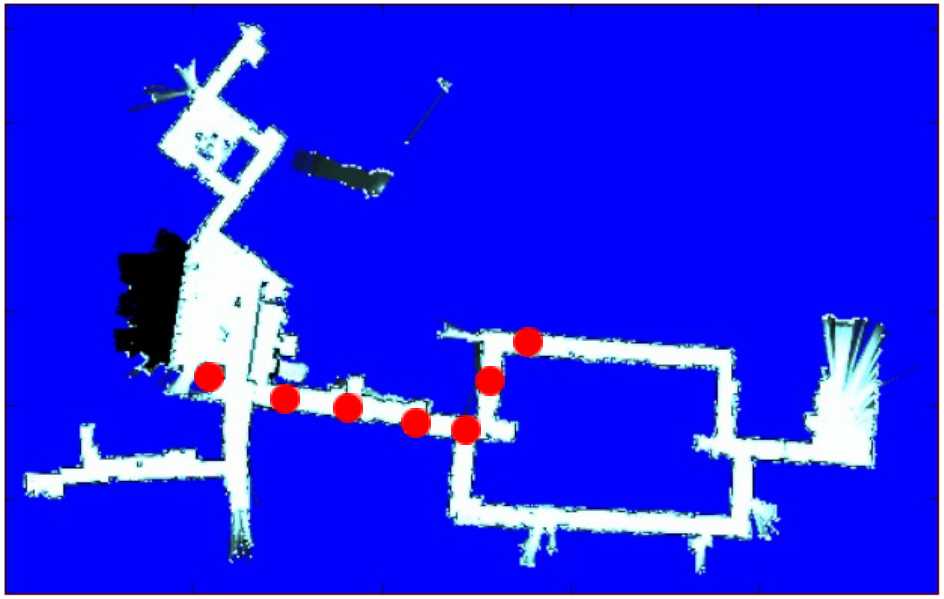

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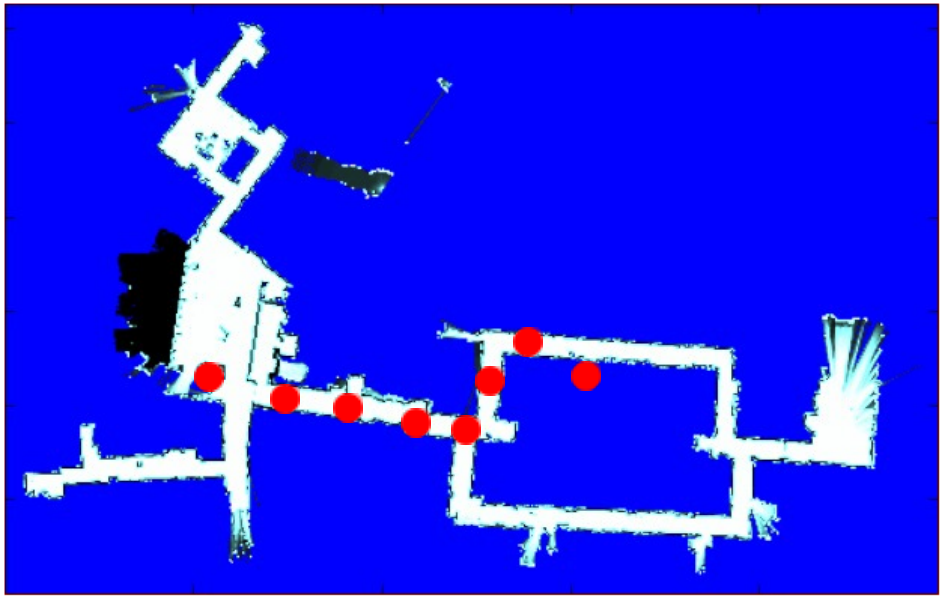


Structure of Natural Language Directions

- Sequential.
- Directive verbs.

Directive Verbs

With your back to the windows, walk straight through the door near the elevators. Continue to walk straight, going through one door until you come to an intersection just past a white board. Turn left, turn right, and enter the second door on your right (sign says "Administrative Assistant").

Structure of Natural Language Directions

- Sequential.
- Directive verbs.
- Landmarks.

Landmarks

With your back to the windows, walk straight through the door near the elevators. Continue to walk straight, going through one door until you come to an intersection just past a white board. Turn left, turn right, and enter the second door on your right (sign says "Administrative Assistant").

Structure of Natural Language Directions

- Sequential.
- Directive verbs.
- Landmarks.
- Spatial relations.

Spatial Relations

With your back to the windows, walk straight through the door near the elevators. Continue to walk straight, going through one door until you come to an intersection just past a white board. Turn left, turn right, and enter the second door on your right (sign says "Administrative Assistant").

Structure of Natural Language Directions

- Sequential.
- Directive verbs.
- Landmarks.
- Spatial relations.

Spatial Description Clause

Go through the door.

Spatial Description Clause

Go through the door.

- Figure: <you>

Spatial Description Clause

Go through the door.

- Figure: <you>
- Verb: Go

Spatial Description Clause

Go through the door.

- Figure: <you>
- Verb: Go
- Spatial relation: through

Spatial Description Clause

Go through the door.

- Figure: <you>
- Verb: Go
- Spatial relation: through
- Landmark: the door.

Spatial Description Clause

Continue to walk straight, going through one door until you come to an intersection just past a white board.

Verb: Continue to walk
Spatial Relation: straight

Spatial Description Clause

Continue to walk straight, going through one door until you come to an intersection just past a white board.

Verb: going
Spatial Relation: through
Landmark: one door

Spatial Description Clause

Continue to walk straight, going through one door until you come to an intersection just past a white board.

Verb: going
Spatial Relation: until
Landmark: you come to an intersection just past a white board

Spatial Description Clause

Continue to walk straight, going through one door until you come to an intersection just past a white board.

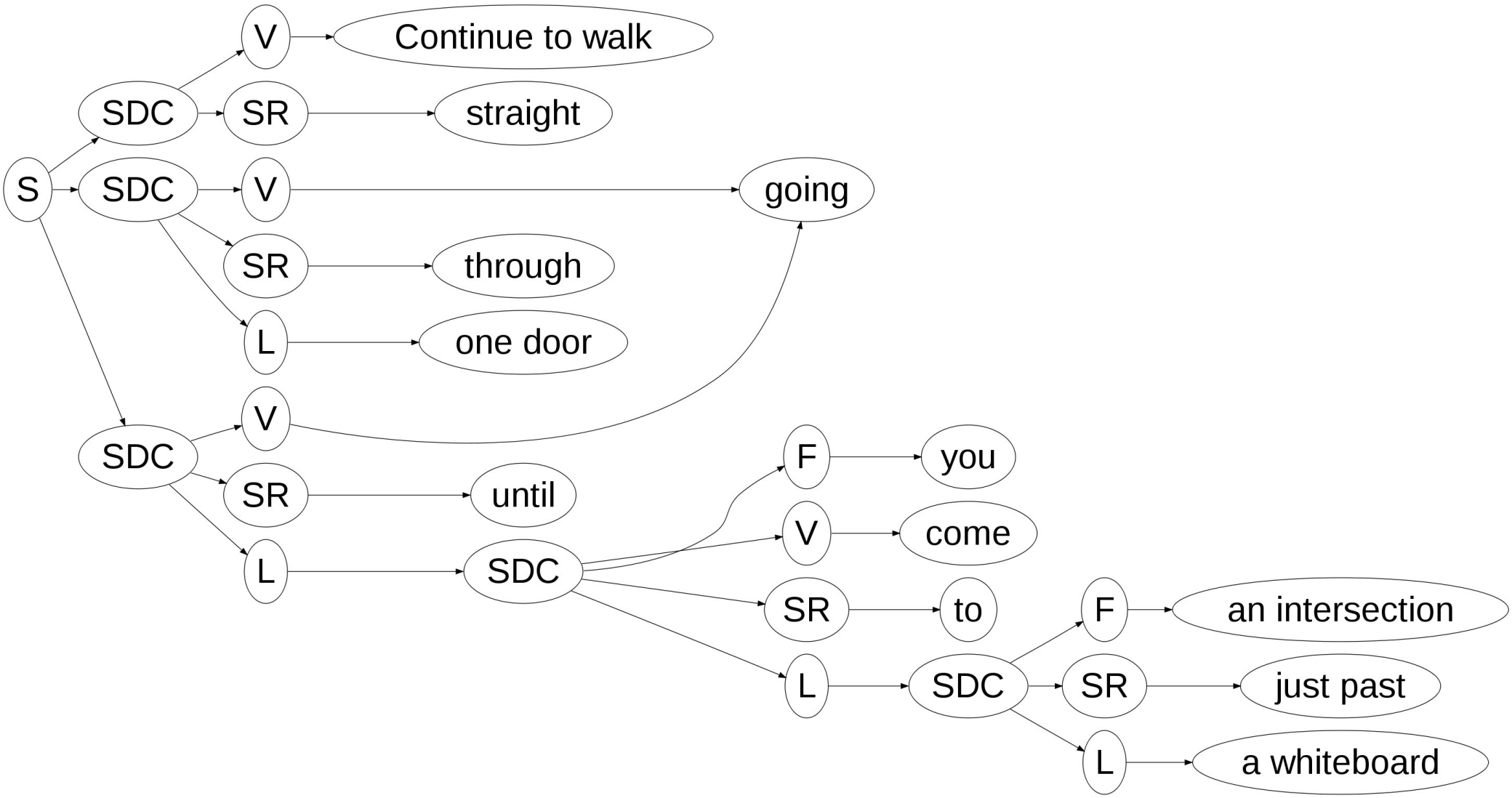
Figure: you
Verb: come
Spatial Relation: to
Landmark: an intersection just past a white board

Spatial Description Clause

Continue to walk straight, going through one door until you come to an intersection just past a white board.

Figure: an intersection
Spatial Relation: just past
Landmark: a white board

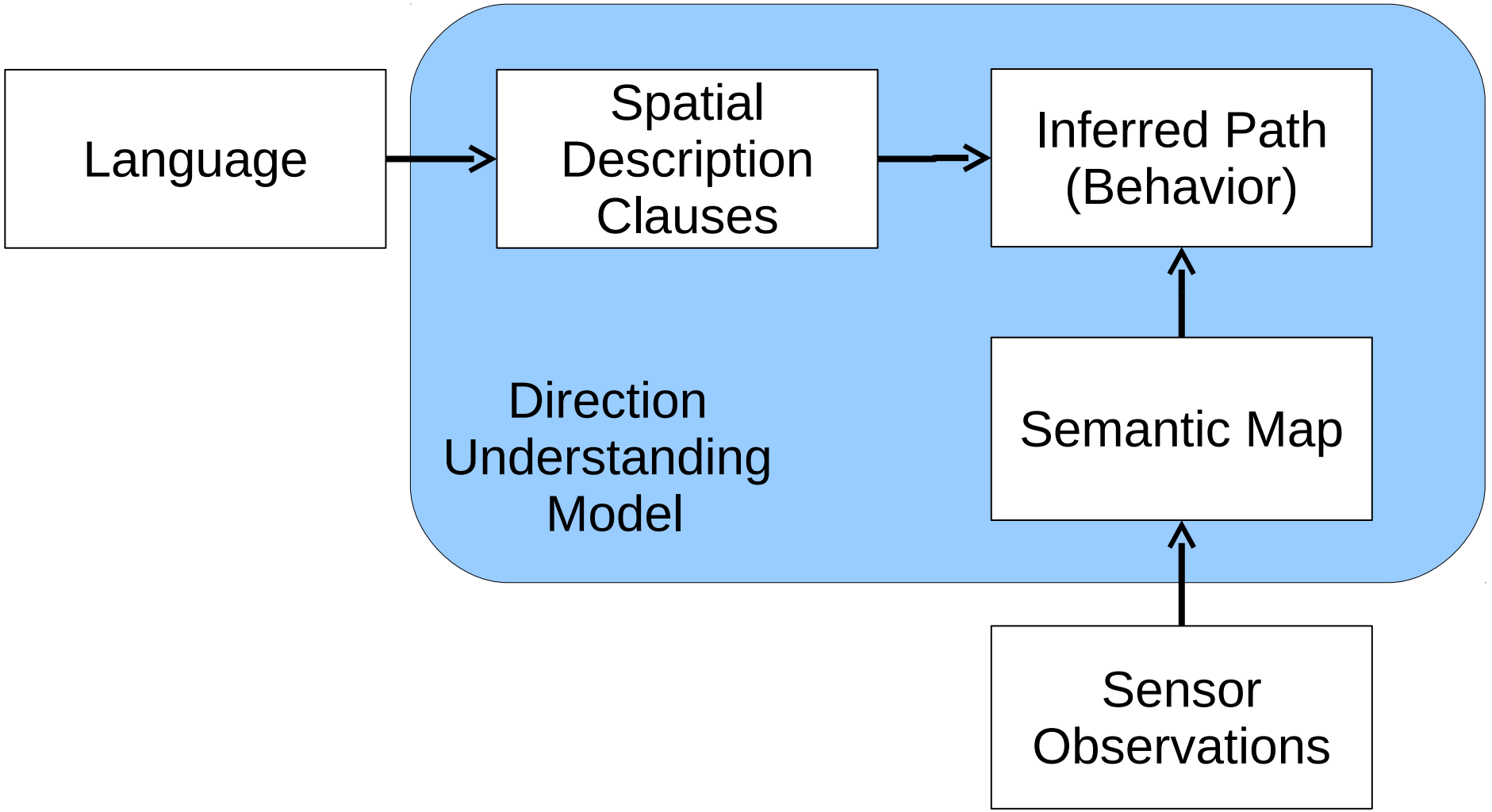
Spatial Description Clause



Outline

- Spatial Prepositions
- Spatial Description Clauses
- **Direction Understanding**
- Spatial Language Video Retrieval
- Conclusion

System


Language
Spatial Description Clauses
Inferred Path (Behavior)
Direction Understanding Model
Semantic Map
Sensor Observations

Model

$$argmax_{path}\, p(path, directions, observations)$$

Model

$$p(path, directions, observations) =$$

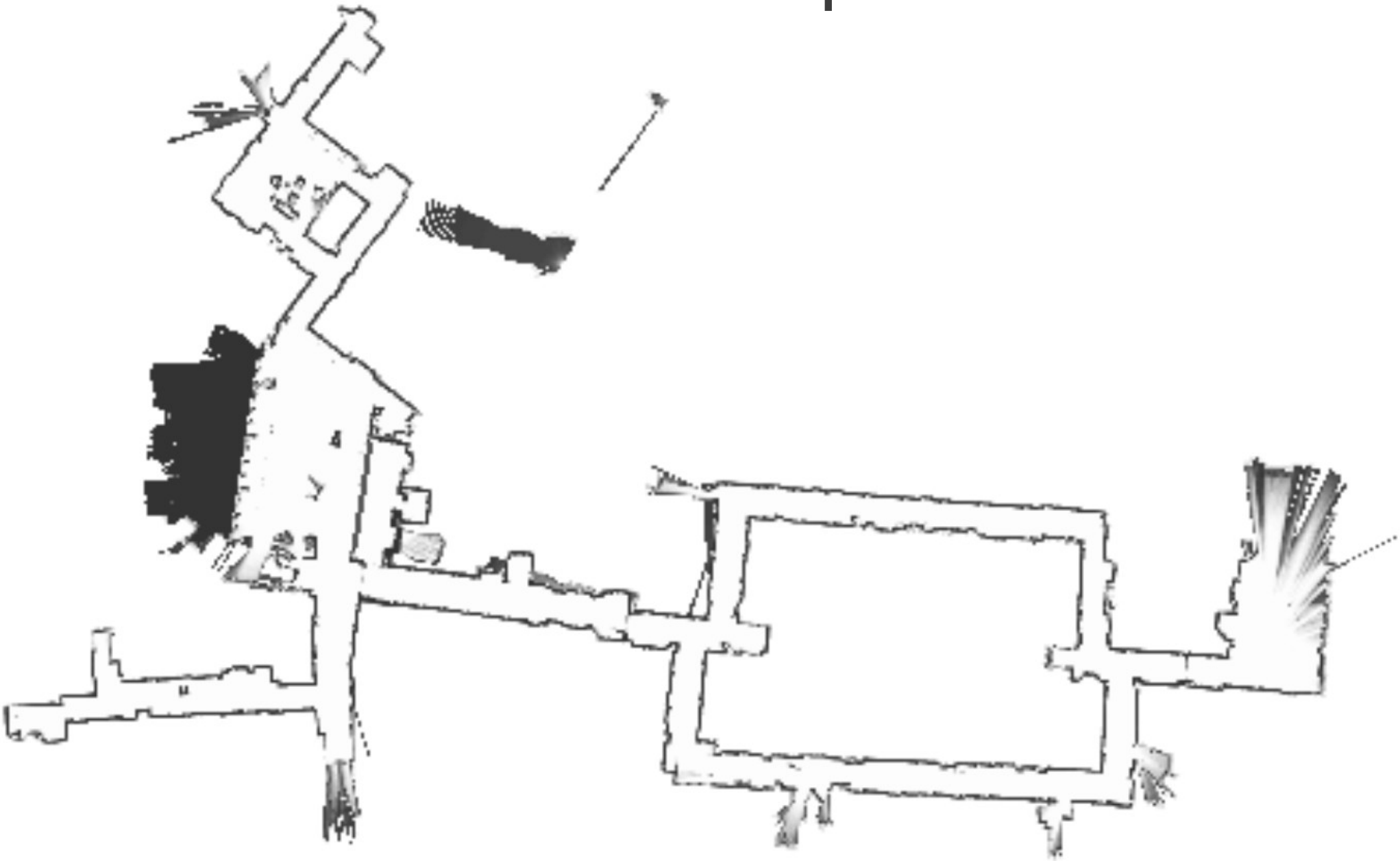
$$p(directions | path, observations)\, p(path)\, p(observations)$$

(independence assumptions)

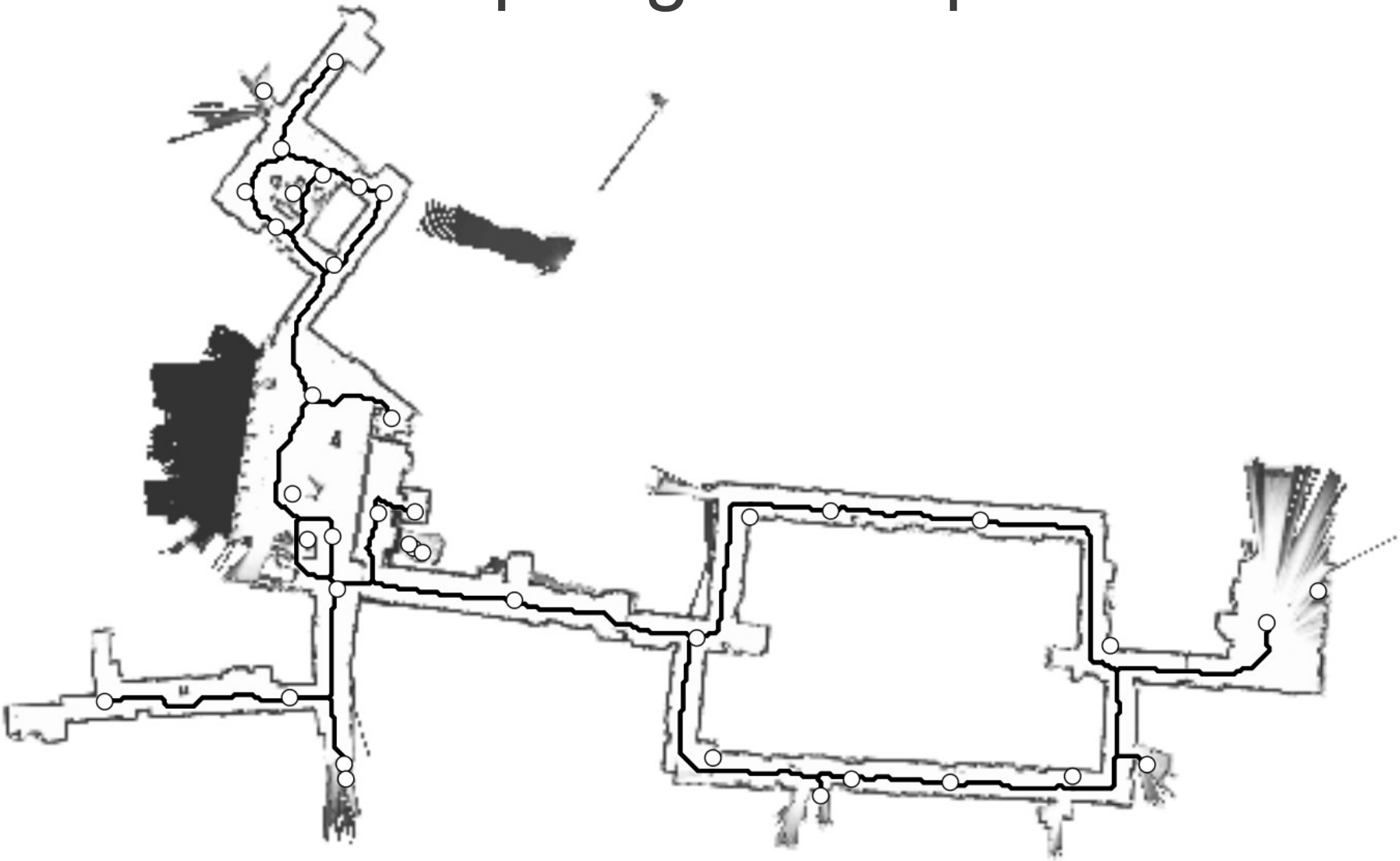
$$p(sdc_1 \ldots sdc_M | vp_1 \ldots vp_{M+1}, o_1 \ldots o_K)\, p(vp_1 \ldots vp_{M+1})\, p(o_1 \ldots o_K)$$

(topological map of viewpoints, and a sequence of SDCs)

Grid Map



Topological Map



Model

$$p(path, directions, observations) =$$

$$p(directions | path, observations)\, p(path)\, p(observations)$$

(path and observations are independent)

$$p(sdc_1 \ldots sdc_M | vp_1 \ldots vp_{M+1}, o_1 \ldots o_K)\, p(vp_1 \ldots vp_{M+1})\, p(o_1 \ldots o_K)$$

(topological map of viewpoints, and a sequence of SDCs)

$$\prod_{i=1}^{M} p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K) \prod_{i=1}^{M} p(vp_{i+1} | vp_1 \ldots vp_i)\, p(o_1 \ldots o_K)$$

(Paths are Markov)

Probability of Directions Given a Possible Movement

$$p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

$$= p(figure_i, verb_i, spatial\_relation_i, landmark_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

(The structure of a spatial description clause.)

Spatial Description Clause

Go through the door.

- Figure: <you>
- Verb: Go
- Spatial relation: through
- Landmark: the door.

