Tutorial on Creating and Accessing Knowledge Graphs for Action Parameterisation

Michael Beetz[1], Philipp Cimiano[2], Michaela Kümpel[1], Enrico Motta[3], Ilaria Tiddi[4] & Jan-Philipp Töberg[2]

[1]Institute for Artificial Intelligence, University of Bremen, Bremen, Germany
[2]Cluster of Excellence Cognitive Interaction Technology (CITEC), Bielefeld University, Bielefeld, Germany
[3]Knowledge Media Institute, The Open University, Milton Keynes, United Kingdom
[4]Vrije Universiteit Amsterdam, The Netherlands

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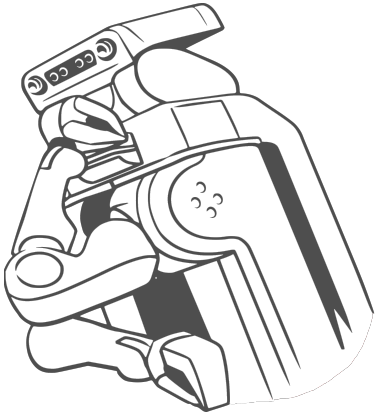
Before we start...

Please download the material from GitHub:

https://github.com/Food-Ninja/Tutorial_WebKGs4PlanParam

Outline



Robots in Open World Situations

Goal

Enable cognitive robots to perform household tasks in varying situations

Robots in Open World Situations

State of the Art

- We see many household robots (lawn mowers, vacuum cleaners)
- Industry (car manufacturers etc.) is relying on robots
- Many people have envisioned meal preparation robots
  $\rightarrow$ but they are yet to be seen in stores

Robots in Open World Situations

Robots perform *well* . . .

- . . . in static environments (car manufacturer)
- . . . given static (or known) objects
- . . . given known tasks

Robots in Open World Situations

Robots perform *well* ...

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- ... given static (or known) objects
- ... given known tasks

Problem

Households are *open worlds* ⇒ unknown environments containing unknown objects and necessitating unknown actions.
Households ...

- ... are never static
- ... have different objects at different locations
- ... are open to unknown tasks

Robots in Open World Situations

Solutions

- Acquiring knowledge via human-robot interaction (learning from demonstration, imitation learning)
- **Dynamically building a knowledge graph / ontology to assist a task planner** - usually used to infer the next step to perform in an action
- Use generative Large Language Models (LLMs) to assist a task planner (e.g. *SayCan* [Ahn+18] or *Code As Policies* [Lia+23])
- Translating language to motion (works well for simple motions)

Robots in Open World Situations

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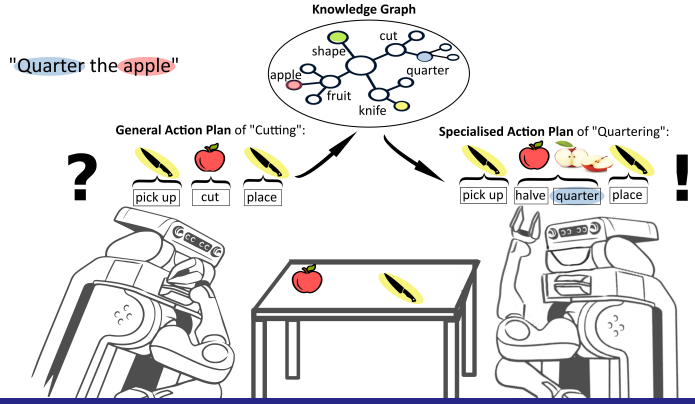
For the domain of cutting fruits and vegetables:

- learning optimal cutting (good when the goal is to have one optimal cut)
- learning number of slices to cut

Robots in Open World Situations

Our idea [Küm+24]

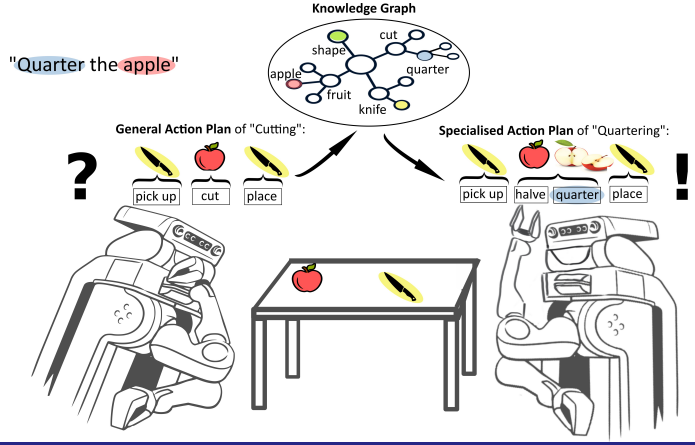
Given a robot that knows how to cut a slice of bread, enable it to quarter an apple, or dice a cucumber



Robots in Open World Situations

What do we need?