Probability of Directions Given a Possible Movement

$$p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

$$= p(figure_i, verb_i, spatial\_relation_i, landmark_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

(The structure of a spatial description clause.)

$$= p(figure_i | vp_i, vp_{i+1}, o_1 \ldots o_K)\, p(verb_i | vp_i, vp_{i+1}) \times$$
$$p(spatial\_relation_i | landmark_i, v_i, v_{i+1}, o_1 \ldots o_K) \times$$
$$p(landmark_i | v_i, v_{i+1}, o_1 \ldots o_K)$$

(Factor according to certain independence assumptions.)

Probability of Directions Given a Possible Movement

$$p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

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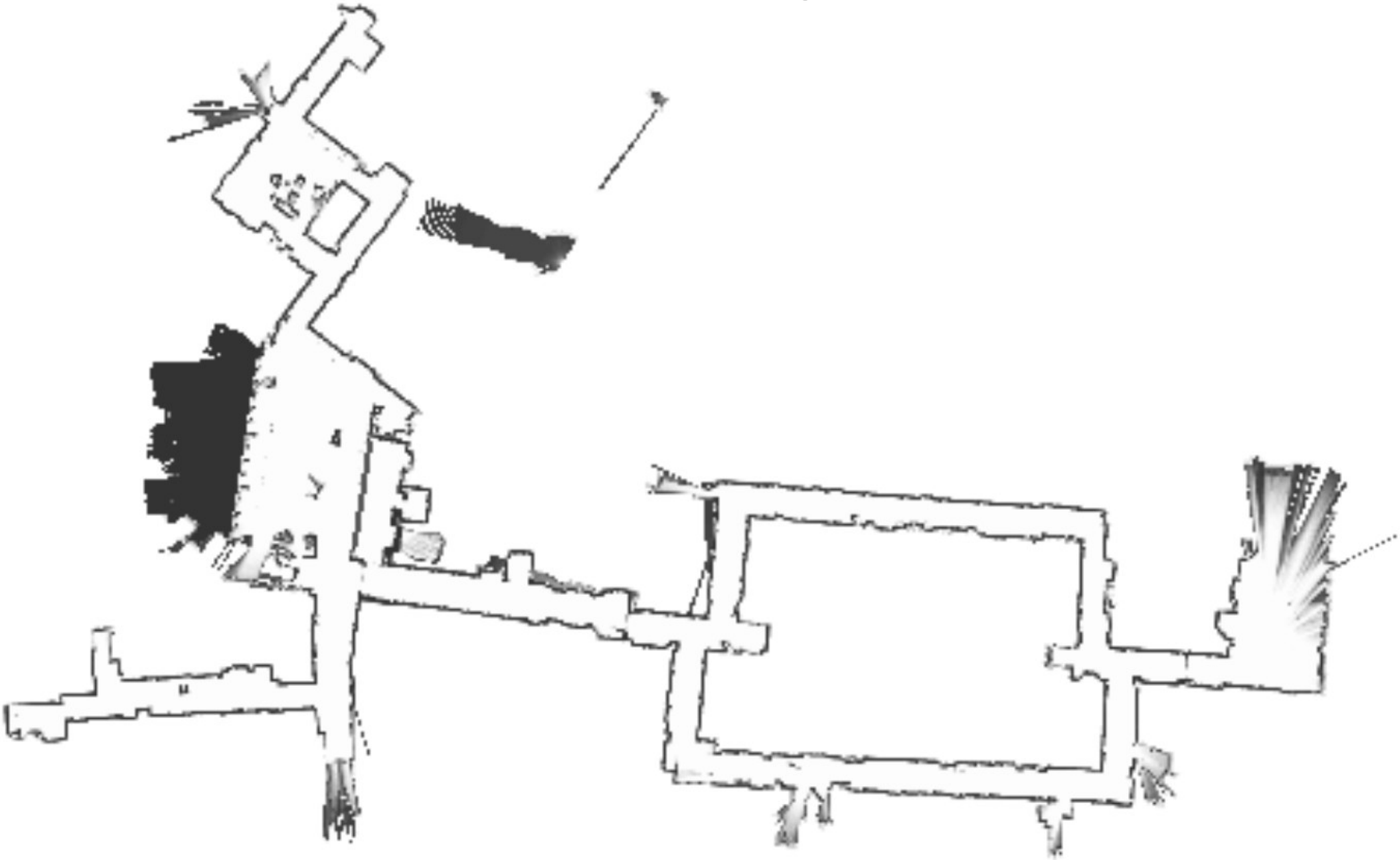
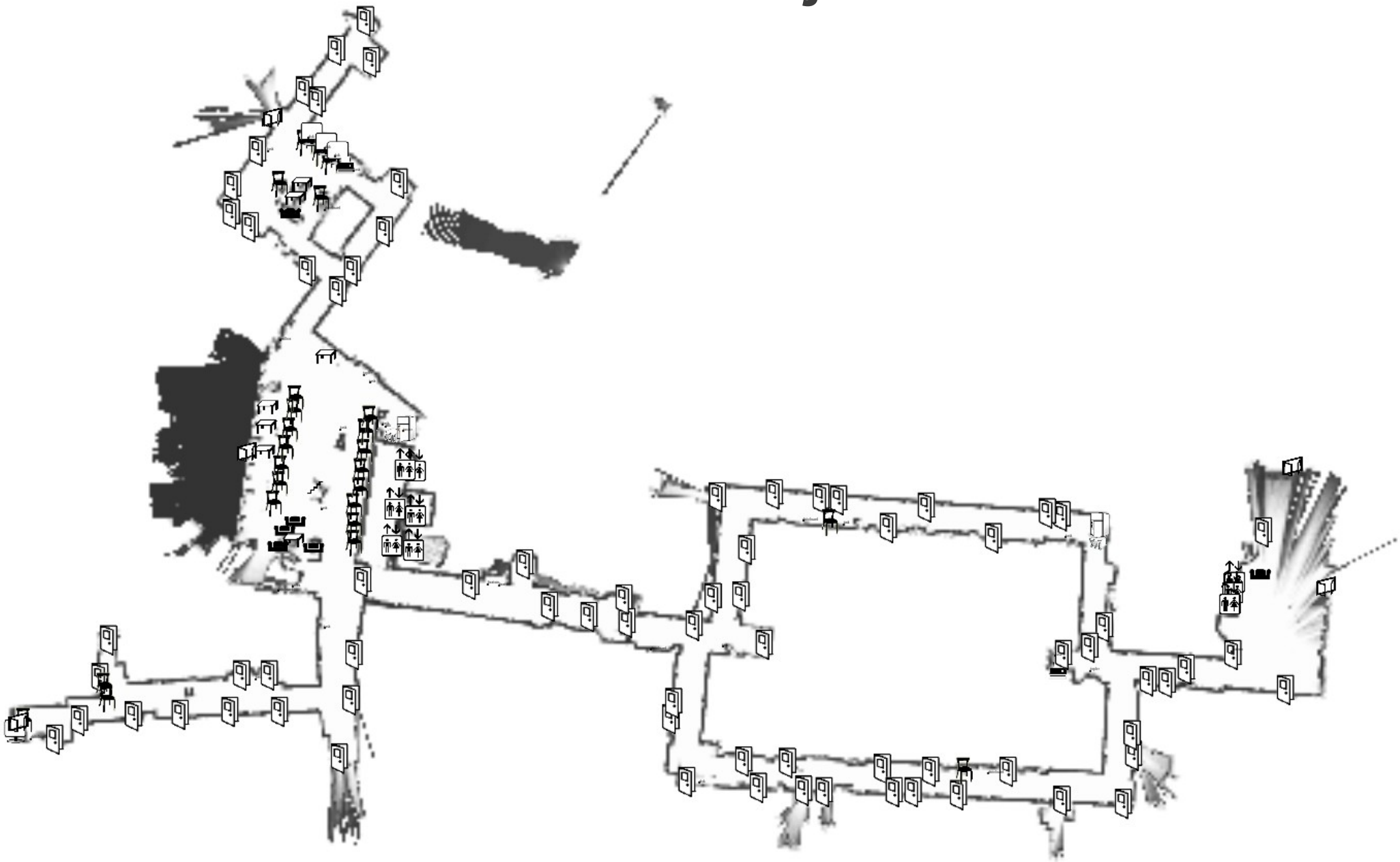
(Factor according to certain independence assumptions.)

Known Objects



Known Objects



Contextual relationships

Tags include: desktop, monitor, computer, keyboard, and mouse
(Kollar and Roy, 2009)

Probability of Directions Given a Possible Movement

$$p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

$$= p(figure_i, verb_i, spatial\_relation_i, landmark_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

(The structure of a spatial description clause.)

$$= p(figure_i | vp_i, vp_{i+1}, o_1 \ldots o_K)\, p(verb_i | vp_i, vp_{i+1}) \times$$
$$p(spatial\_relation_i | landmark_i, v_i, v_{i+1}, o_1 \ldots o_K) \times$$
$$p(landmark_i | v_i, v_{i+1}, o_1 \ldots o_K)$$

(Factor according to certain independence assumptions.)

Probability of Directions Given a Possible Movement

$$p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

$$= p(figure_i, verb_i, spatial\_relation_i, landmark_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

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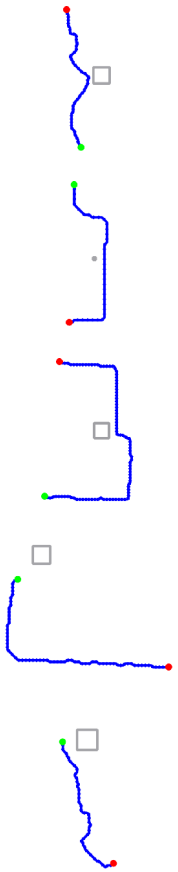
$$= p(figure_i | vp_i, vp_{i+1}, o_1 \ldots o_K)\, p(verb_i | vp_i, vp_{i+1}) \times$$
$$p(spatial\_relation_i | landmark_i, v_i, v_{i+1}, o_1 \ldots o_K) \times$$
$$p(landmark_i | v_i, v_{i+1}, o_1 \ldots o_K)$$

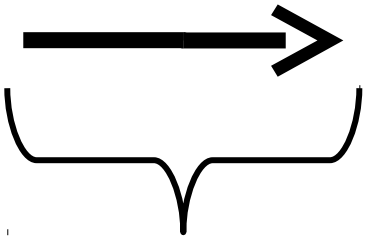
(Factor according to certain independence assumptions.)

Learning Spatial Relations

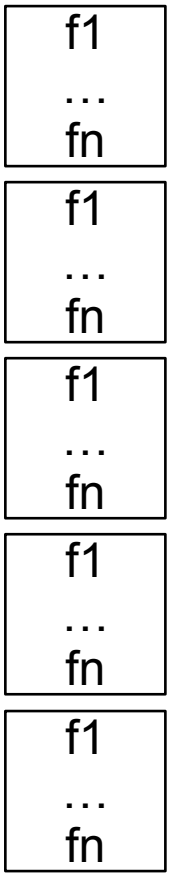
Examples of *past*



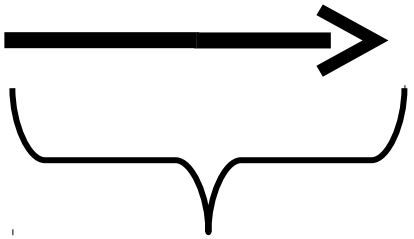
Features



e.g., the minimum distance between the robot and the landmark



Probability of *past*



e.g., naïve Bayes, decision tree, SVM

Probability of Directions Given a Possible Movement

$$p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

$$= p(figure_i, verb_i, spatial\_relation_i, landmark_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

(The structure of a spatial description clause.)

$$= p(figure_i | vp_i, vp_{i+1}, o_1 \ldots o_K)\, p(verb_i | vp_i, vp_{i+1}) \times$$
$$p(spatial\_relation_i | landmark_i, v_i, v_{i+1}, o_1 \ldots o_K) \times$$
$$p(landmark_i | v_i, v_{i+1}, o_1 \ldots o_K)$$

(Factor according to certain independence assumptions.)

Verbs in Route Directions

- Almost always “left,” “right,” or “straight.”
  - “Continue to walk straight.”
  - “Take a right at the photocopier.”
- Exceptions
  - “Follow the wall into the small kitchen.”
  - “Orient yourself with your back to the computers.”

Probability of Directions Given a Possible Movement

$$p(sdc_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

$$= p(figure_i, verb_i, spatial\_relation_i, landmark_i | vp_i, vp_{i+1}, o_1 \ldots o_K)$$

(The structure of a spatial description clause.)

$$= p(figure_i | vp_i, vp_{i+1}, o_1 \ldots o_K)\, p(verb_i | vp_i, vp_{i+1}) \times$$
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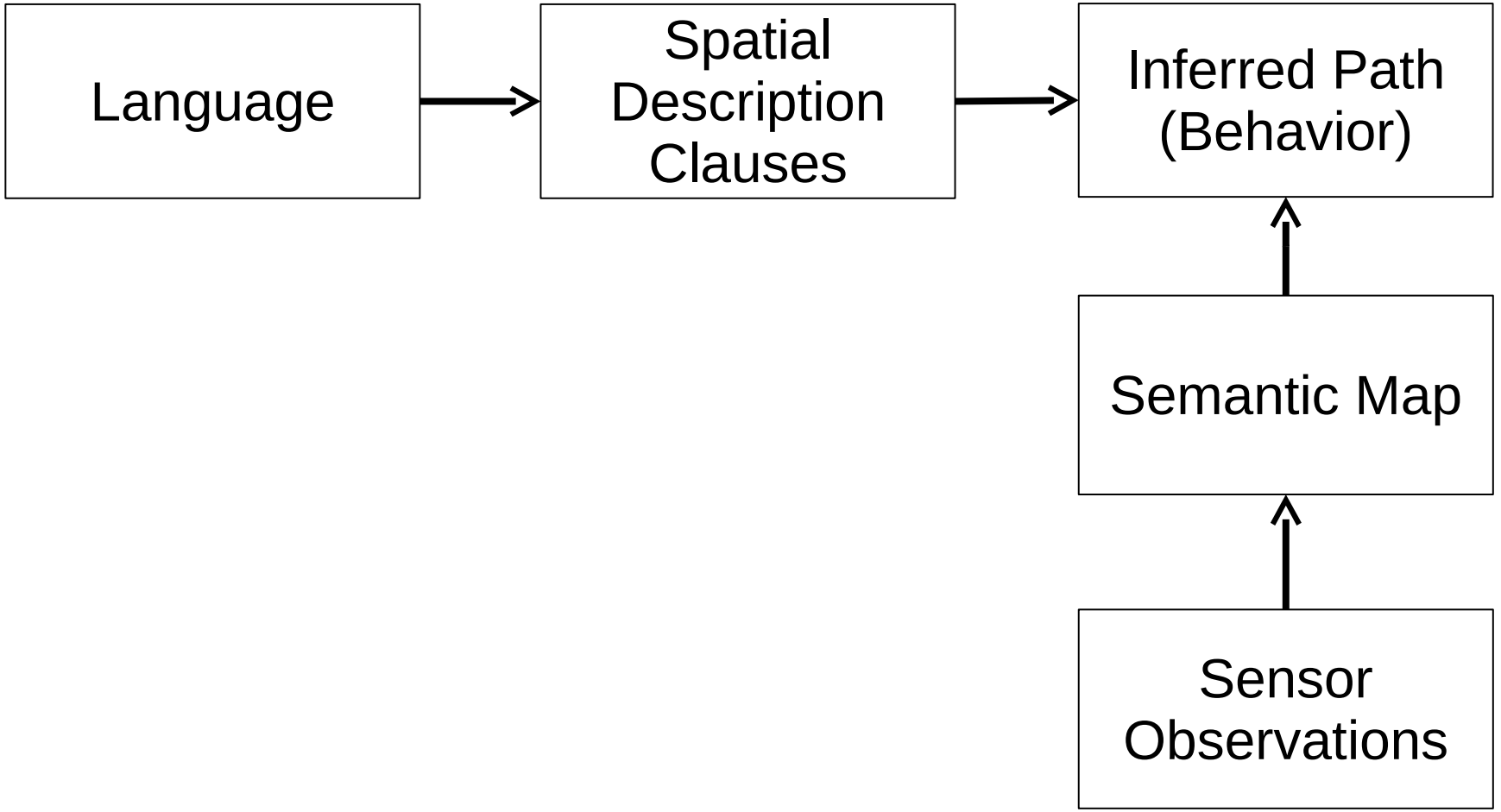
$$p(landmark_i | v_i, v_{i+1}, o_1 \ldots o_K)$$

(Factor according to certain independence assumptions.)

System

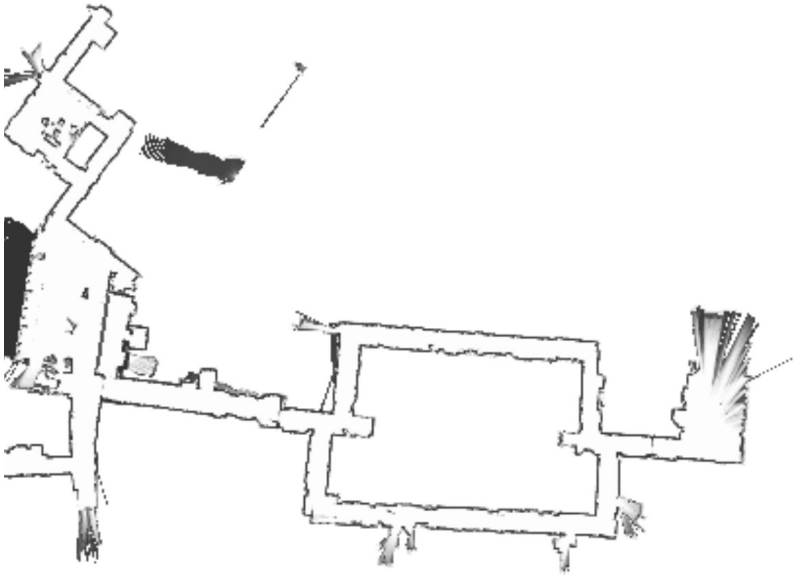

Language
Spatial Description Clauses
Inferred Path (Behavior)
Semantic Map
Sensor Observations

Corpus of Natural Language Directions

- Subjects asked to write directions as if they were giving them to a person.
- 30 subjects, 300 directions, two indoor environments.

With your back to the windows, walk straight through the door near the elevators. Continue to walk straight, going through one door until you come to an intersection just past a whiteboard. Turn left, turn right, and enter the second door on your right (sign says "Administrative Assistant").

Corpus of Natural Language Directions



Task

Given the text of the directions, a starting location, and a semantic map of the environment, follow the directions to the correct destination.

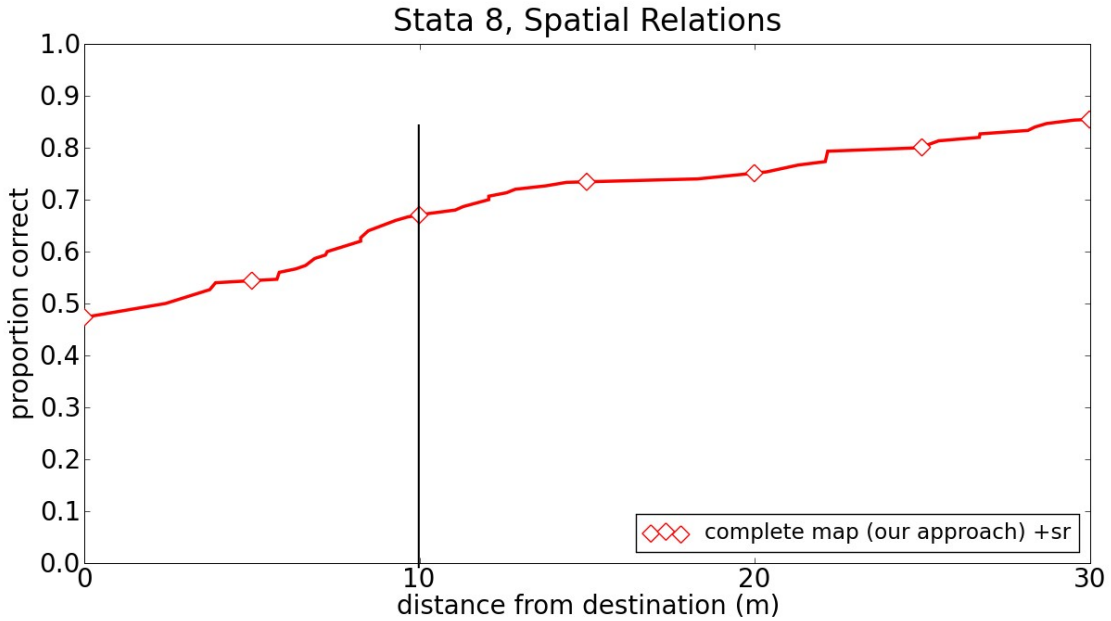
Performance

	Study 1
Humans (All directions)	85%

Performance

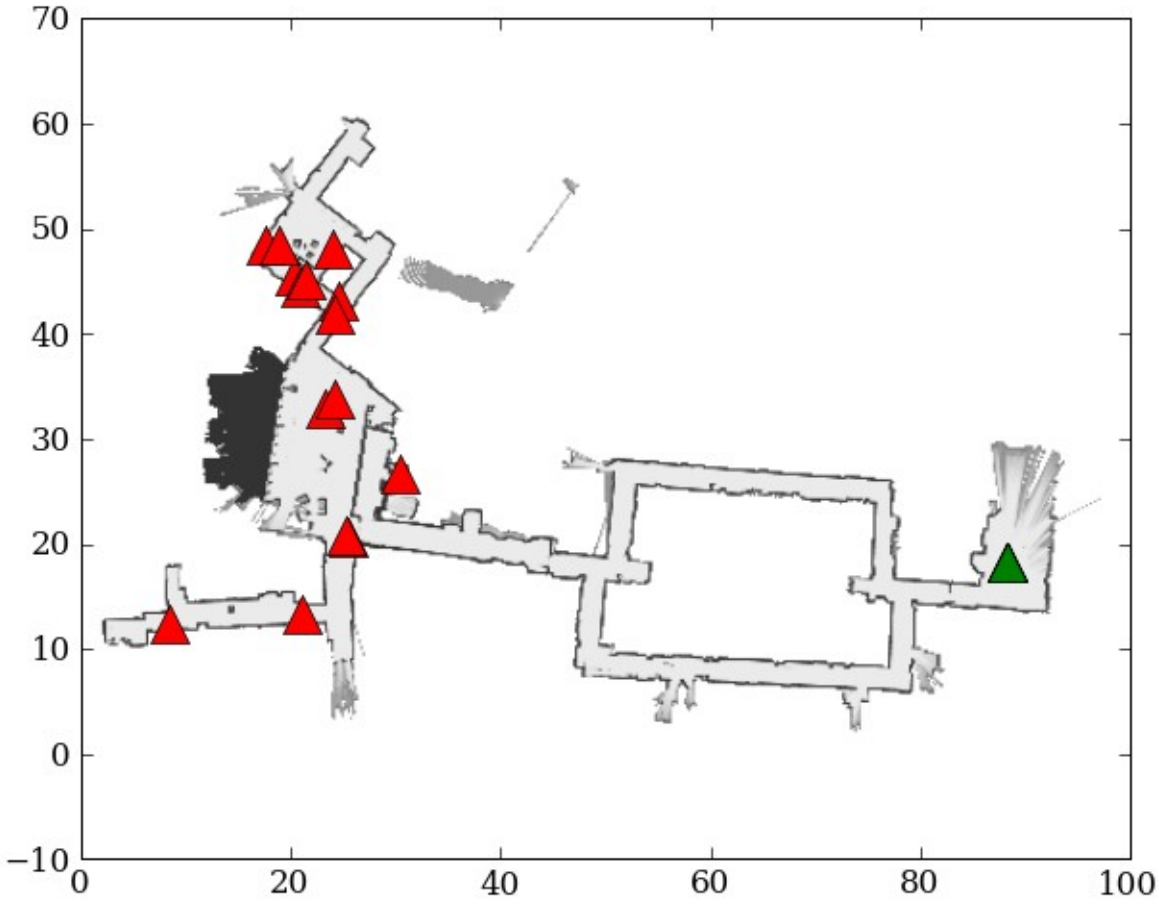
	Study 1
Humans (All directions)	85%
Our approach	67%

Spatial Relations

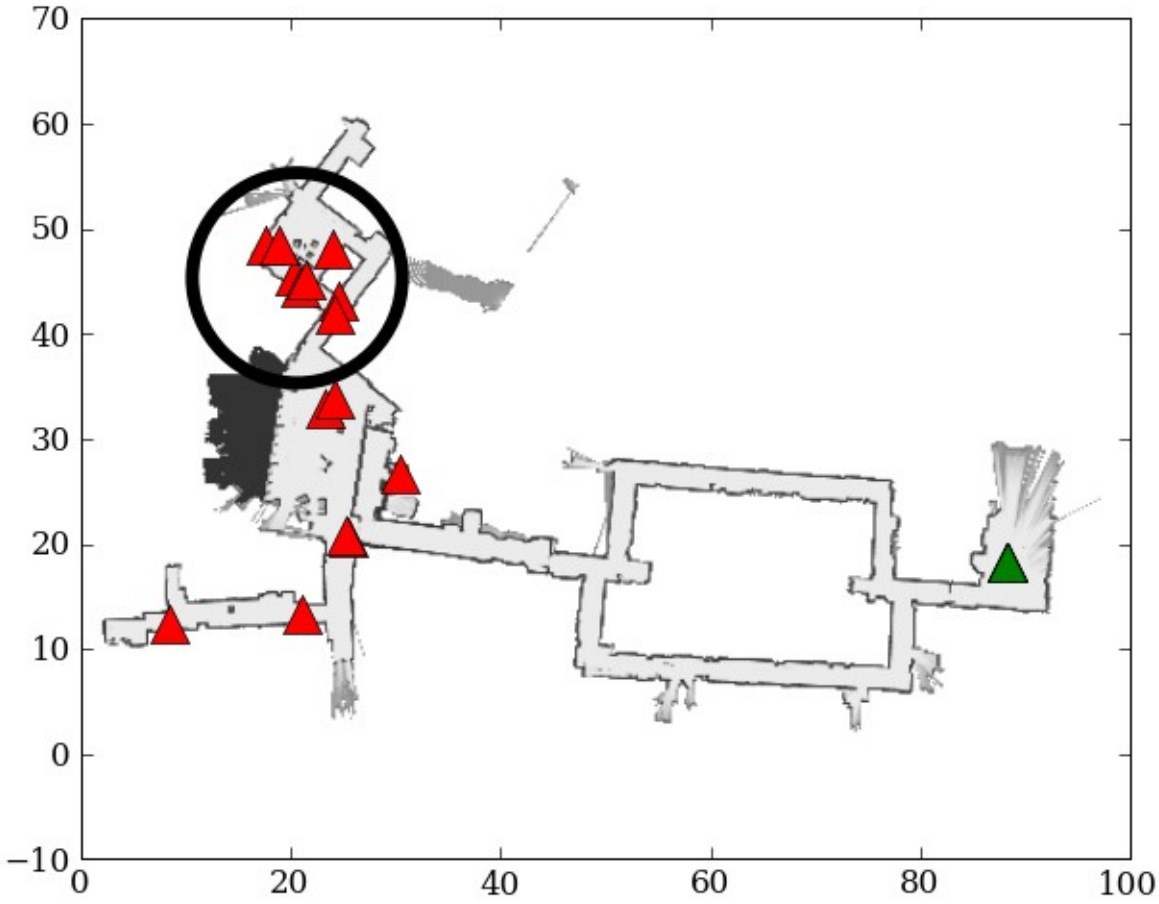


	Study 1
Complete Map +sr	67%

Performance

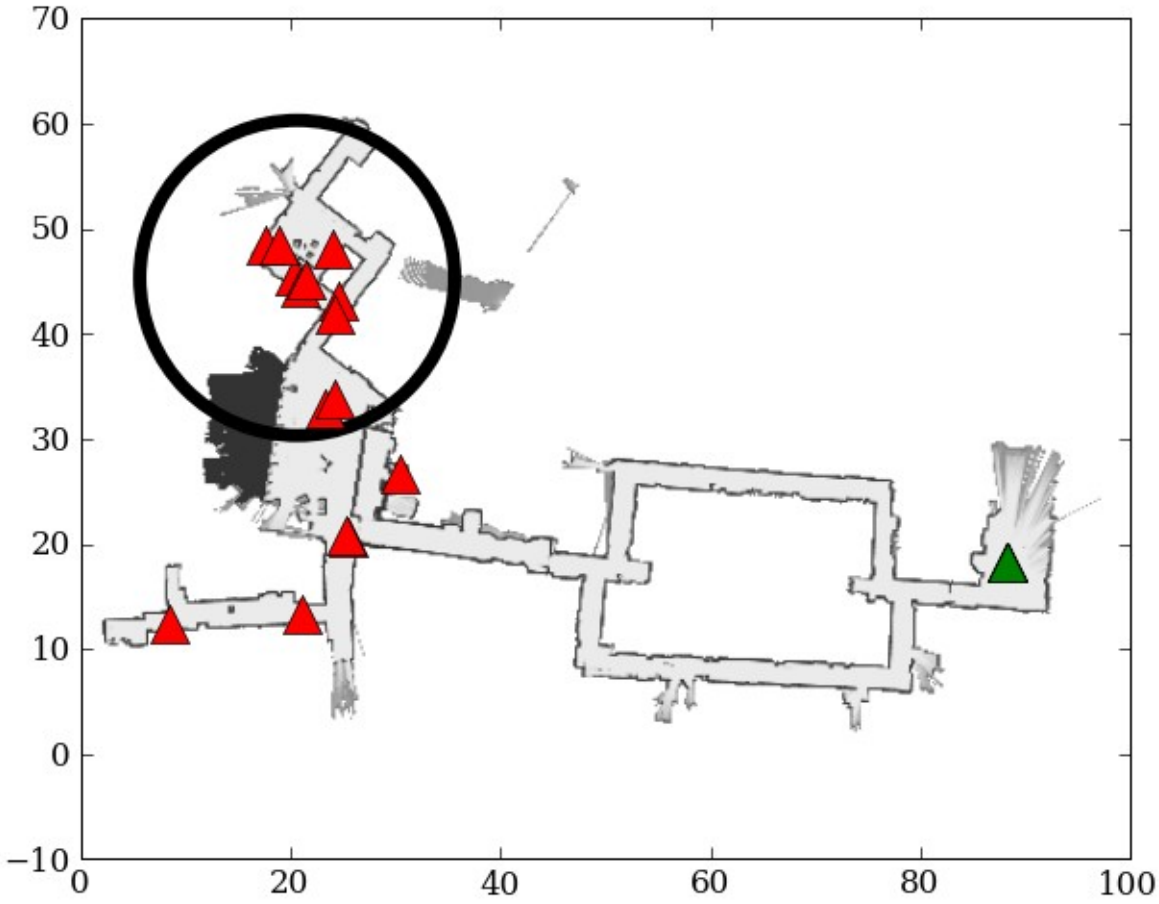


Performance



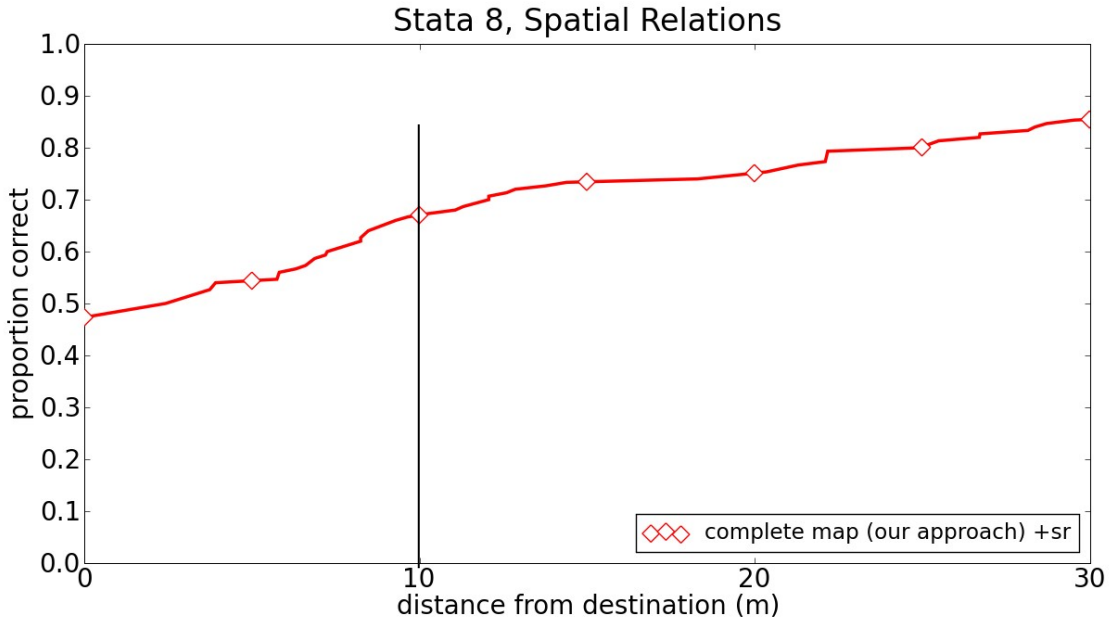
Proportion correct at 10 meters: 0.53

Performance



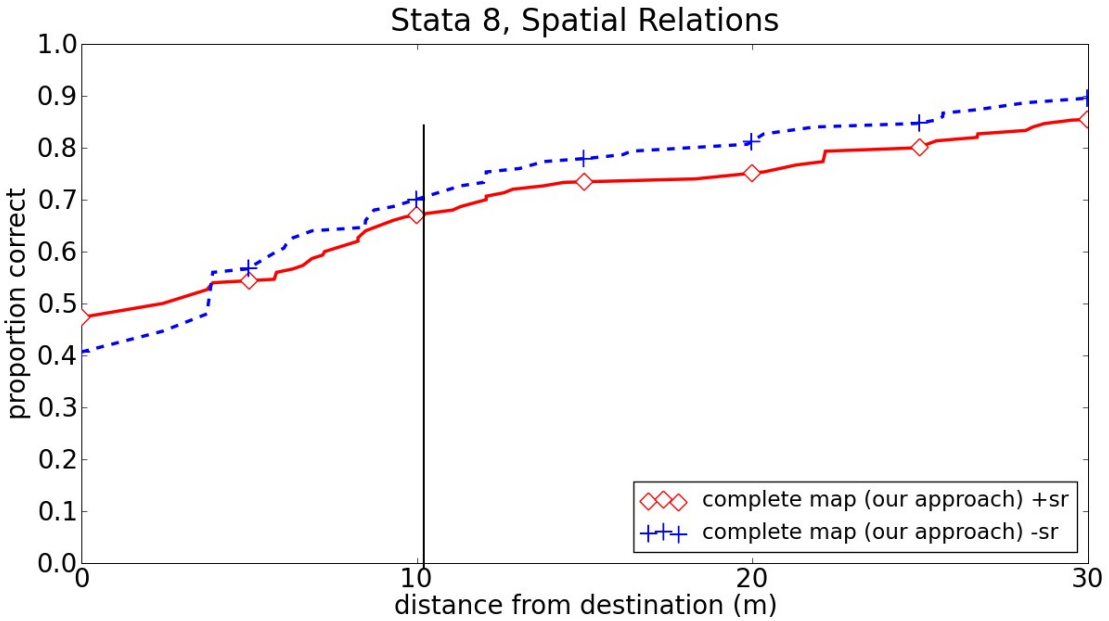
Proportion correct at 15 meters: 0.67

Spatial Relations



	Study 1
Complete Map +sr	67%

Spatial Relations

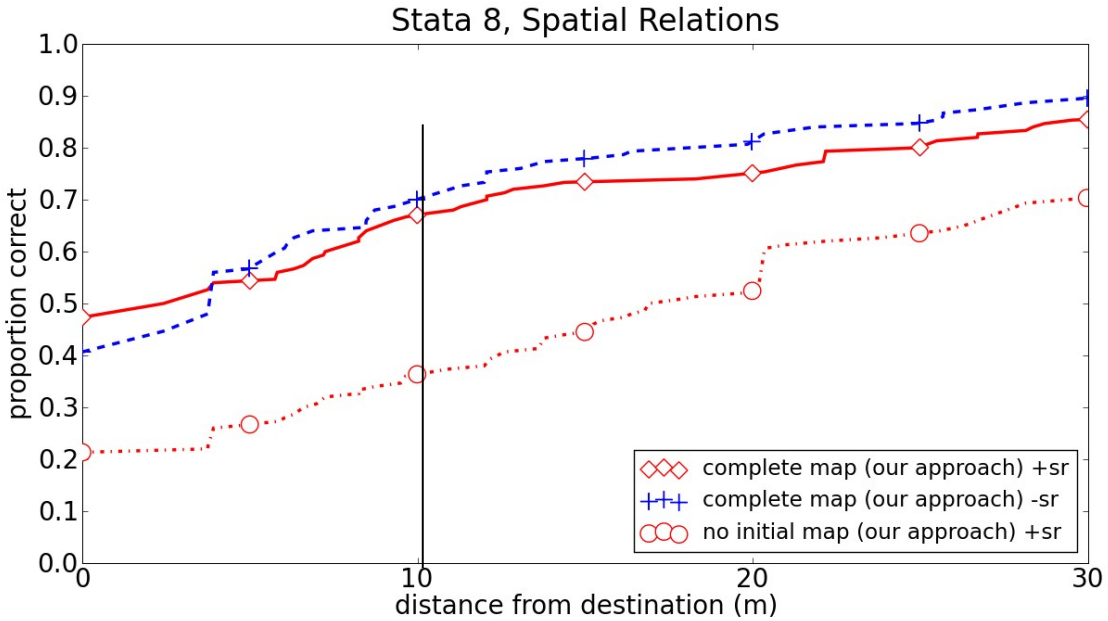


	Study 1
Complete Map +sr	67%
Complete Map -sr	68%

Inference Methods

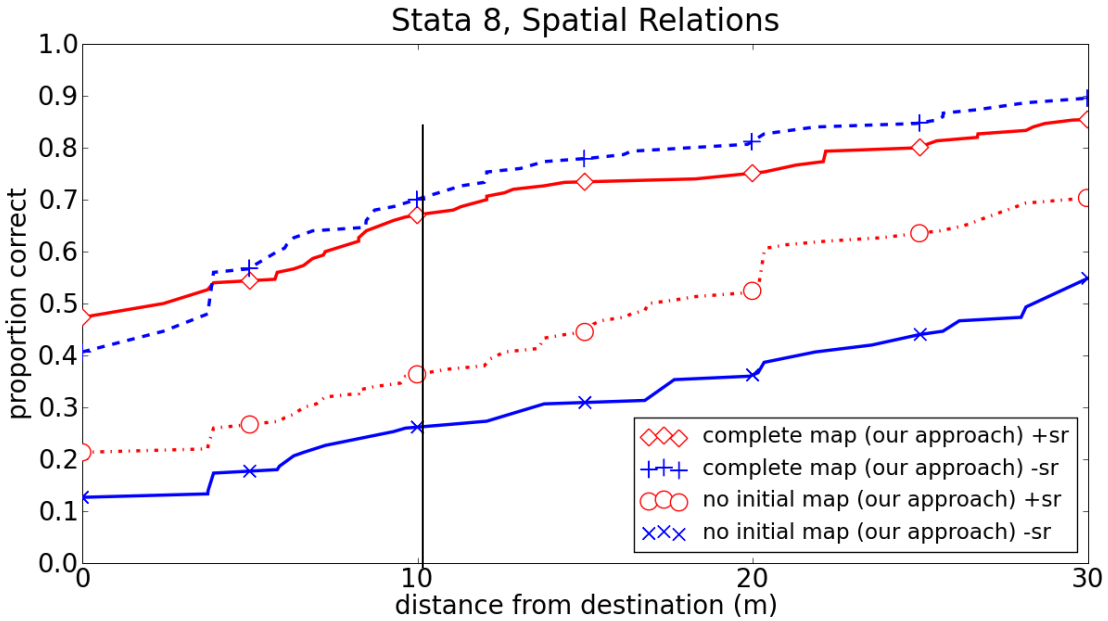
- Complete map.
  - Find the globally best path using a complete map of the environment.
- Partial map.
  - Greedy algorithm that uses local information from the environment.

Spatial Relations



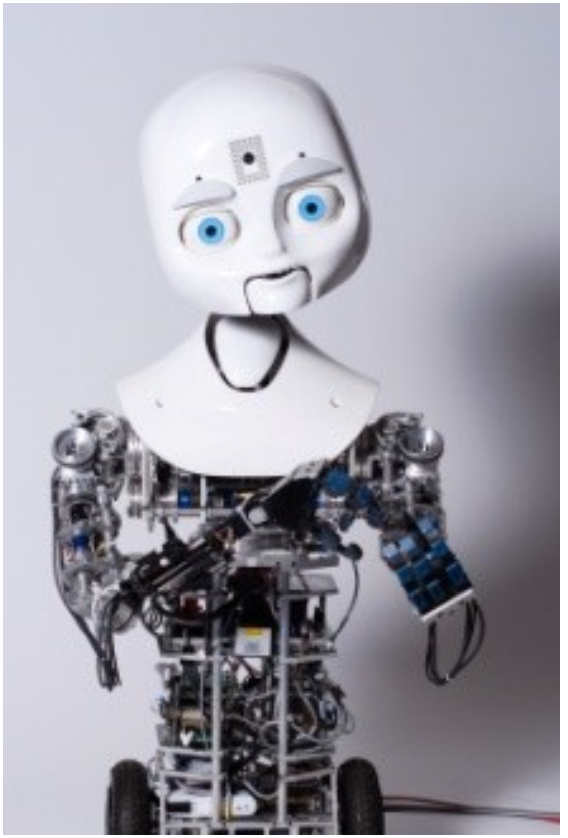
	Study 1
Complete Map +sr	67%
Complete Map -sr	68%
Partial Map +sr	36%