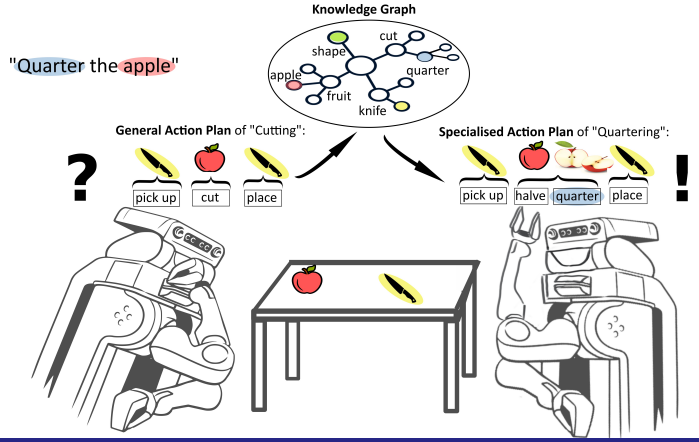
?



Robots in Open World Situations

What do we need?

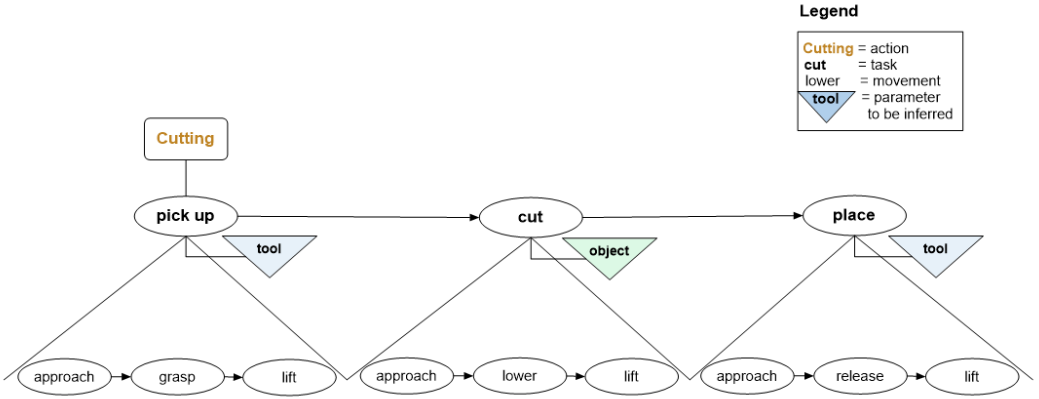
1: motion parameters



Knowledge Engineering Methodology: Step 1

General Action Plans

To enable a robot to perform task variations, we have to look at action plans



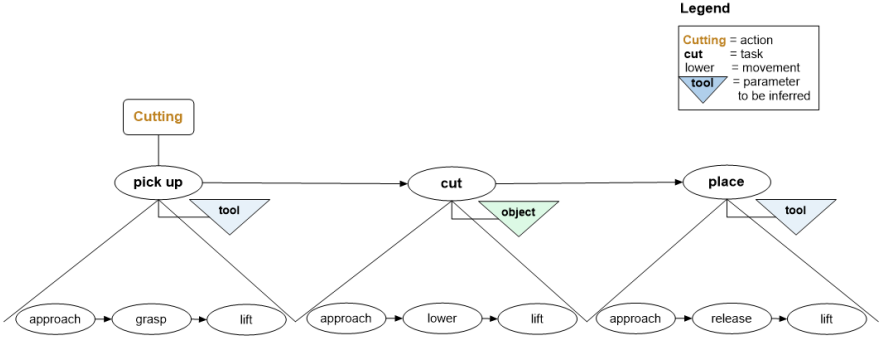
Knowledge Engineering Methodology: Step 1

General Action Plans

With the given plan

- a robot can cut a given object once at a set position

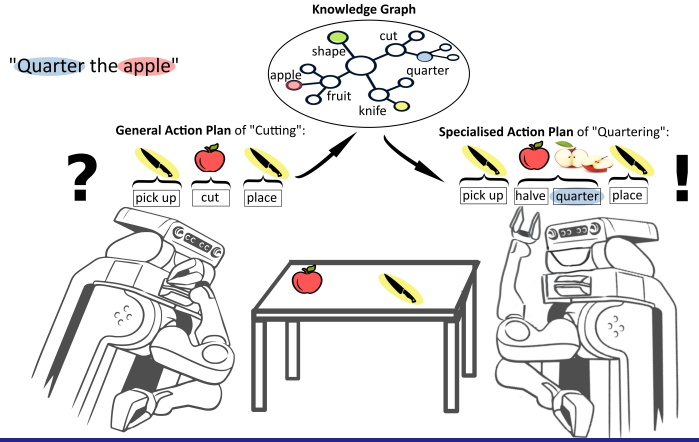
→ How can a robot be enabled to perform different cutting tasks?



Robots in Open World Situations

What do we need?

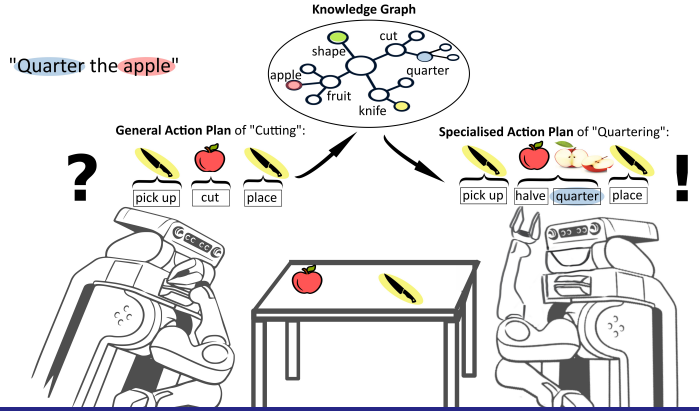
1: motion parameters - but, what actions do we have?



Robots in Open World Situations

What do we need?

1: motion parameters
2: verbs



Knowledge Engineering Methodology: Step 2

Action Knowledge

- Action verbs that are associated with the manipulation action
- Properties of the action verbs necessary for manipulation
- Information for grouping of similar actions into *action groups*

Knowledge Engineering Methodology: Step 2

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- Properties of the action verbs necessary for manipulation
- Information for grouping of similar actions into *action groups*

Possible Sources

- Action Verbs: VerbNet [Sch05], FrameNet [BFL98], WordNet [Mil95]
- In the domain context (meal preparation)
- Differentiating between preparation tasks (peeling, filleting, coring) and cutting tasks (slicing, snipping, cubing)

Extraction of Action Knowledge

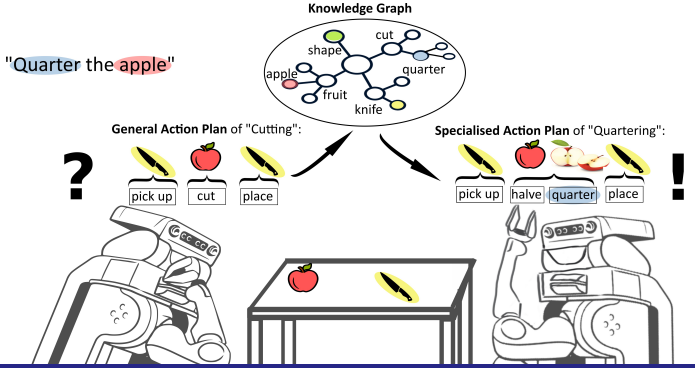
Demonstration 01

Jupyter Notebook on Action Knowledge Extraction:
`Tut-ExeWebKnow/Knowledge Extraction/action_extract.ipynb`
https://framenet.icsi.berkeley.edu/

Robots in Open World Situations

What do we need?

1: motion parameters
2: verbs
3: objects



Knowledge Engineering Methodology: Step 2

Object Knowledge

- Relevant information about involved objects, their usage & their purpose
- Properties for grounding basic manipulation actions (e.g. grasp, hold)
- Task-specific object knowledge

Knowledge Engineering Methodology: Step 2

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Possible Sources

- Food taxonomy: FoodOn food ontology [Doo+18]
- Food classification: plant ontology [Jai+05]
- Food parts: LLMs, biology textbooks (e.g. [CLW18])

Extraction of Action Knowledge

Demonstration 02

Search for fruit properties
https://ontobee.org/

Knowledge Engineering Methodology: Step 2

Task-Specific Knowledge

- Relevant information about involved object parts
- Information about tools
- Information about environment (e.g. object orientation)

Knowledge Engineering Methodology: Step 2

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- Relevant information about involved object parts
- Information about tools
- Information about environment (e.g. object orientation)

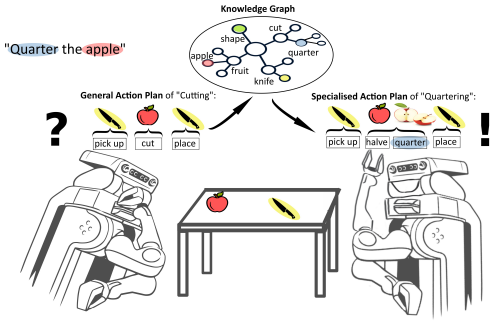
Possible Sources

- Object parts and their involvement in meal preparation: WikiHow, Recipe1M+ [Mar+21]
- Tools for action execution: Product websites

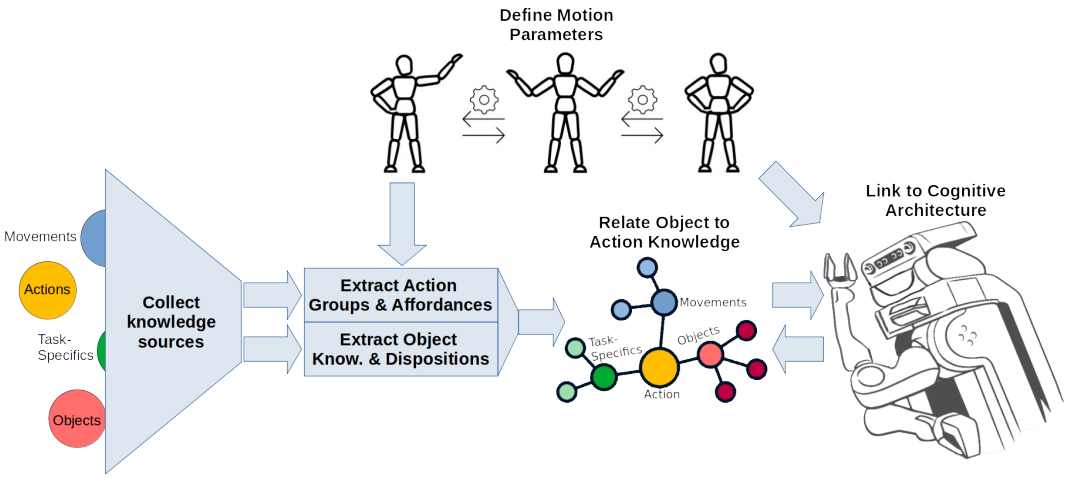
Robots in Open World Situations

What do we need?