Spatial Relations

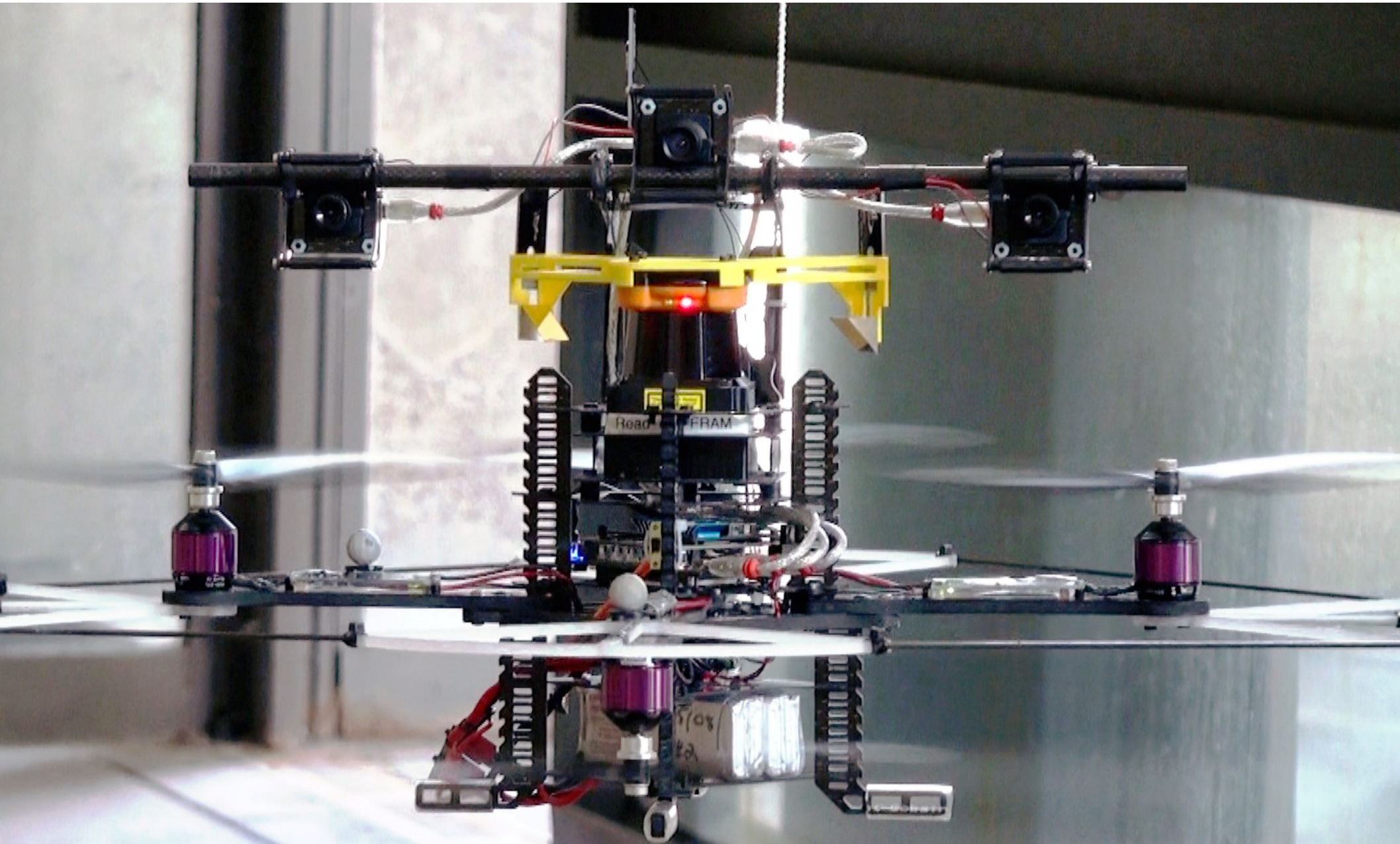


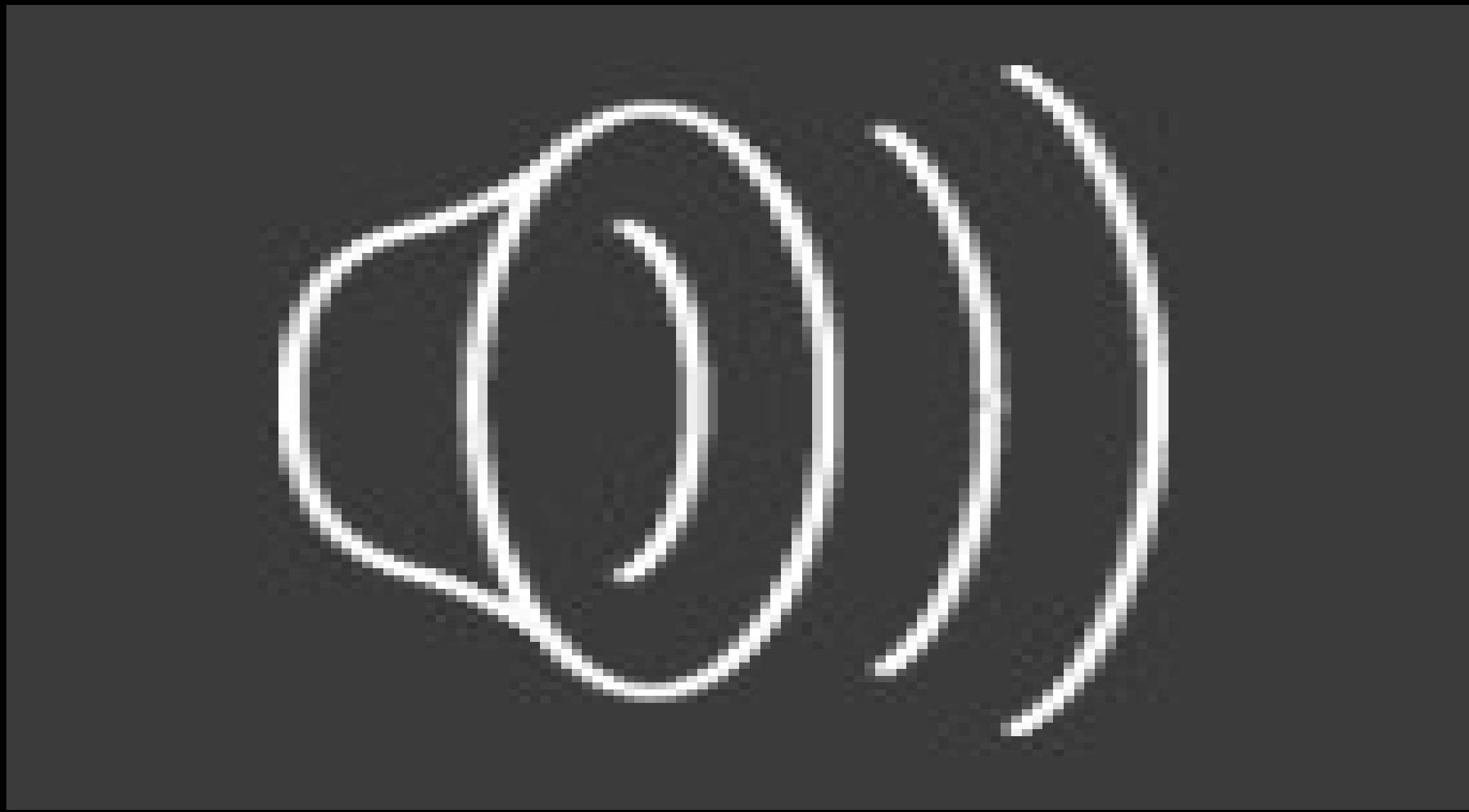
	Study 1
Complete Map +sr	67%
Complete Map -sr	68%
Partial Map +sr	36%
Partial Map -sr	26%

Platforms



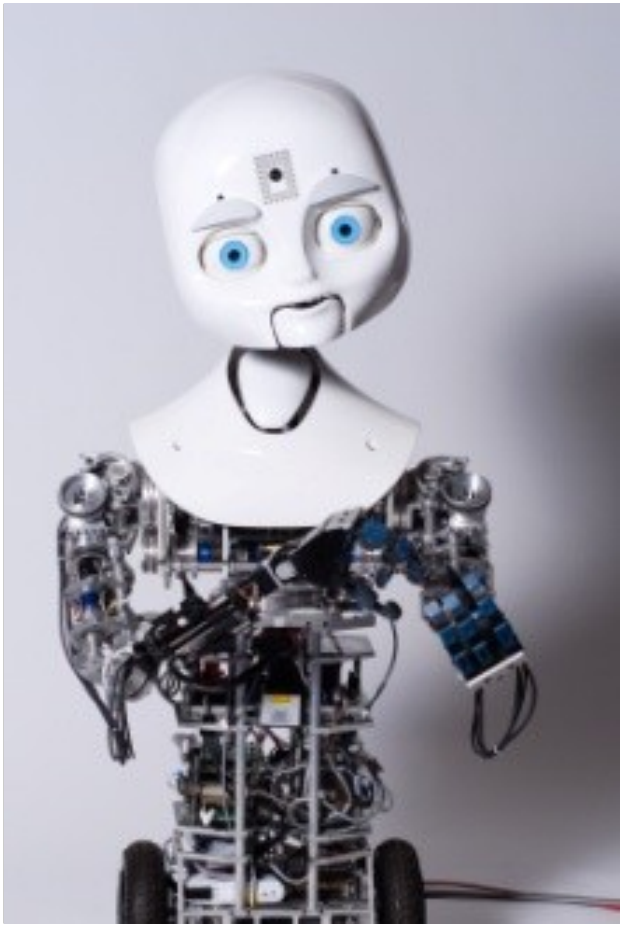
Robotic Helicopter





Two Different Domains

- Direction Understanding



- Video Retrieval

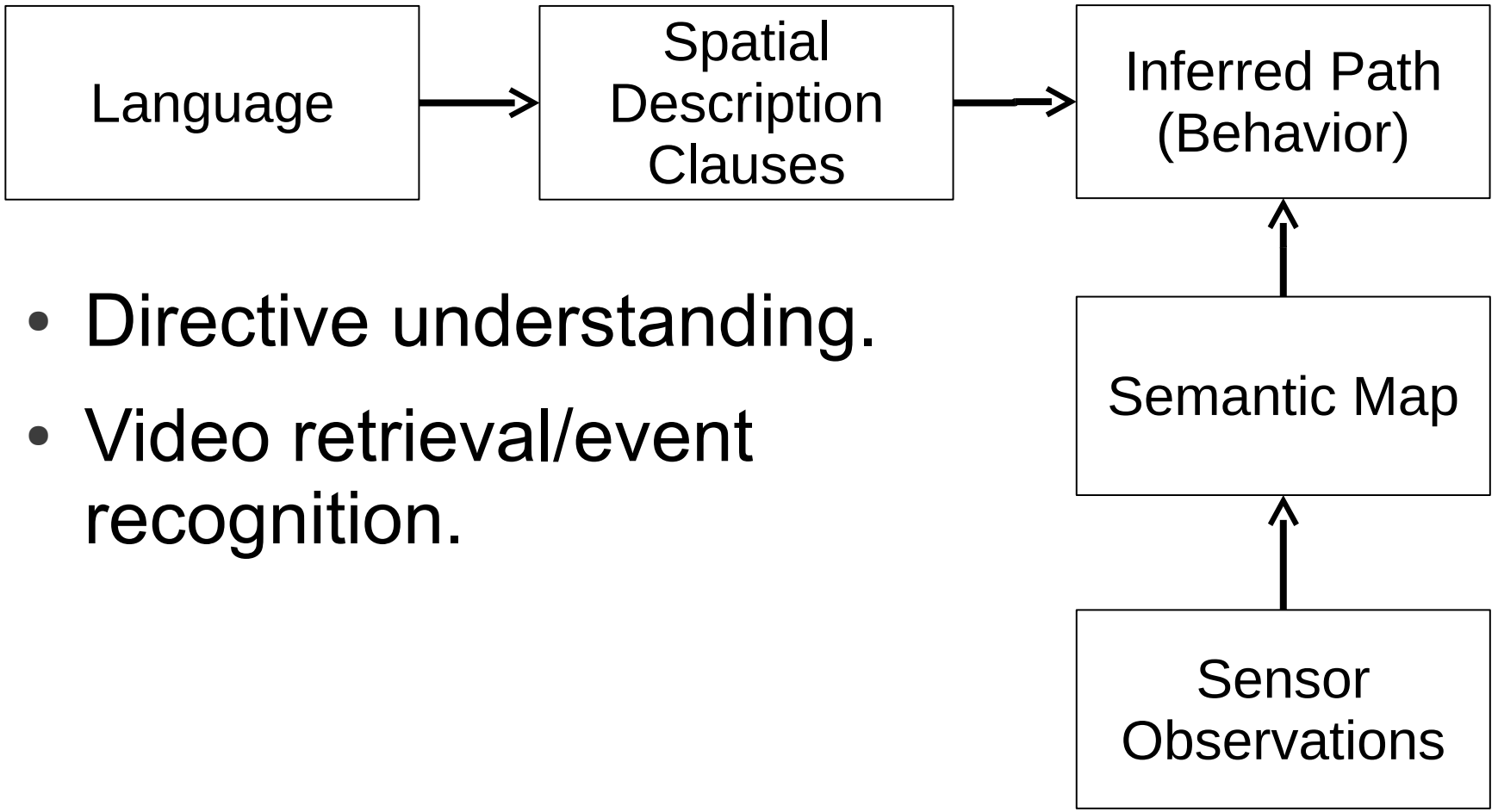
Outline

- Spatial Prepositions
- Spatial Description Clauses
- Direction Understanding
- **Spatial Language Video Retrieval**
- Conclusion

Show me people going across the kitchen.

People walking from the hallway door, around the island, to the kitchen sink

System



- Directive understanding.
- Video retrieval/event recognition.

Corpus

- Watch a video clip.
- Write a natural language description of the movement of a person in the clip, so that another person could draw the trajectory.
- Not asked to simplify language in any way, or use a particular vocabulary.
- 696 descriptions from fourteen annotators.

“The person walked from the couches in the living room to the dining room table.”

“The woman entered the dining room from the living room.”

“She walks from the hallway into the dining room and stands by the side of the dining room table that is nearest to the kitchen.”

“The person walked from the couch in the living to the dining table in the dining room.”

“The person enters the dining room from the living room and goes to the table near the entrance to the kitchen.”

“She starts in the living room and walks to in front of the desk.”

“The person enters the dining room from the stairway or living room area. She goes to the long side of the table nearest to the kitchen doorway.”

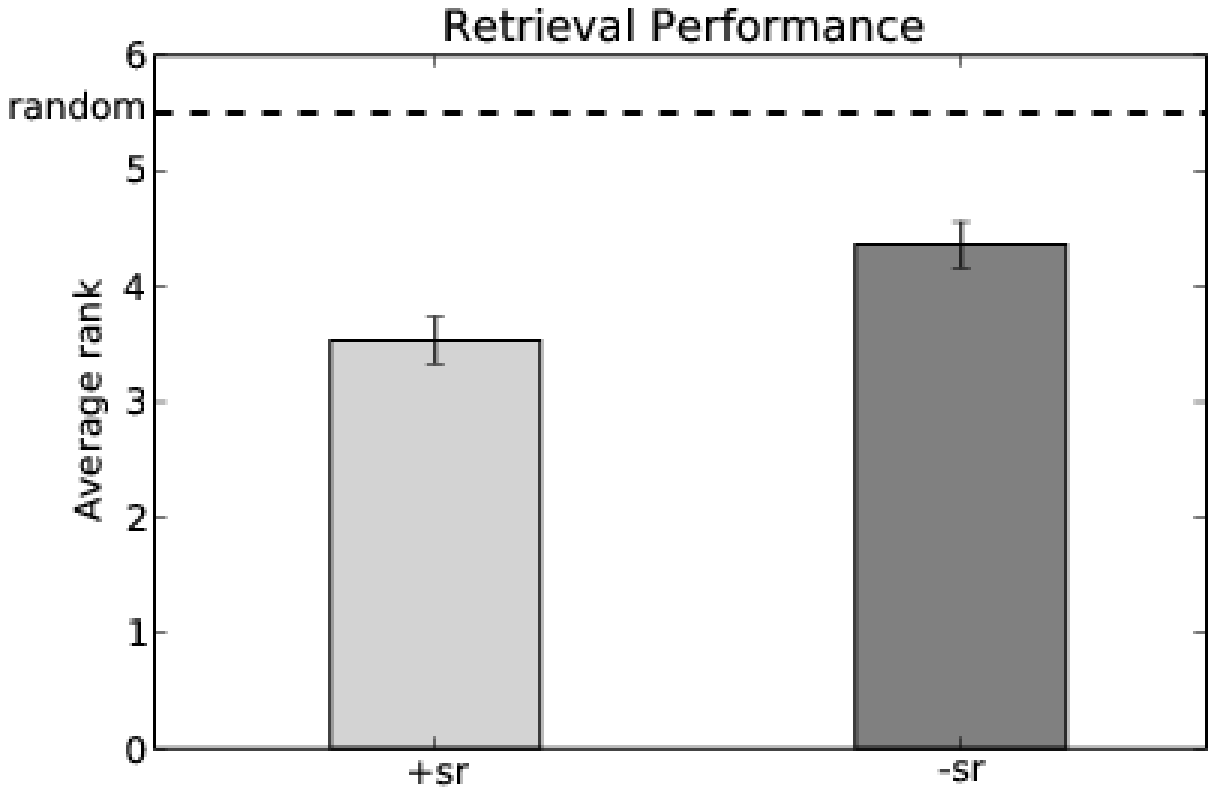
“The person walks from the left-bottom side of the dining room table over tot he (*sic)* shelves.”

Evaluation Metric

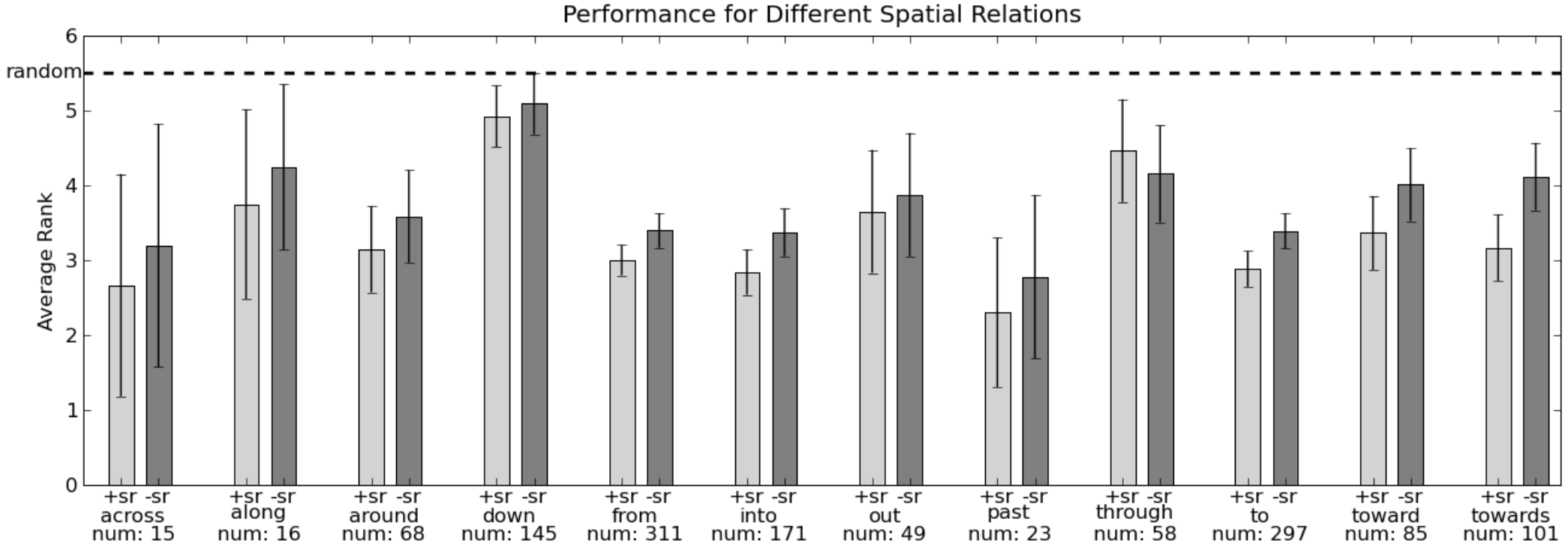
- Take a trajectory.
- Add in 9 other random clips.
- Rank all ten clips according to the original description.
- Report average rank of the original clip.

Performance With and Without Spatial Relations

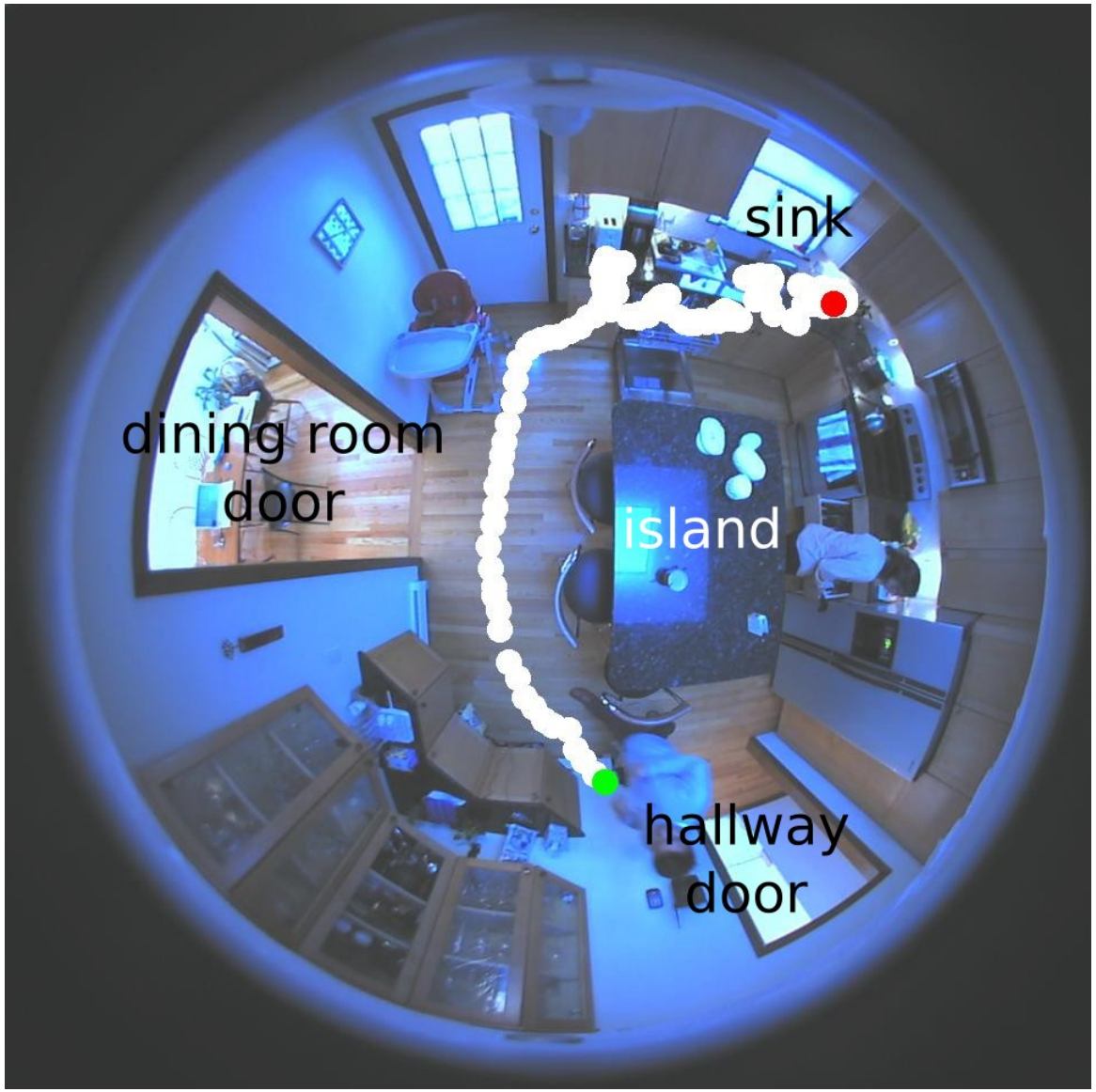
	+sr	-sr
% Ranked 1 or 2:	58%	40%



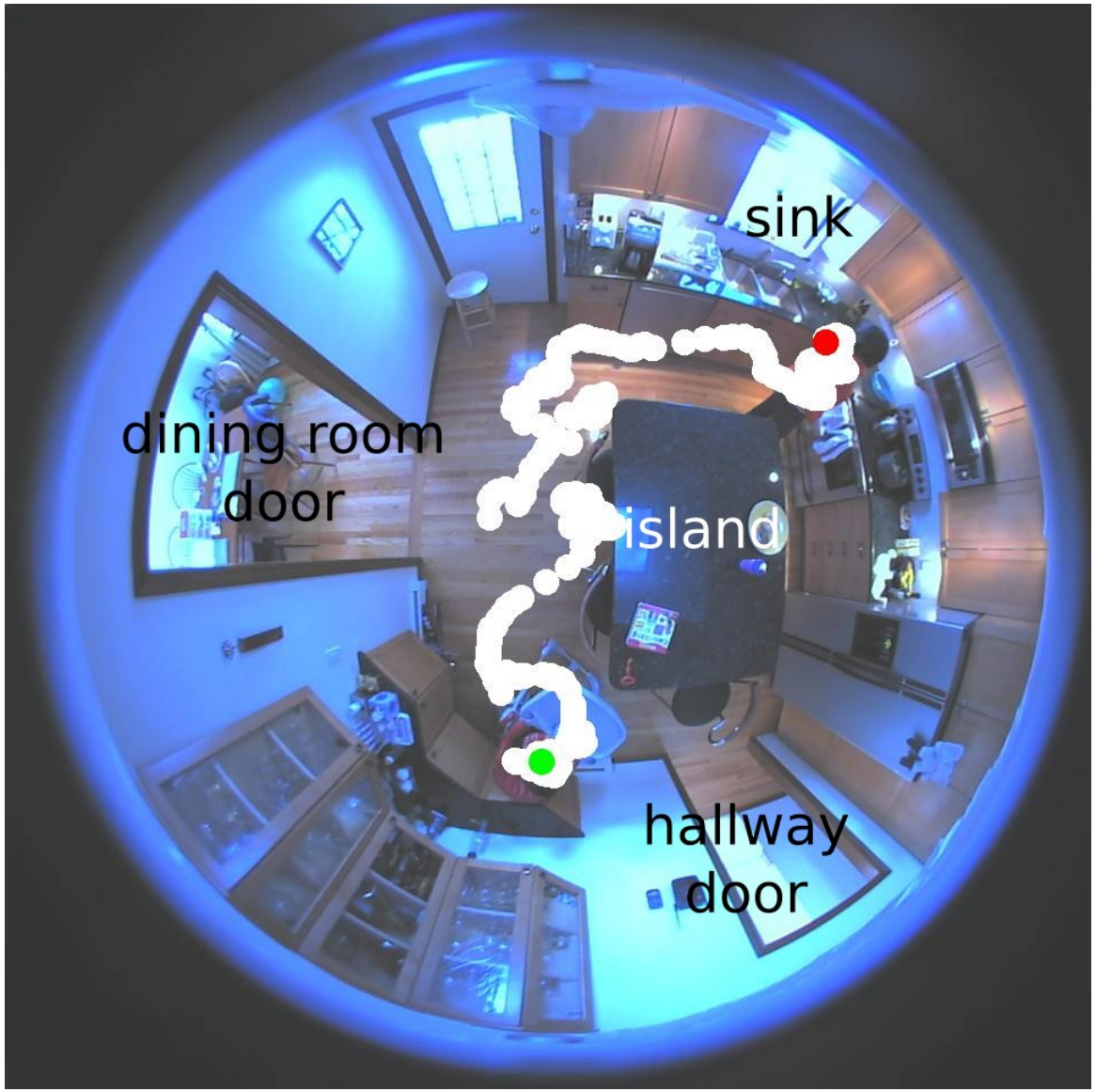
Performance With and Without Particular Spatial Relations