1: motion parameters
2: verbs
3: objects
→ how do we make this work?



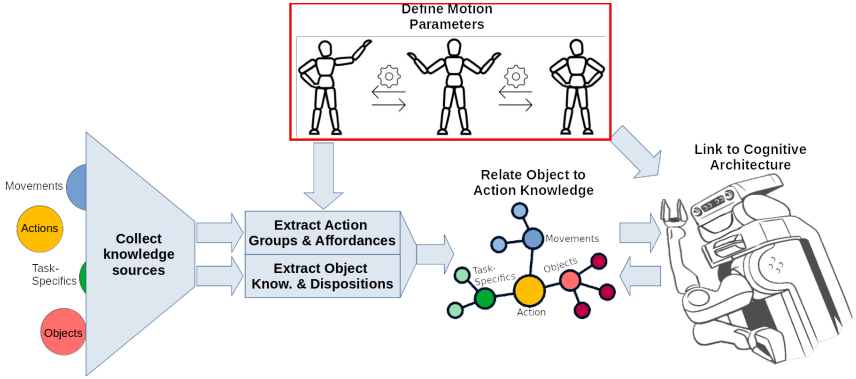
Knowledge Engineering Methodology [Küm+24]



Knowledge Engineering Methodology: Step 1

Motion Parameters

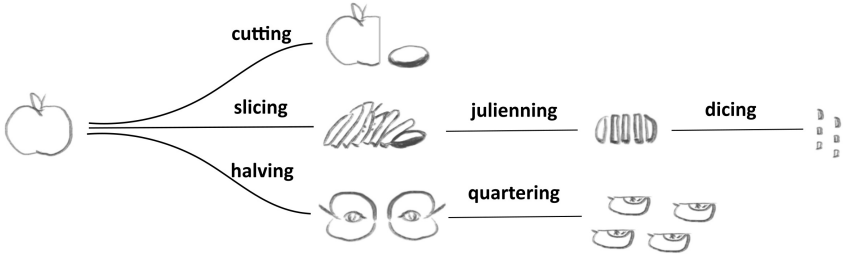
angle, duration, position, number of repetitions



Knowledge Engineering Methodology: Step 1

Generate Action Groups

For a general action, inspect task variations and how they influence body movements

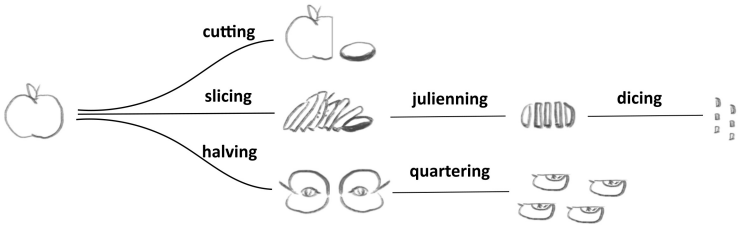


Knowledge Engineering Methodology: Step 1

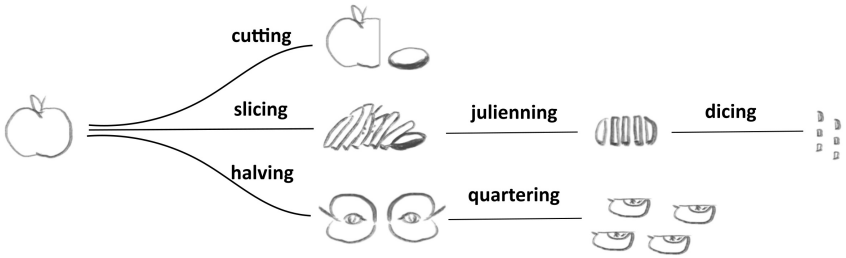
Generate Action Groups

Cutting tasks differ by

- the cutting position (middle or end of an object)
- number of repetitions
- object being cut (important for perception)
- resulting objects (number, shape)



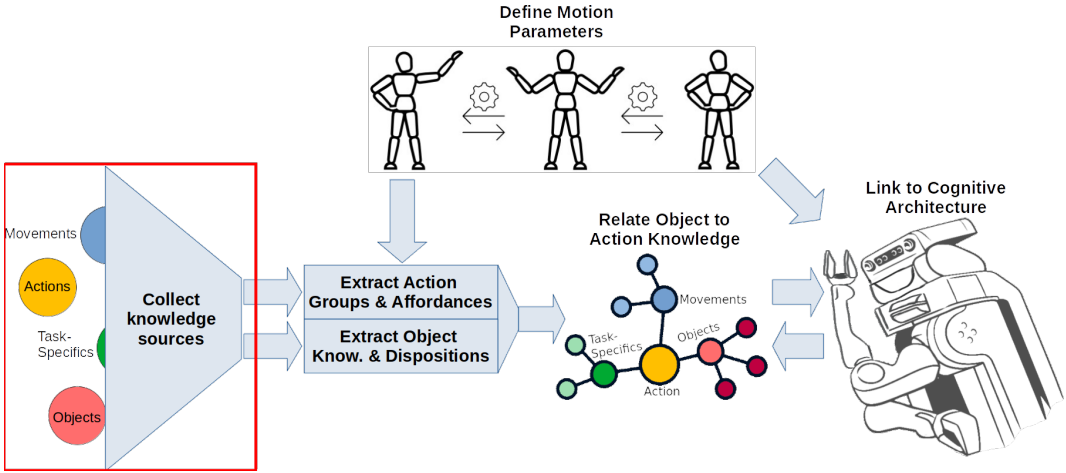
Knowledge Engineering Methodology: Step 1