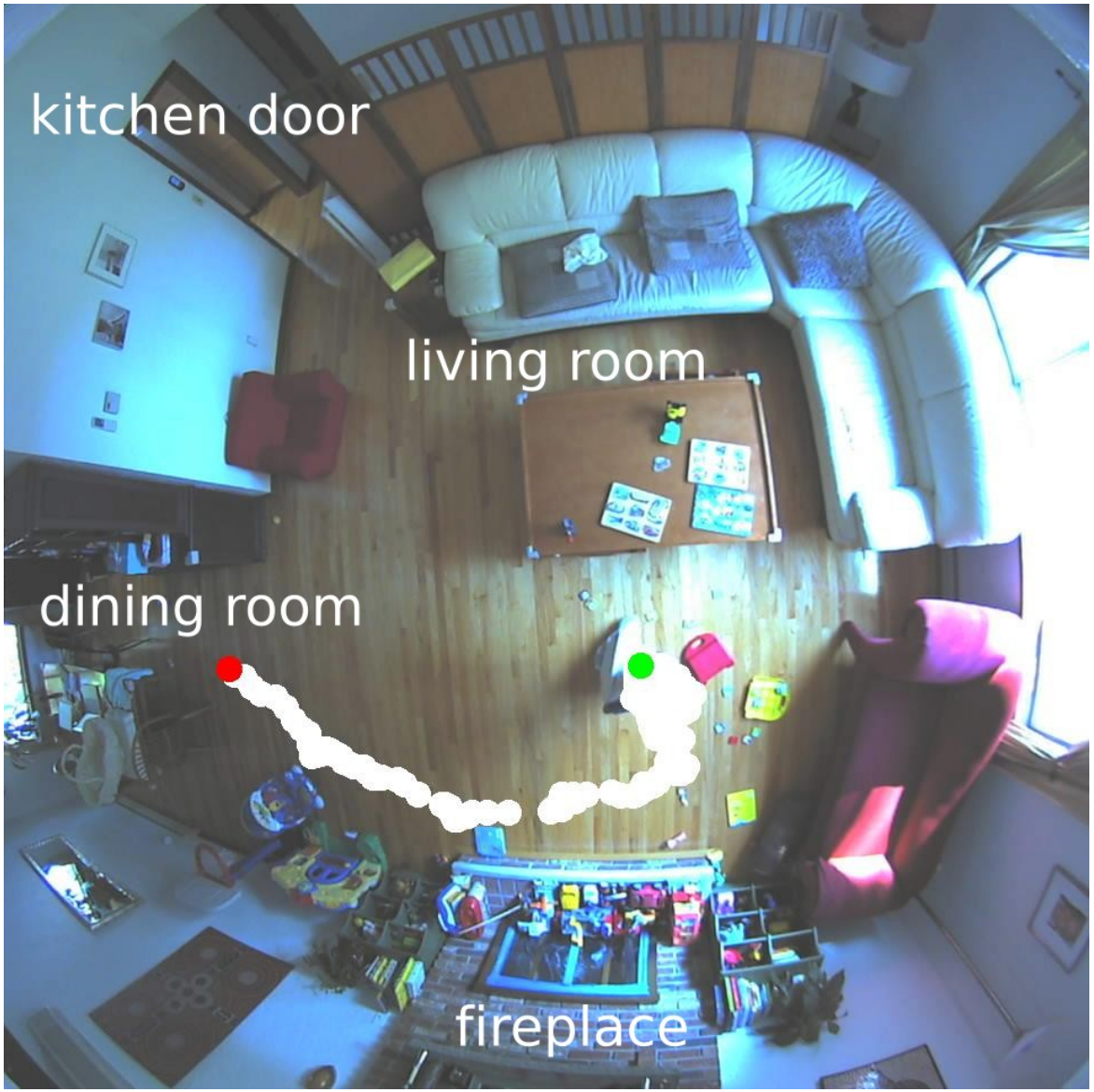
People walking from the hallway door, around the island, to the kitchen sink



People walking from the hallway door, around the island, to the kitchen sink



She walks past the fireplace and stands by the bookshelf.



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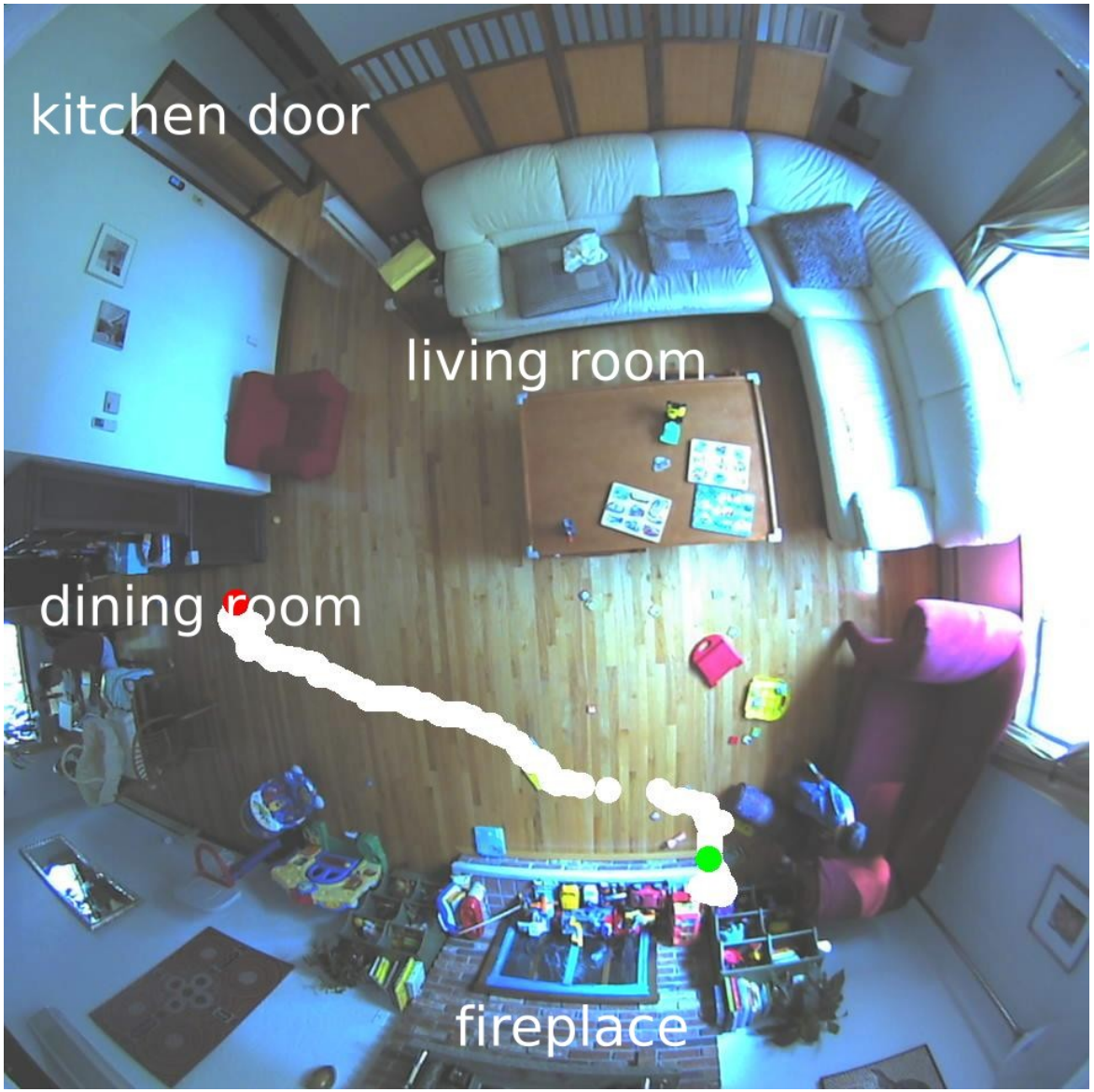

Results

- Effective video retrieval system that takes arbitrary spatial language.
- Corpus-based evaluation shows robustness.

Outline

- Spatial Prepositions
- Spatial Description Clauses
- Direction Understanding
- Spatial Language Video Retrieval
- **Conclusion**

Future Work

- From paths to plans.
  - “Empty the dishwasher.”
  - “Unload the truck.”
- Dialogue.
  - “Drive to the door near the elevators.”
  - “Where are the elevators?”
- Less supervision.

Contributions

- Developed a library of features that capture the semantics of spatial prepositions.
- Analyzed which features work best for each preposition.
- Spatial Description Clauses to decompose spatial language discourse.
- Systems for understanding natural language directions and spatial language video retrieval.
- Corpus-based evaluations show robustness.

Acknowledgements

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Gremio, Dave, Carie, Kai-yuh, Lin
Ania & Seth & Moby
Staci & Seth, Shannon & Jon, Scott & Onna
Grandma Patches and Grandma Nicholas
Mom and Dad

What's New Since Proposal

- Analysis of what features for spatial prepositions.
- Models for time-based verbs like “meet” and “follow.”
- Extending it to 3d. (Helicopter video!)
- Spatial language video retrieval.

Video Retrieval Metrics

Query	Avg. Precision
People coming out of the bathroom.	0.833
People walking into the baby's bedroom.	0.917
People walking down the hall.	0.967
People walking around the table. in the living room	1.000
People walking into the kitchen.	1.000
People walking out of the kitchen.	0.704
People walking from the hallway door, around the island, to the kitchen sink.	0.583
Mean Average Precision	0.858

Related Work – Cognitive Semantics

- Talmy. (2005) The Fundamental System of Spatial Schemas in Language.
- Landau and Jackendoff. (1993) “What” and “Where” in Spatial Language and Spatial Cognition.
- Regier. (1992) The Acquisition of Lexical Semantics for Spatial Terms: A Connectionist Model of Perceptual Categorization.
- Regier and Carlson. (1991) Grounding Spatial Language in Perception: An Empirical and Computational Investigation.
- Siskind. (1993) Grounding the Lexical Semantics of Verbs in Visual Perception Using Force Dynamics and Event Logic.

Related Work – Direction Understanding

- Hsiao et. al (2008) – Conversational table-top robot.
- Skubic et. al (2002) – Natural language commands for robots.
- MacMahon et. al (2005) – Following natural language directions.
- Matuszek et. al (2010) – Learning to follow natural language directions.
- Levit and Roy (2007) – Spatial language dialog understanding.

Related Work – Video Retrieval

- Katz et al. (2004) - “Show me all the cars leaving the garage.”
- Ivanov and Wren (2006) – Query by example trajectory.
- Fleischman et al. (2006) - “Show me people making coffee.”
- Naphade et al. (2006) - Large-Scale Concept Ontology for Multimedia

Extracting Spatial Description Clauses

- CRF chunker tags each word.
- Trained from annotated data.
- Features (tri-grams)
  - Words
  - Part-of-speech tags
  - Label sequence
- Greedy algorithm groups tagged words together.

Extracting Spatial Description Clauses

Continue to walk straight, going through one door until you come to an intersection just past a white board.

Extracting Spatial Description Clauses

Continue to walk straight, going through one door until you come to an intersection just past a white board.

V: Continue to walk straight

Extracting Spatial Description Clauses

Continue to walk straight, going through one door until you come to an intersection just past a white board.

V: going, SR: through, L: one door

Extracting Spatial Description Clauses

Continue to walk straight, going through one door until you come to an intersection just past a white board.

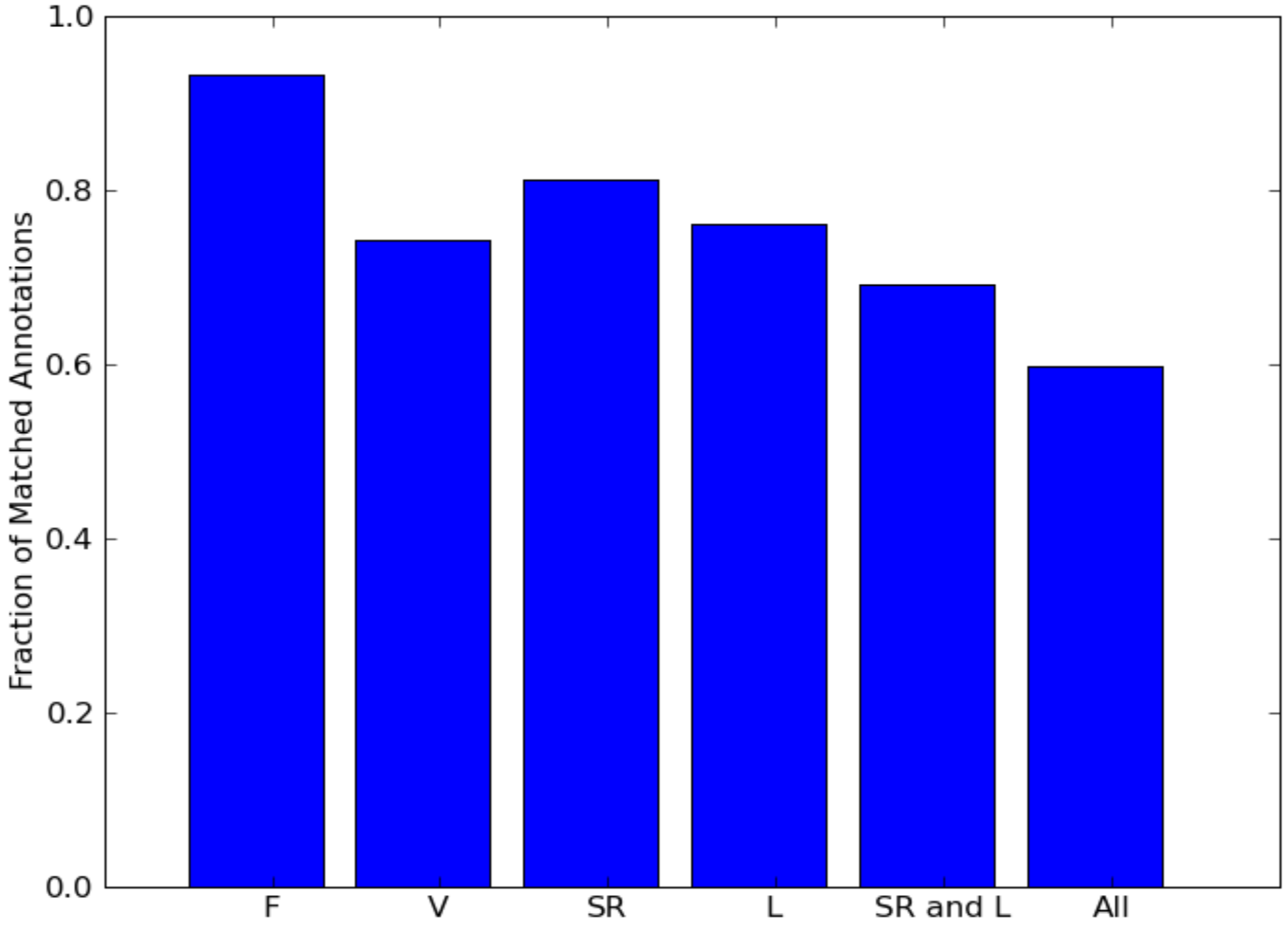
SR: until, L: you come to an intersection

Extracting Spatial Description Clauses

Continue to walk straight, going through one door until you come to an intersection just past a white board.

SR: just past, L: a white board

Extracting Spatial Description Clauses



Contributions

- Create a library of features for grounding spatial prepositions.
- Analyze which features perform best for specific prepositions.
- Compare semantics of spatial prepositions in two different domains.
- Model for understanding spatial language discourse.

Spatial Prepositions in English

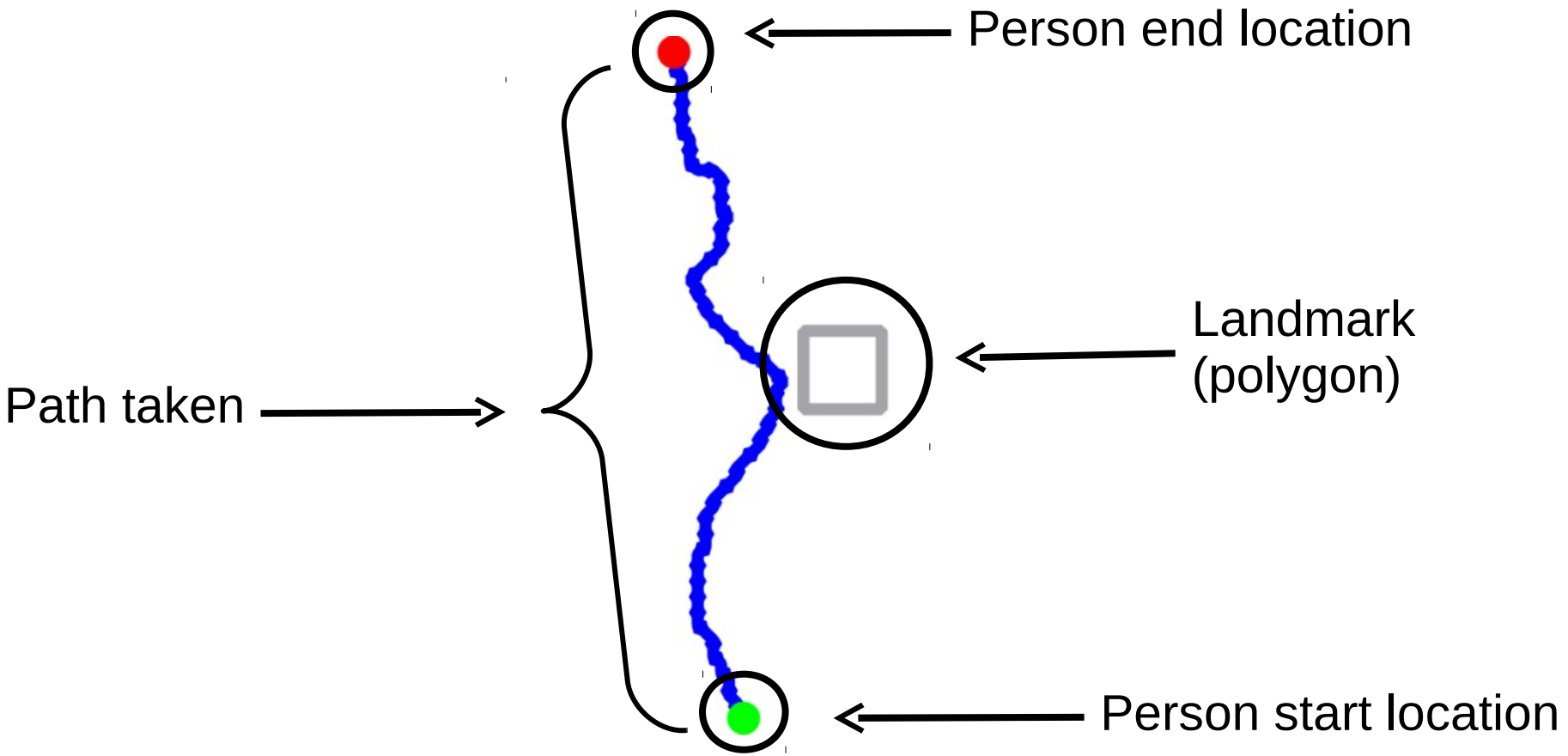
about, above, across, after, against, along, alongside, amid(st), among(st), around, at, atop, behind, below, beneath, beside, between, betwixt, beyond, by, down, from, in, inside, into, near, nearby, off, on, onto, opposite, out, outside, over, past, through, throughout, to, toward, under, underneath, up, upon, via, with, within, without, far from, in back of, in between, in front of, in line with, on top of, to the left of, to the right of, to the side of

(from Landau and Jackendoff, 1993)

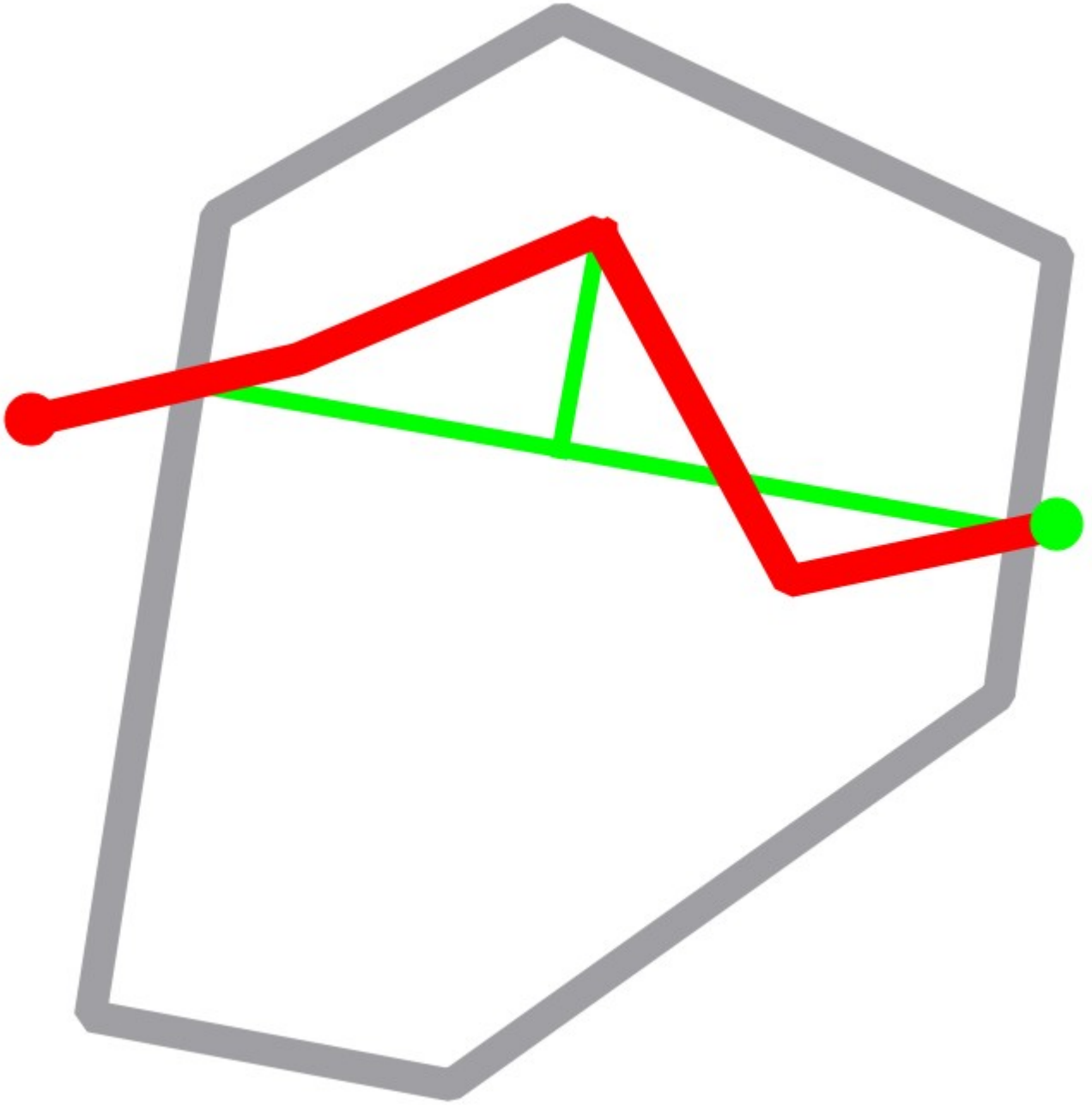
With your back to the windows, walk straight through the door near the elevators. Continue to walk straight, going through one door until you come to an intersection just past a whiteboard. Turn left, turn right, and enter the second door on your right (sign says "Administrative Assistant").

the windows, walk the door the elevators. Continue to walk , going one door you come an intersection a whiteboard. Turn left, turn right, and enter the second door (sign says "Administrative Assistant").

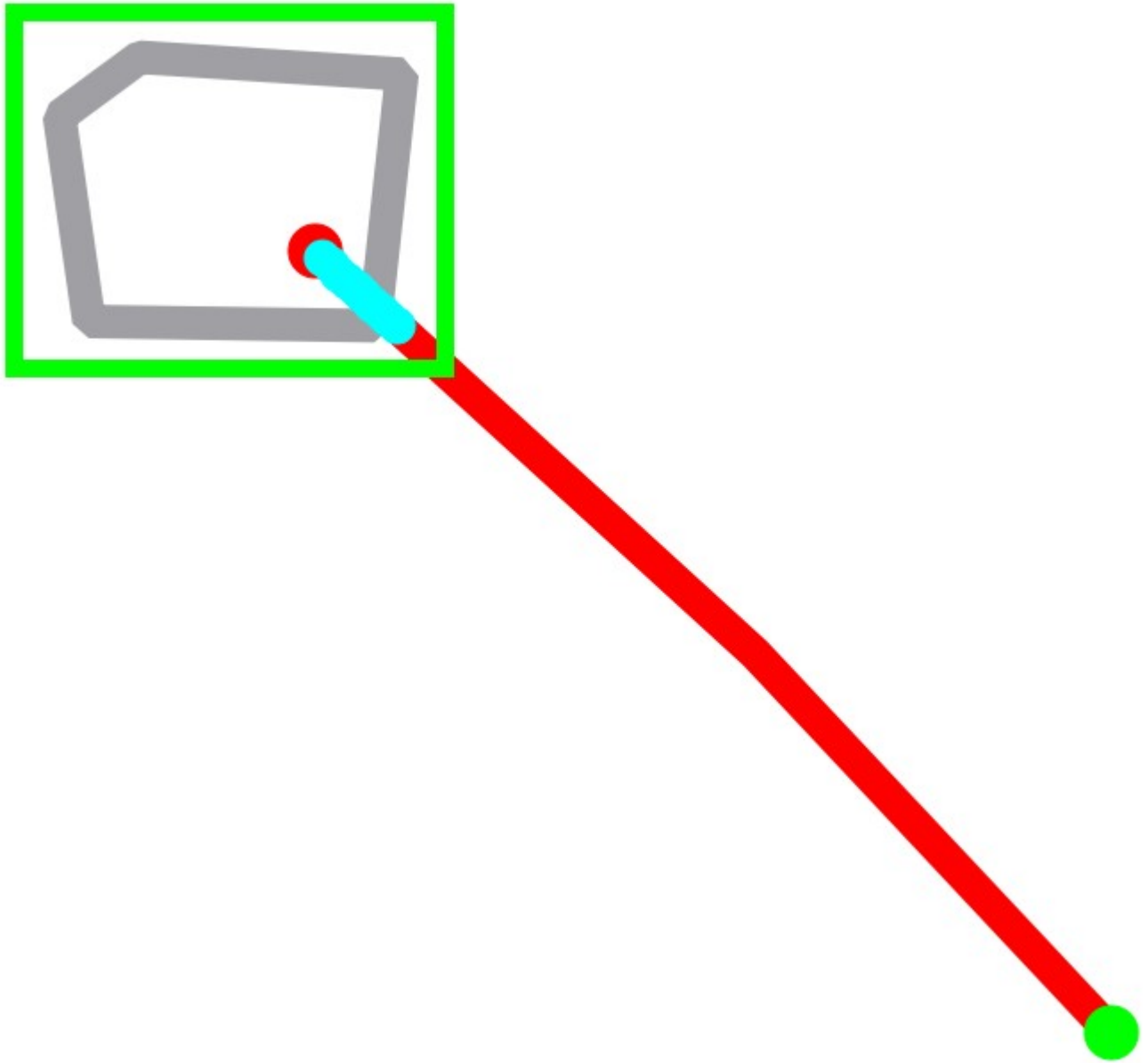
“Go past the chair.”



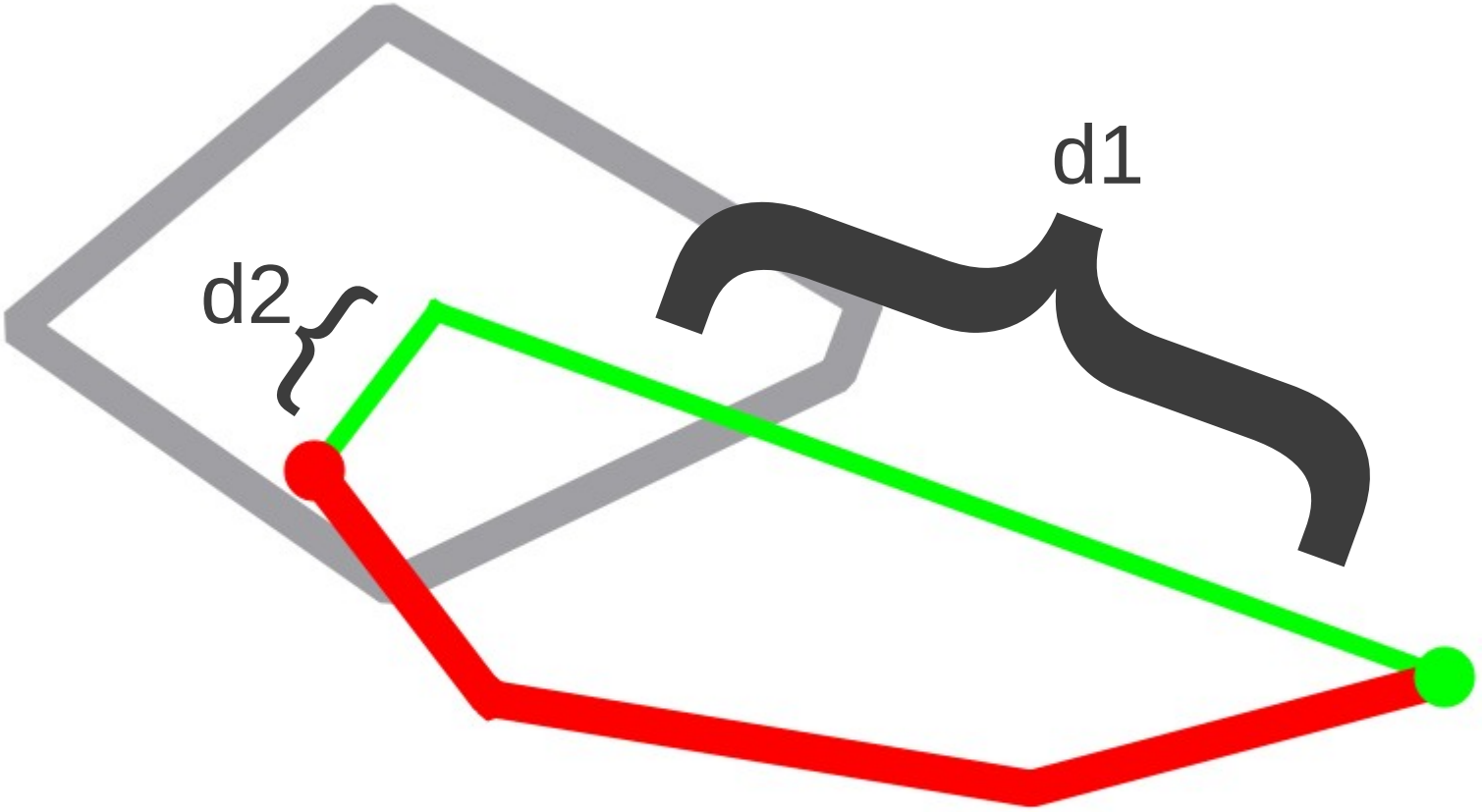
peakDistanceToAxes = max(dist(figure, axes))



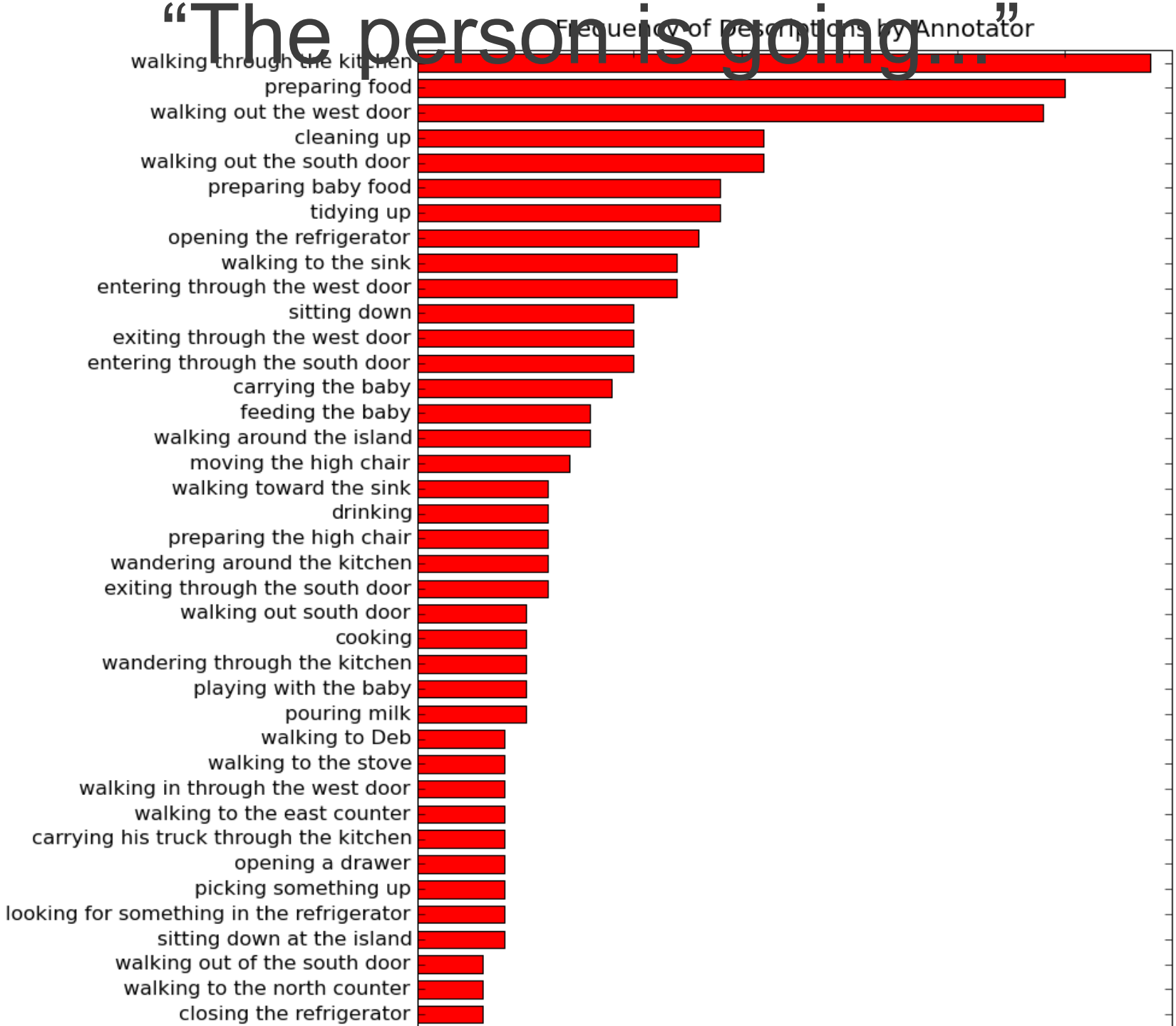
endPointsInGroundBoundingBox



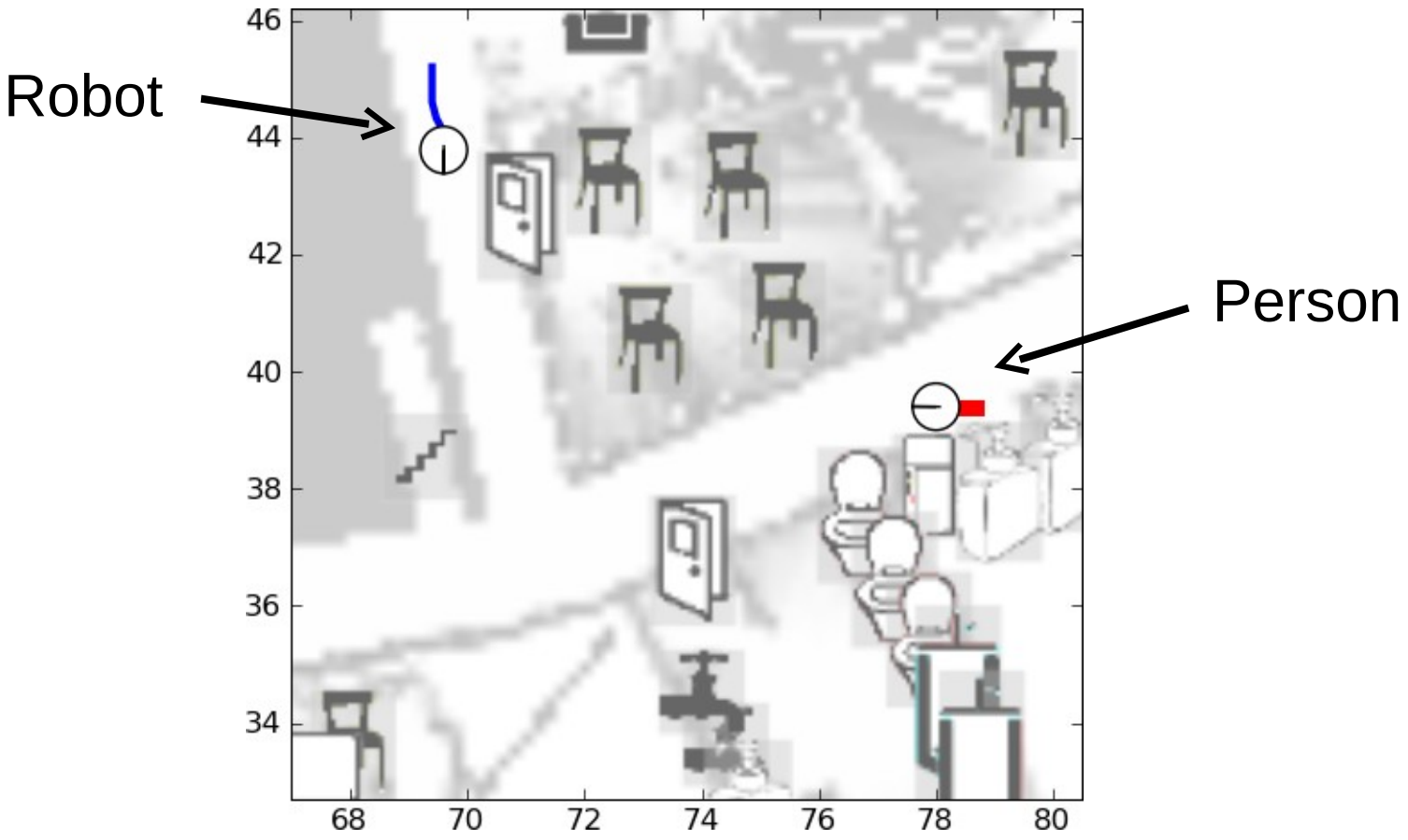
displacementFromGround=d2 - d1



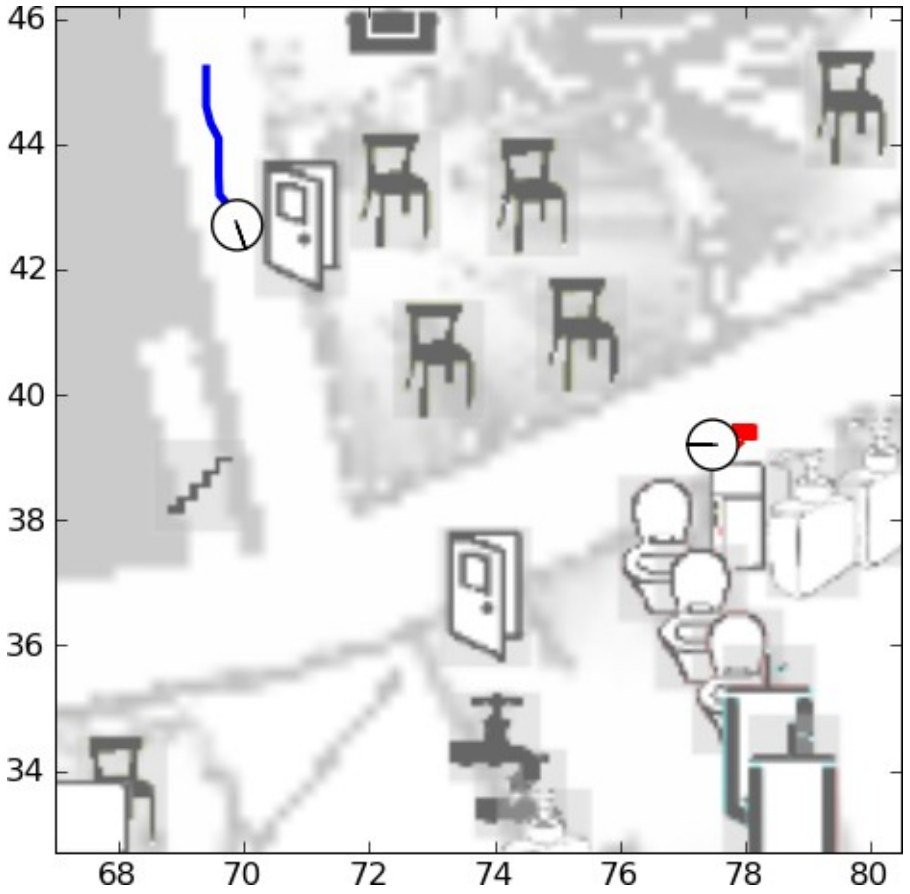
“The person is going...”



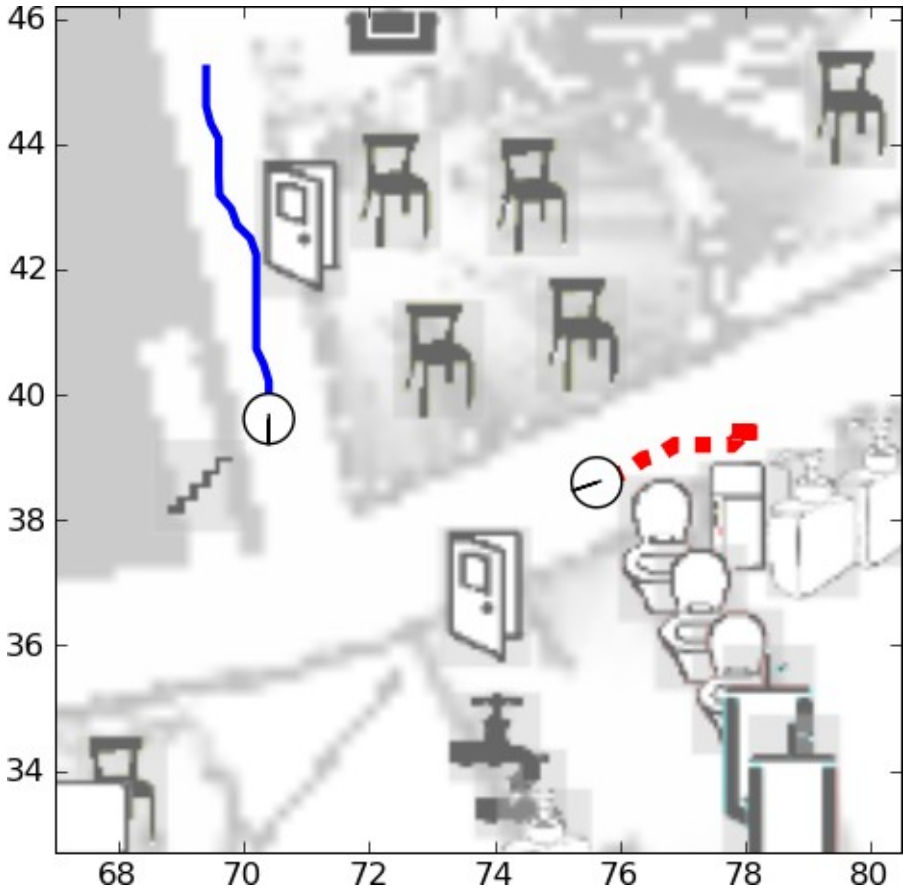
Meet the person.