Action Groups

Hypothesis:
Different action verbs can be classified into these action groups since they achieve similar results.
Example: dicing, cubing, chopping all result in cube-shaped pieces

Knowledge Engineering Methodology: Step 2



Knowledge Engineering Methodology: Step 2

Align everything using top-level ontologies

Reuse a top-level ontology, e.g.

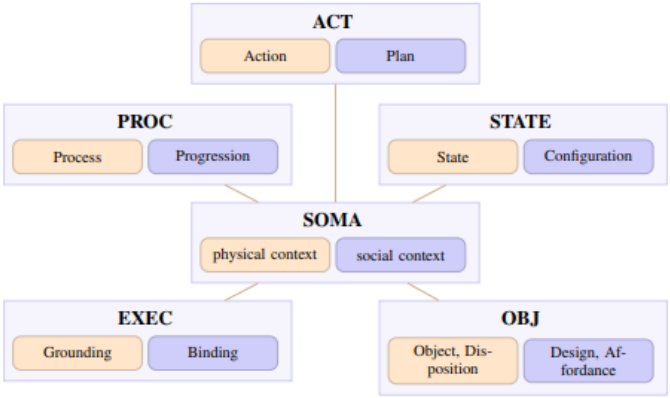
- Schema.org
- basic formal ontology bfo [ASS15]:
  `https://ncorwiki.buffalo.edu/index.php/BFO_Release_History`
- DOLCE+DnS Ultralite (DUL) [PG16]:
  `http://www.ontologydesignpatterns.org/ont/dul/DUL.owl`

→ only DUL relates agents to objects and actions they are involved in

Knowledge Engineering Methodology: Step 2

SOMA (Socio-Physical Model of Activities) [Beß+22]

Reuse an upper level ontology: SOMA, which extends DUL with the focus on household activities

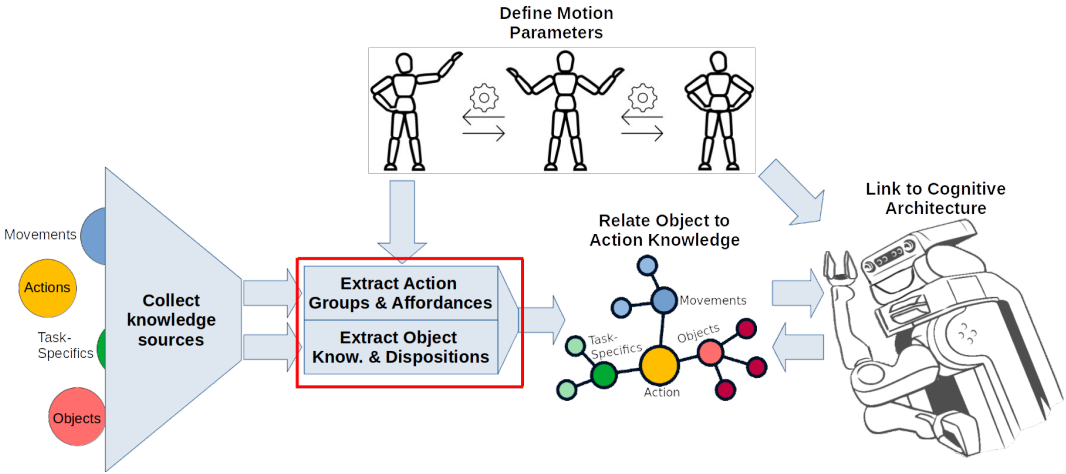


Knowledge Engineering Methodology: Step 2

Demonstration 03

Jupyter Notebook on Ontology Alignment

Knowledge Engineering Methodology: Step 3



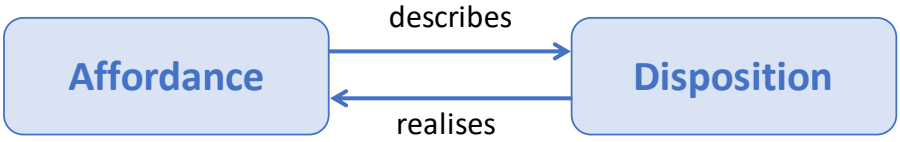
Knowledge Engineering Methodology: Step 3

Affordance [BG80]