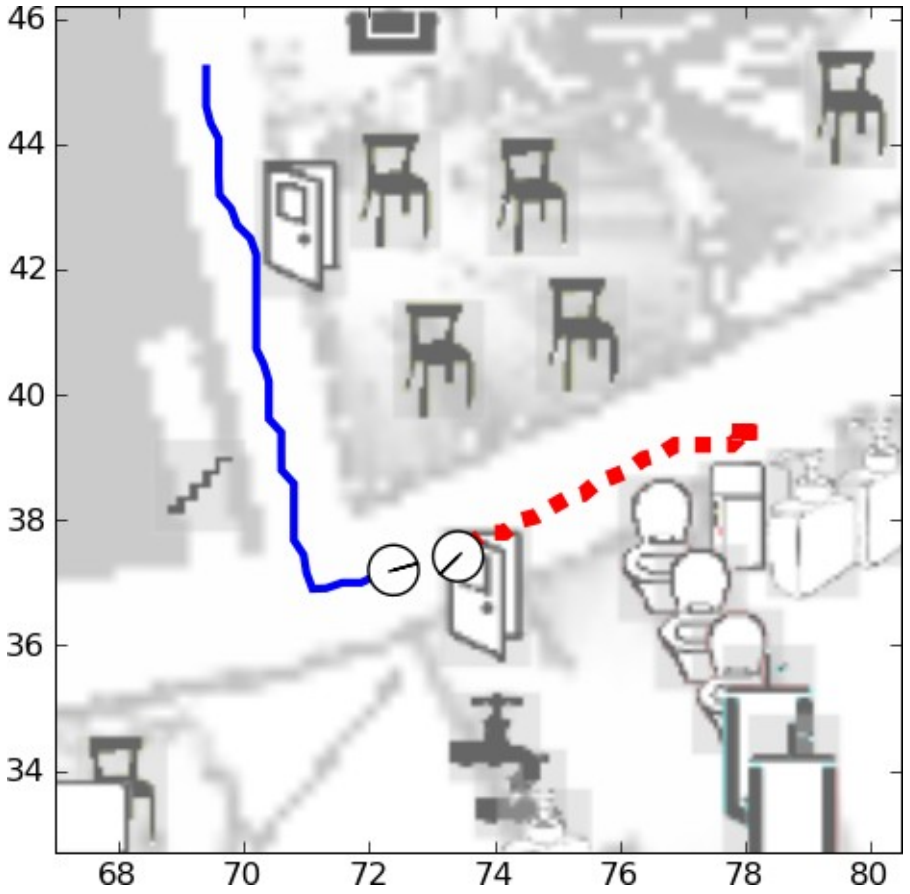
Meet the person.



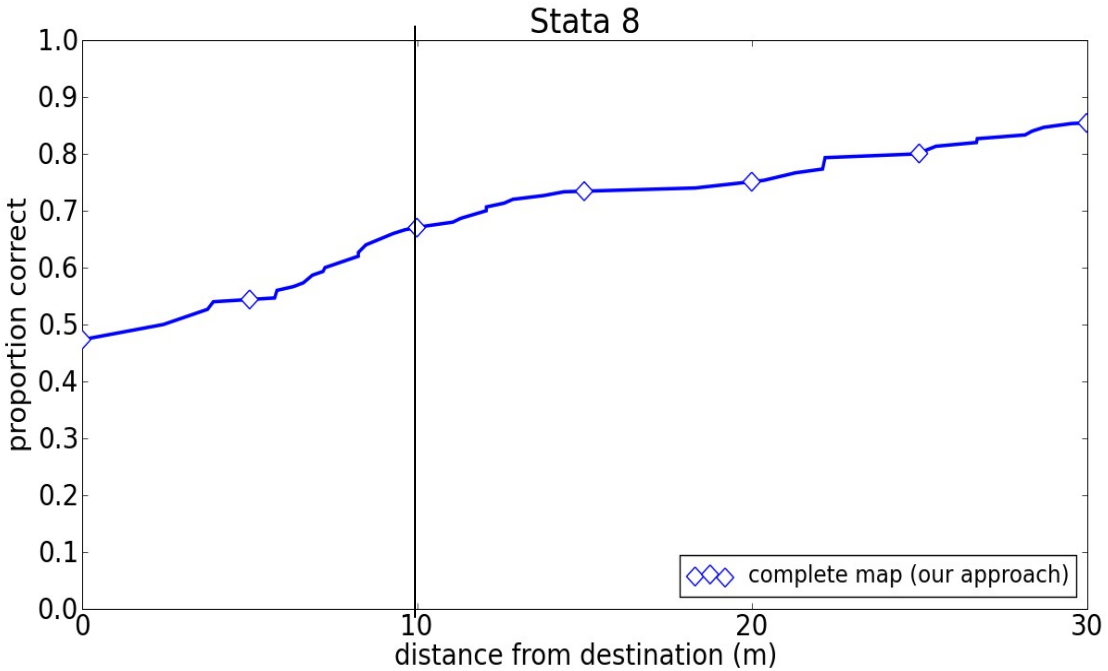
Meet the person.



Meet the person.

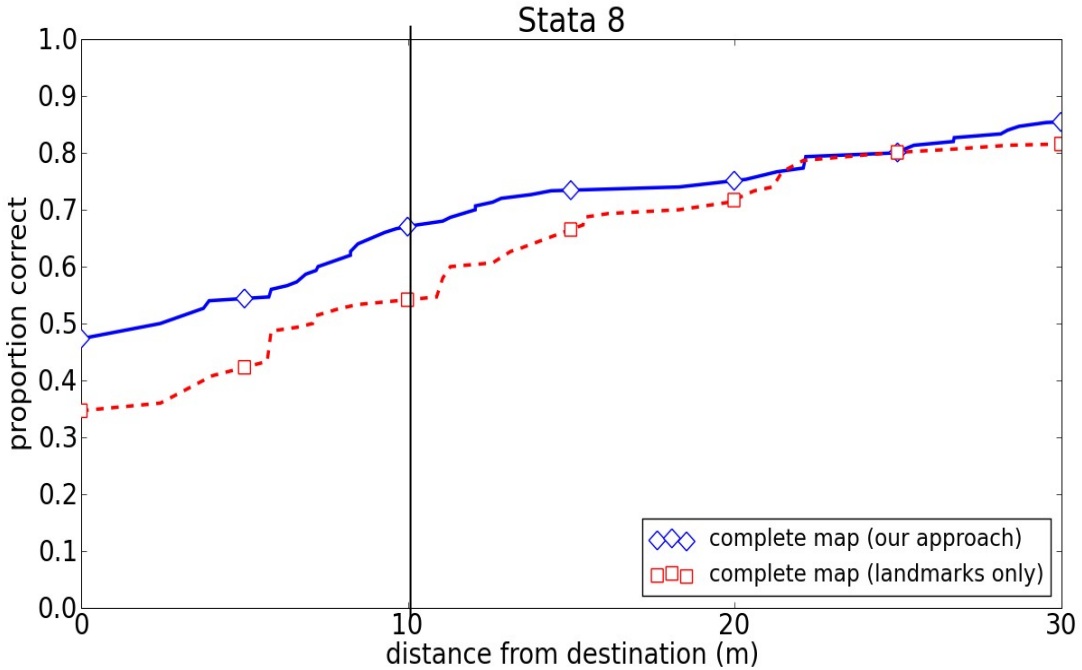


Comparison to Baselines



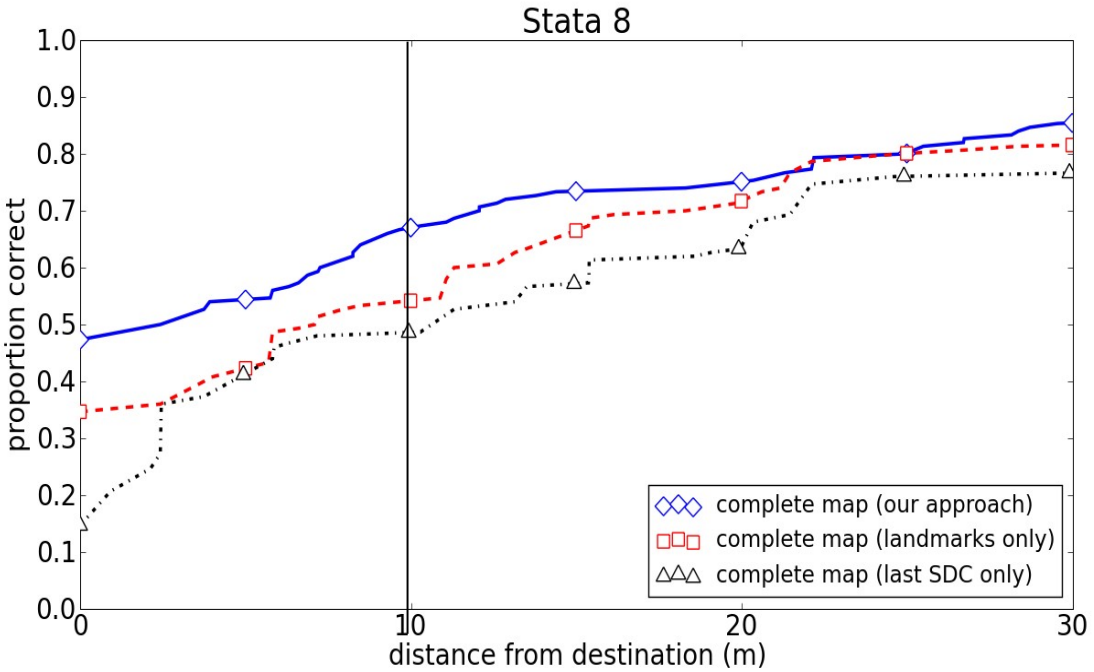
	Study 1
Complete Map	67%

Comparison to Baselines



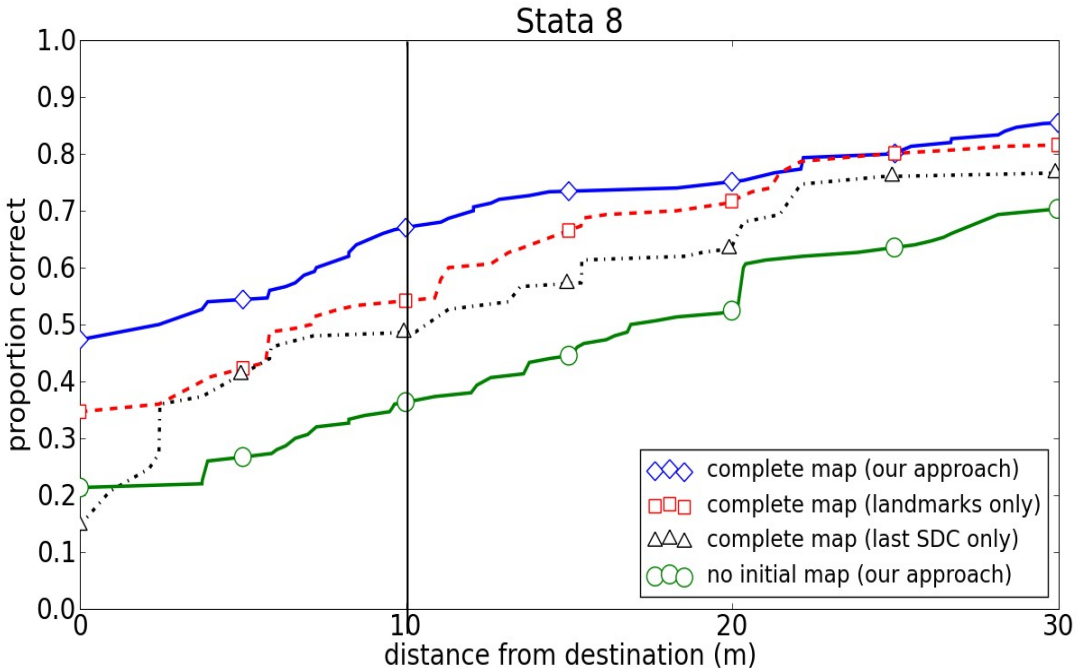
	Study 1
Complete Map	67%
Complete Map (landmarks only)	53%

Comparison to Baselines



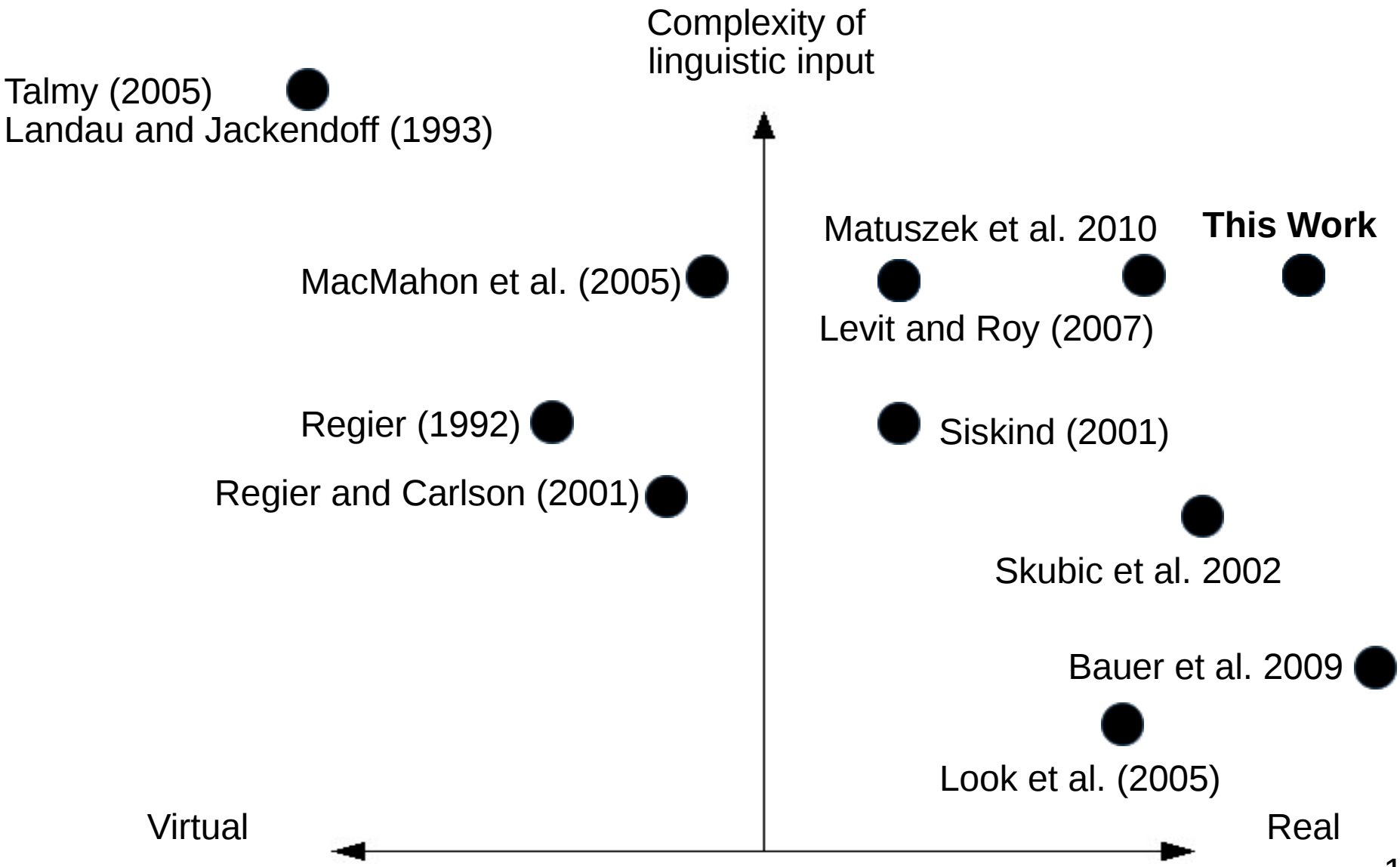
	Study 1
Complete Map	67%
Complete Map (landmarks only)	53%
Complete Map (last SDC)	48%

Comparison to Baselines



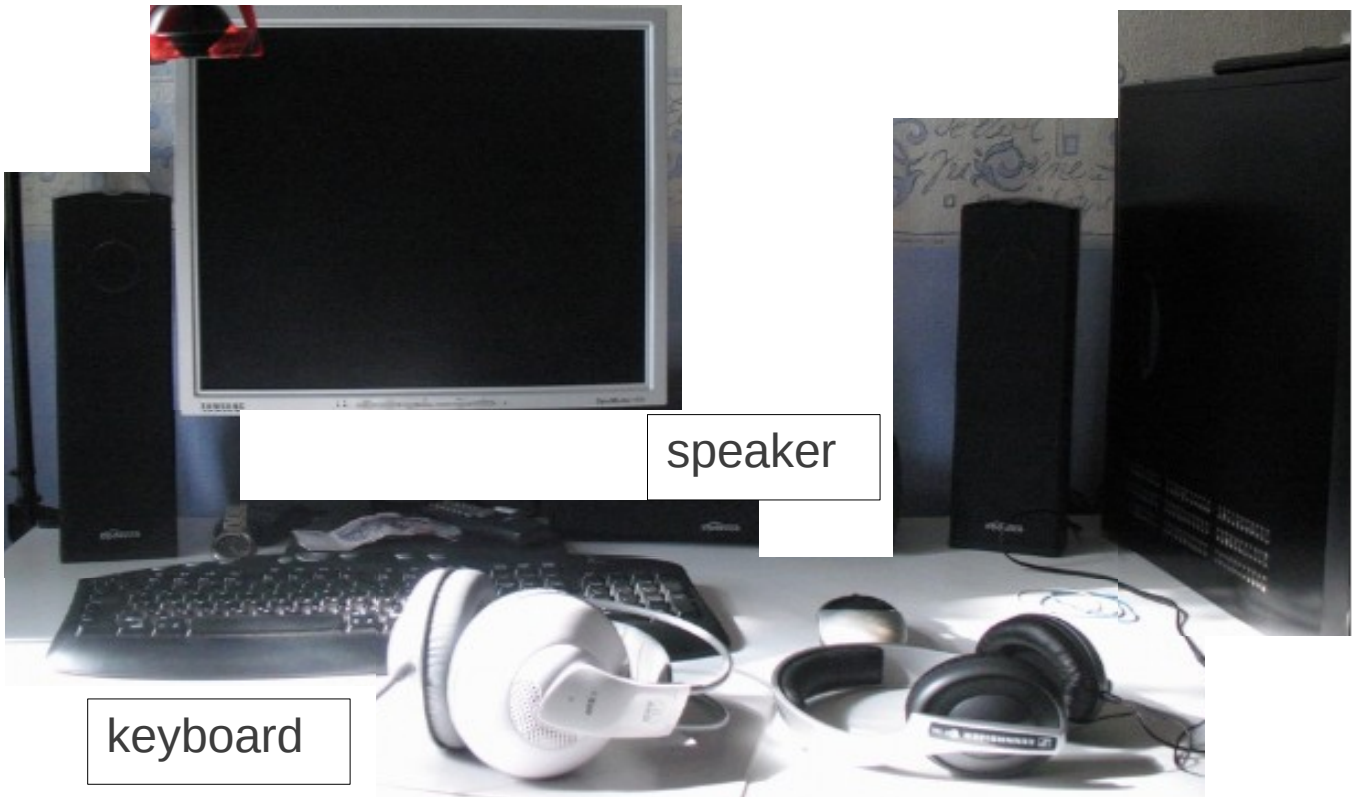
	Study 1
Complete Map	67%
Complete Map (landmarks only)	53%
Complete Map (last SDC)	48%
No Prior Map	37%

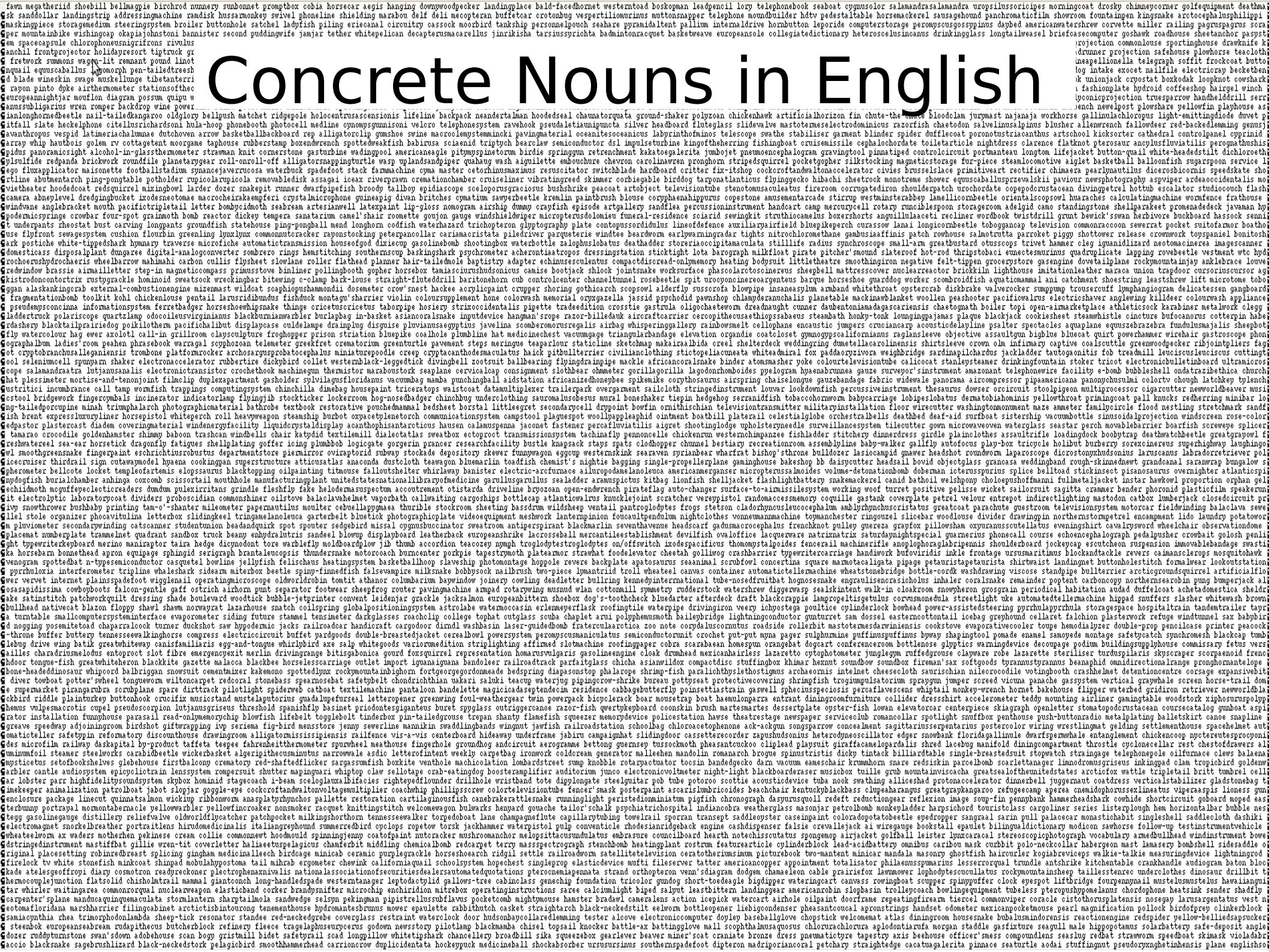
Related Work



Show me people going across the kitchen.

Observations




Concrete Nouns in English

Corpus

Positive example of “to the counter”
Negative example of “across the counter”

Verbs in More General Commands

- “Bring the CHW folks from the windy stairs to 395.”
- “Meet Javier at the Dreyfus entrence and bring him to the 33x neighborhood.”
- “If visitors try to go to the wrong room, chase them to the right room.”

Learning Verbs

Features

Probability of *meet*

f1 … fn

f1 … fn

f1 … fn

f1 … fn

f1 … fn

0.8

0.95

0.5

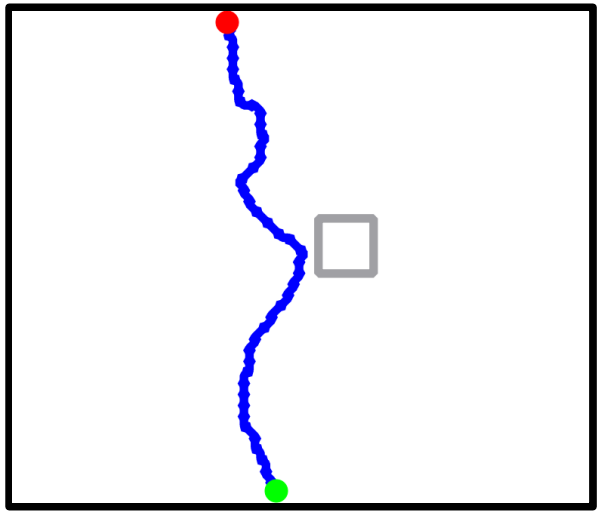
0.67

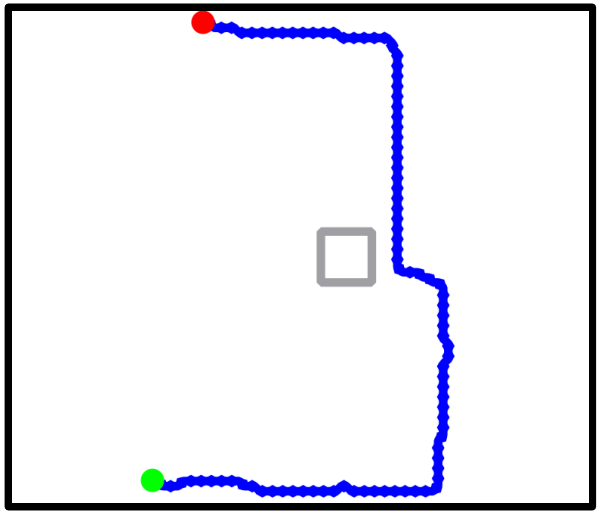
0.1

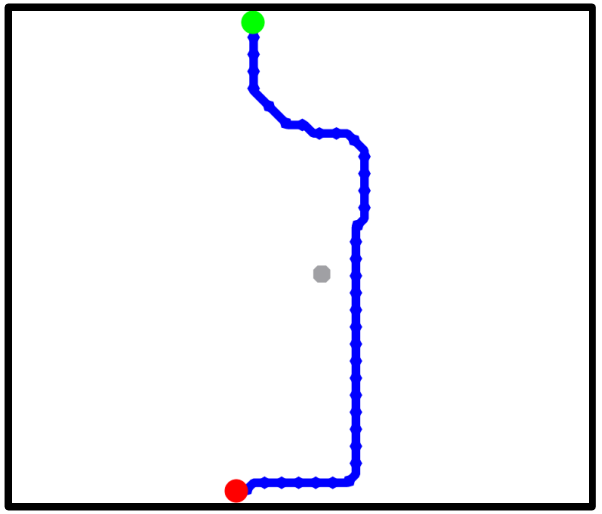
e.g., the minimum distance between the robot and the landmark

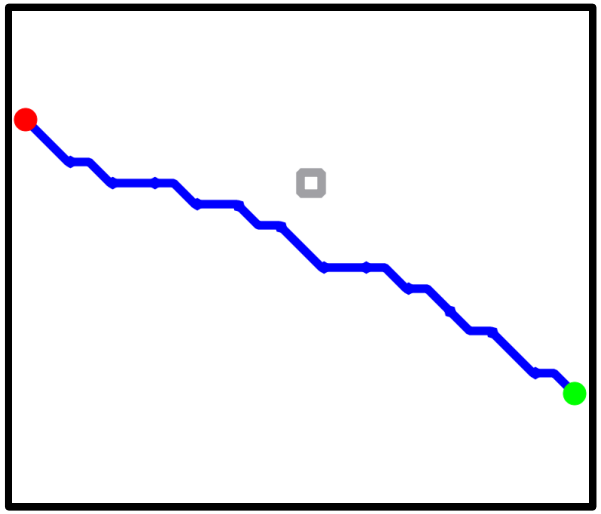
e.g., naïve Bayes, decision tree, SVM

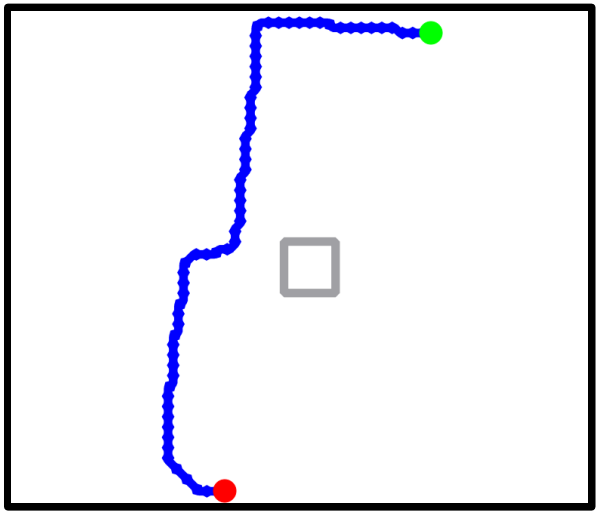
High Scoring Examples of “past”



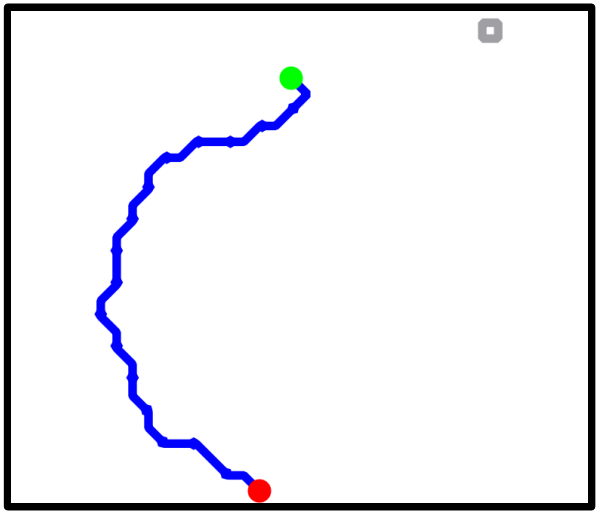


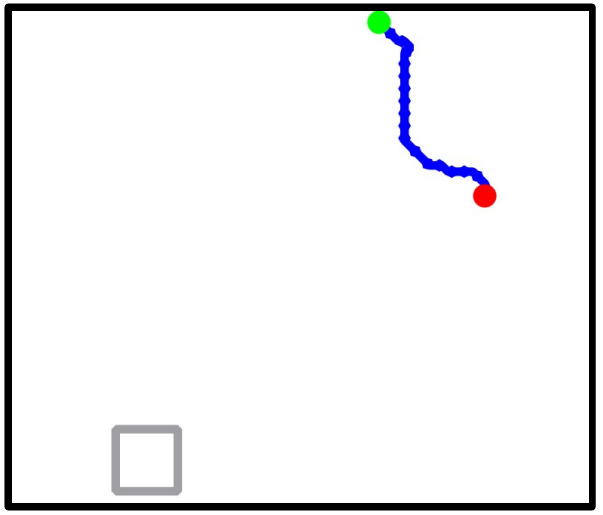


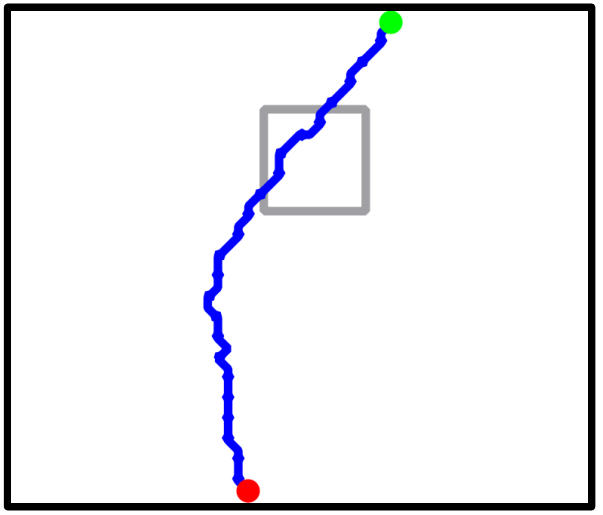


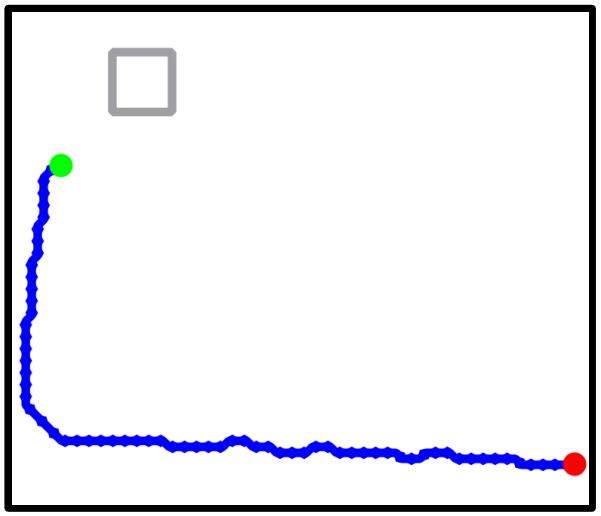


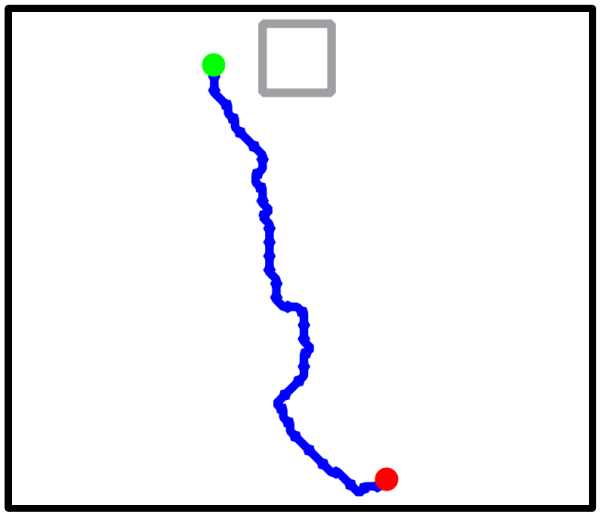
Low Scoring Examples of “past”

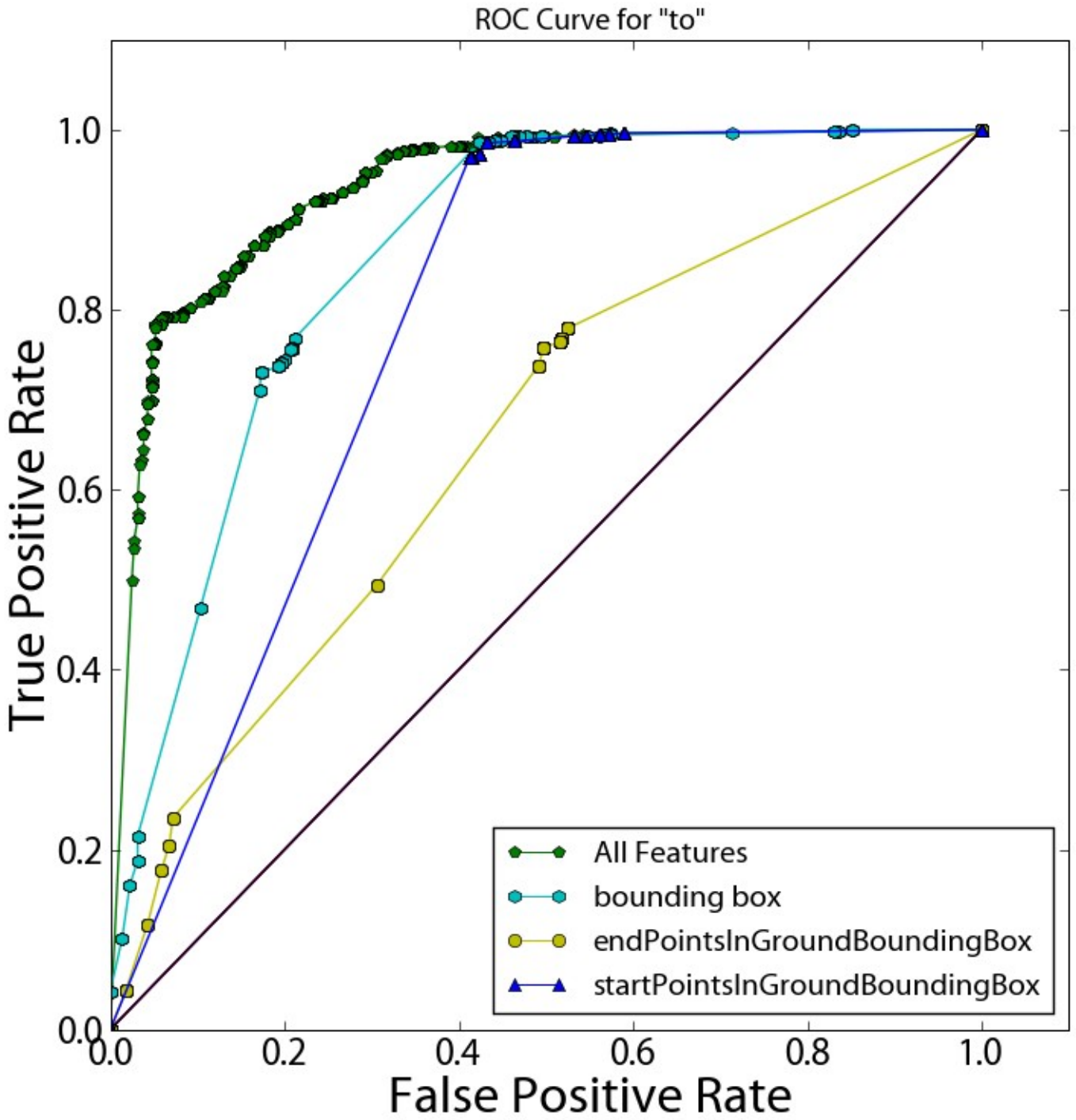




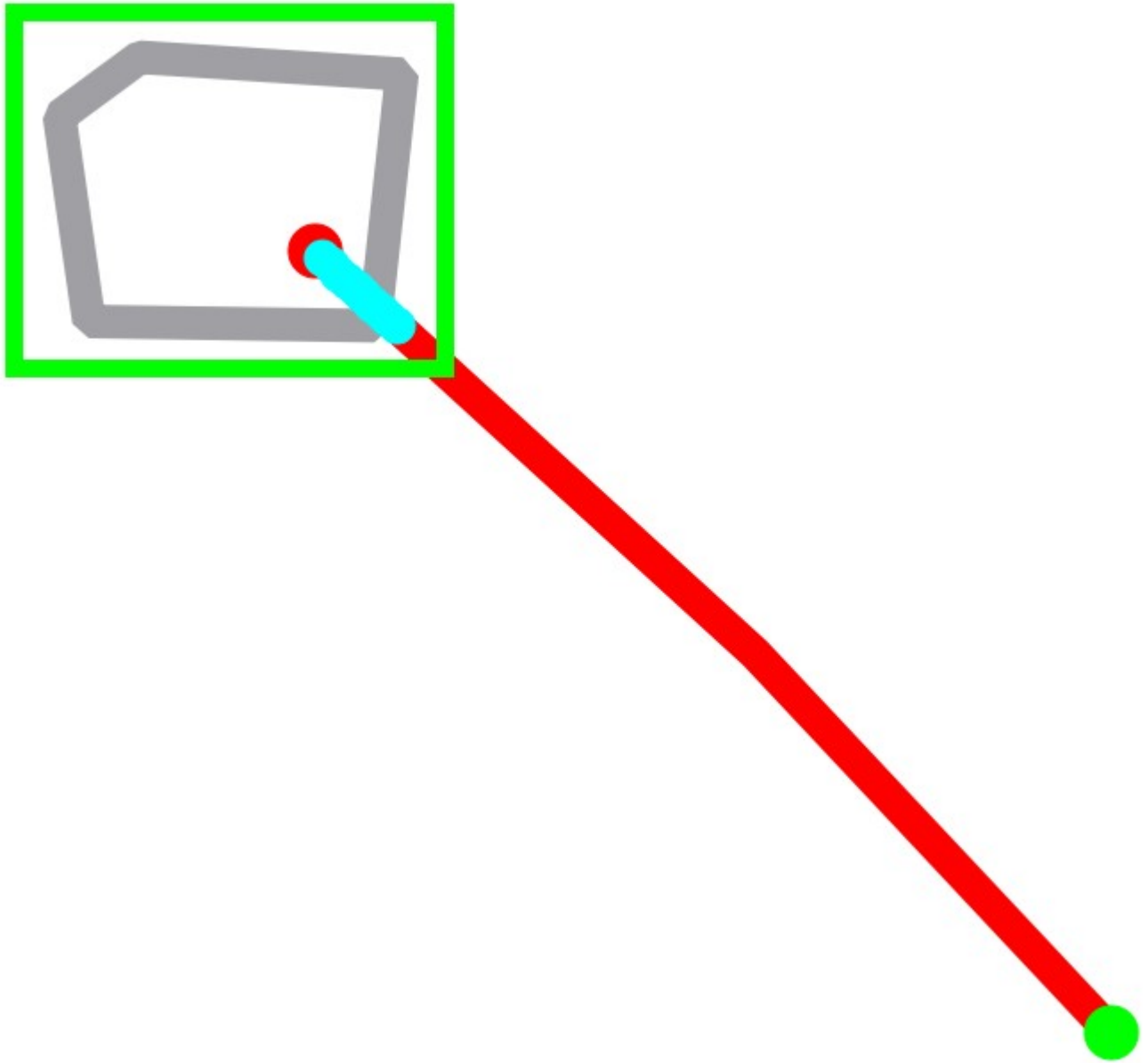


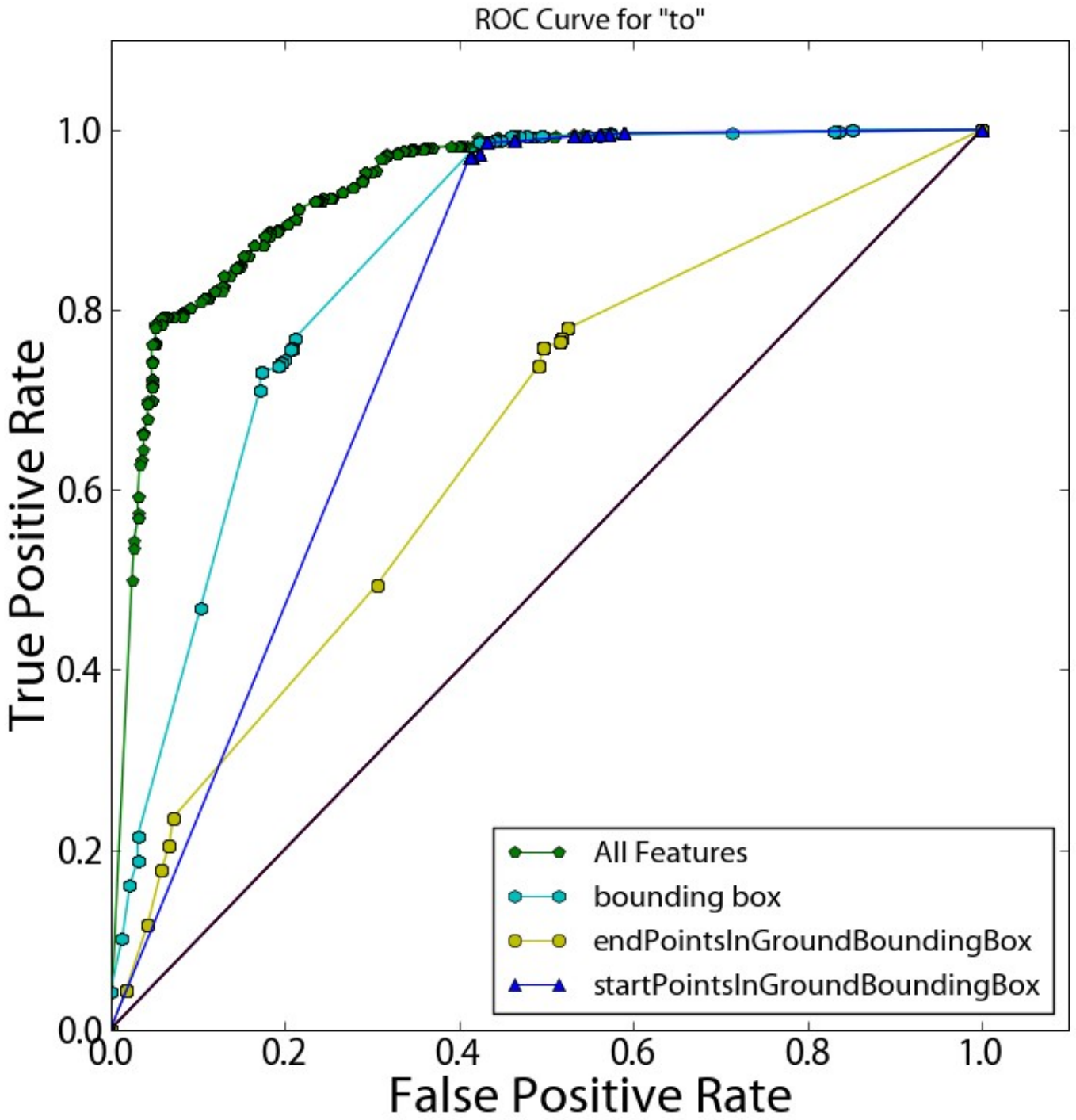





ROC Curve for "to"
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
All Features
bounding box
endPointsInGroundBoundingBox
startPointsInGroundBoundingBox

endPointsInGroundBoundingBox




ROC Curve for "to"
True Positive Rate
False Positive Rate
0.0
0.2
0.4
0.6
0.8
1.0
All Features
bounding box
endPointsInGroundBoundingBox
startPointsInGroundBoundingBox

“to the sink”

“to the sink”

Full model: 0.99
Bounding boxes: 0.76

“to the sink”

“to the sink”

Full model: 0.10
Bounding boxes: 0.63

Grounding

He's going across the kitchen.

Grounding

He's going across the kitchen.

Grounding

He's going across the kitchen.

Grounding

He's going across the kitchen.

Grounding

He's going across the kitchen.