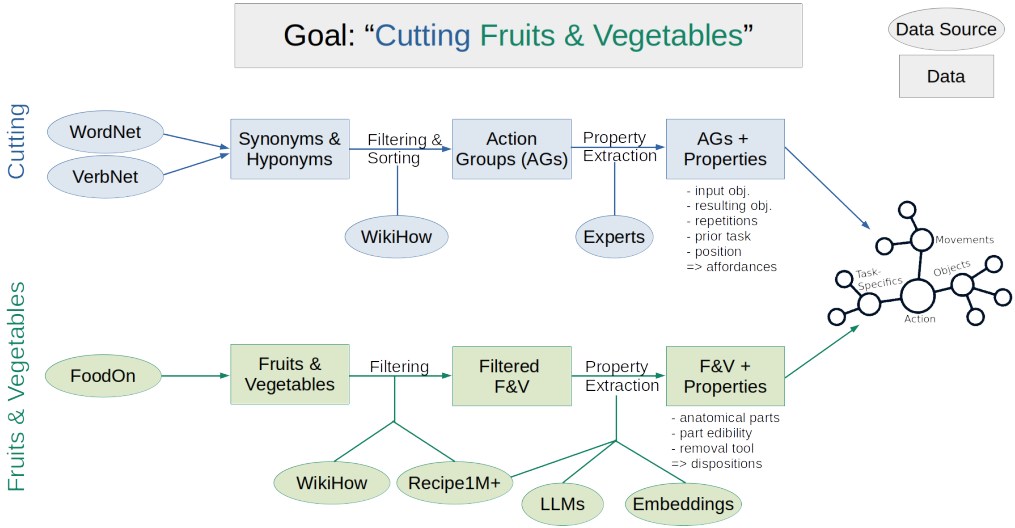
Describes what an object or the environment offers an agent.
Example: *An apple affords to be cut*

Disposition [Tur92]

Describes a property of an object that enables an agent to perform a certain task.
Example: *A knife can be used for cutting*



Extraction of Action and Object Knowledge

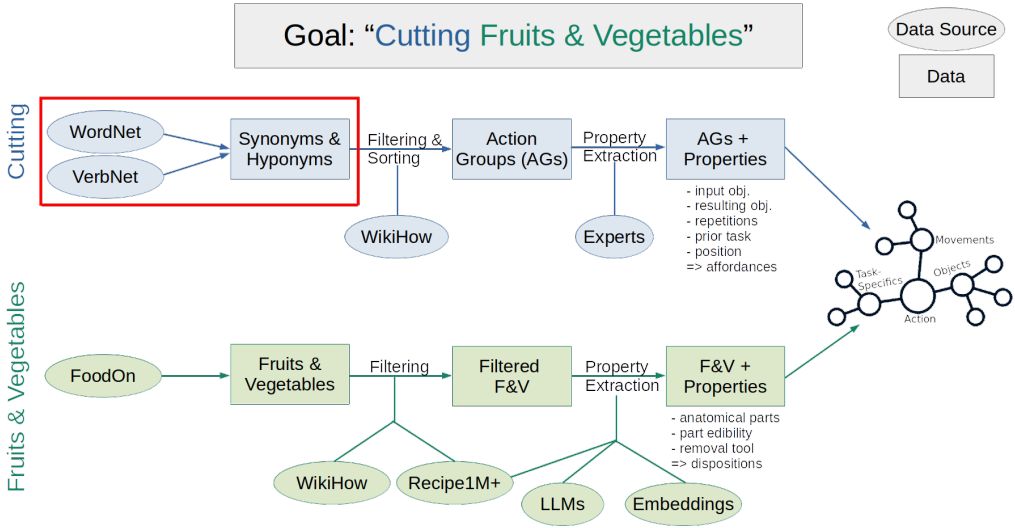


Knowledge Engineering Methodology: Step 3a (Action Groups)

TABLE I: Analysing the occurrences of 15 different hyponyms for *cut* in the WikiHow data from [10].

Verb	Occurrences	Action Group/ Cutting Position	Goal/ Repetitions	Input Object/ Prior Task
cut	23486	cutting/ slicing pos	one slice/ $= 1$ repetitions	food/ no prior task
pare	921			
carve	888			
saw	149			
slice	8200	slicing/ slicing pos	multiple slices/ > 1 repetitions	food or food part/ no prior task
snip	162			
sliver	54			
julienne	189	julienning/ slicing pos	multiple stripes/ > 1 repetitions	food slices / slicing
chop	9221	dicing/ slicing pos	multiple cubes/ > 1 repetitions	food stripe/ julienning
mince	2164			
dice	1631			
cube	516			
halve	346	halving/ halving pos	halves/ $= 1$ repetitions	food/ no prior task
quarter	125	quartering/ halving pos	quarters/ $= 1$ repetitions	food halve/ halving

Extraction of Action Knowledge



Synonyms and Hyponyms - Definition

Synoynms

- Relation between two words
- Different words with the same meaning
- Example: *movie* is a synonym for *film*

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Hyponyms

- Relation between two words
- One word is a more specific / concrete definition of the other
- Example: *apple* is a hyponym to *fruit*

Resources for Synonyms and Hyponyms

WordNet [Mil95]

- Machine-readable lexical database containing (English) nouns, verbs, adjectives & adverbs
- Words are organized into *sets of synonyms* (= Synsets)
- Contains $\sim 166,000$ synsets

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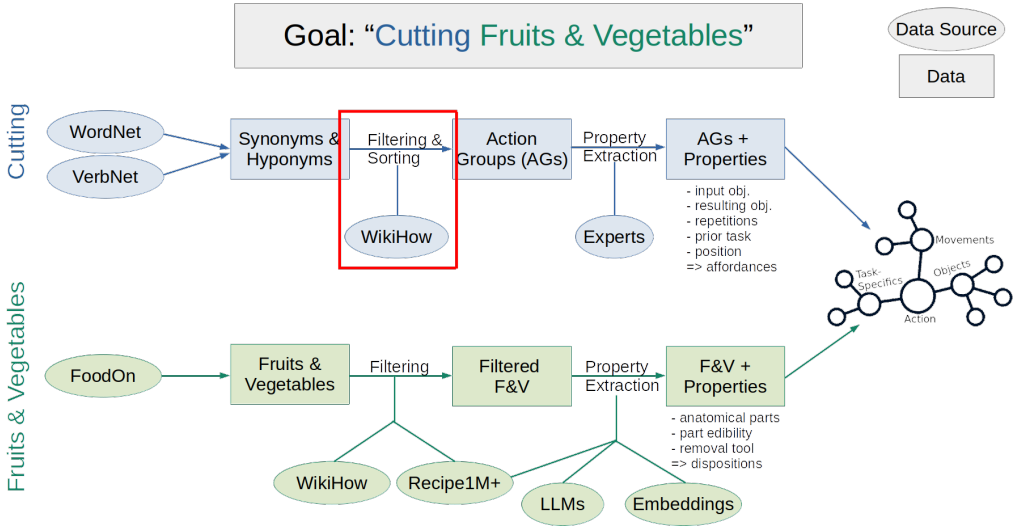
VerbNet [Sch05]

- Hierarchical, domain-independent verb lexicon for the English language
- Verbs are organized in classes that describe their thematic roles (e.g. Agent, Destination or Product), syntactic frames and semantic predicate structures
- Contains $\sim 5,300$ different word senses

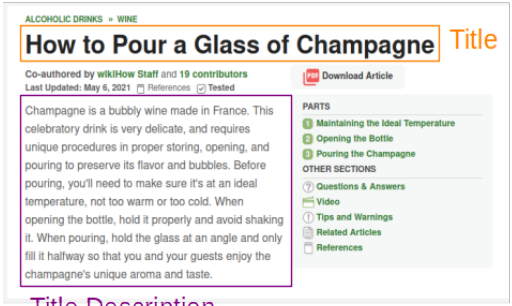
Extraction of Action Knowledge



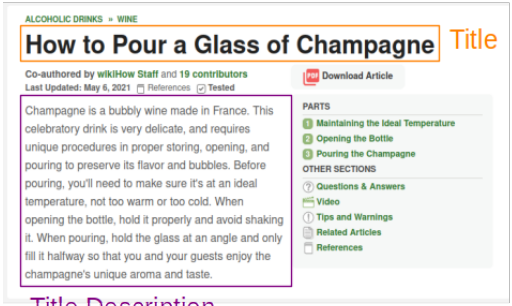
Filtering the Extracted Verbs

1. Pre-Processing to split all synonyms/hyponyms that consist of 2 words (e.g. `snip_off` $\Rightarrow$ include only `snip`)
2. Remove all duplicates
3. Use the *WikiHowAnalysisTool* [Töb22] to count the occurrences of the remaining verbs in different parts of a WikiHow article
4. Remove all words that do not occur more than a certain number of times

WikiHow Article Structure



WikiHow Article Structure



⇒ Focus on step description since it provides the highest amount of information

Extraction of Action Knowledge - Results I

1. Synonyms/Hyponyms from WordNet: 211
   Synonyms/Hyponyms from VerbNet: 147
2. Duplicate removal: 181
3. No. of verbs occurring in at least 1 article: 131
4. No. of verbs with ≥ 100 occurrences: 46

Extraction of Action Knowledge - Results II

46 Remaining verbs:

bite, break, bring, bruise, build, burn, **carve**, check, **chop**, condense, **cube**, curl, **cut**, **dice**, dilute, draw, drop, kill, make, **pare**, peel, play, powder, pull, push, reduce, rinse, roll, **scrape**, set, shape, shave, skip, **slice**, slip, spill, **split**, strain, switch, take, tap, tear, **trim**, turn, write

Extraction of Action Knowledge - Results II

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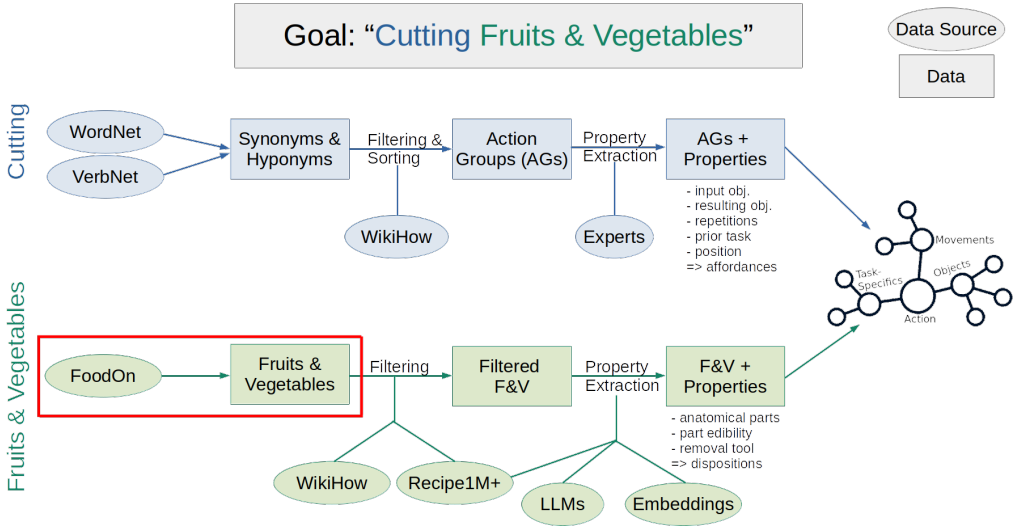
Findings & Challenges:

- Only a fraction of verbs are really relevant for **cutting fruits & vegetables**
- Some verbs are included due to their generality (e.g. `make` or `pull`)
- Some verbs should not be performed by a robot (e.g. `bite` or `kill`)
- Relevant verbs are missing (e.g. `halve` or `quarter`)

Extraction of Object Knowledge



Extraction of Object Knowledge

Demonstration 03

Jupyter Notebook on Object Knowledge Extraction:
`Tut-ExeWebKnow/Knowledge Extraction/object_extract.ipynb`

FoodOn [Doo+18] I

- Global Farm-to-Fork Ontology describing foods commonly known in cultures from around the world
- Vocabulary is based on a food indexing thesaurus (*LanguaL*)
- Covers different food-related aspects like:
  - food product terminology gaps
  - **animal and plant food sources**
  - food categories and products
  - preservation processes
  - food traceability
  - contact surfaces & packaging
  - regional variants of food products & terms (e.g. *biscuit*)

Querying FoodOn for Fruits

```
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX foodon: <http://purl.obolibrary.org/obo/>
SELECT ?fruit_label (SAMPLE(?fruit_id) AS ?rndm_fruit_id) (SAMPLE(?def) AS ?rndm_def)
WHERE {
        ?fruit_id rdfs:label ?label.
        ?fruit_id rdfs:subClassOf+ food:PO_0009001.
        OPTIONAL { ?fruit_id food:IAO_0000115 ?def. }

        BIND (LCASE(STR(?label)) AS ?str_label).
        BIND (STRBEFORE(?str_label, "(") AS ?fruit_label).
        FILTER CONTAINS(?str_label, "whole").
        FILTER NOT EXISTS { ?fruit_id rdfs:subClassOf* food:PO_0030104. }
        FILTER (?fruit_id != food:FOODON_03304644).
}
GROUP BY ?fruit_label
ORDER BY ?fruit_label
```

fruit

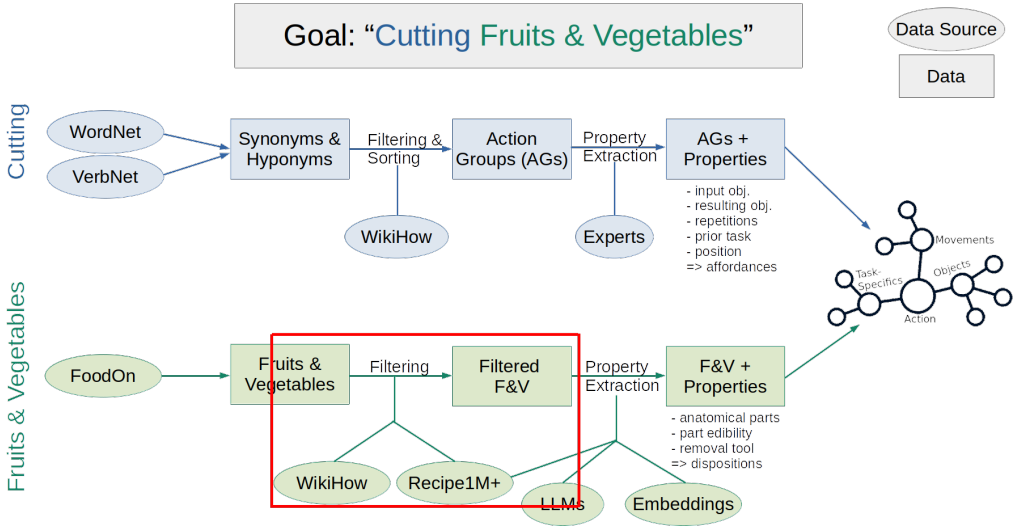
textual definition

caryopsis fruit

fruit (whole, raw)

Result: 257 different fruits

Extraction of Object Knowledge



Filtering Fruits and Vegetables - Motivation

- Not all 288 fruits & vegetables are equally important for Everyday cutting tasks
- Is there enough knowledge available to reason about a fruits property?
- Example: *Mangosteen* occurs in 6 out of $\geq$ 1.000.000 recipes - relevant?

Filtering Fruits and Vegetables - Method

- Search for fruits & vegetables using the WikiHow Analysis Tool [Töb22] and the a tool for analyzing the Recipe1M+ corpus [Mar+21; Töb23]
- Search in all parts of the recipe & all parts of a WikiHow article
- Only include fruits/vegetables occurring in $\geq 1\%$ of any part

Filtering Fruits and Vegetables - Results

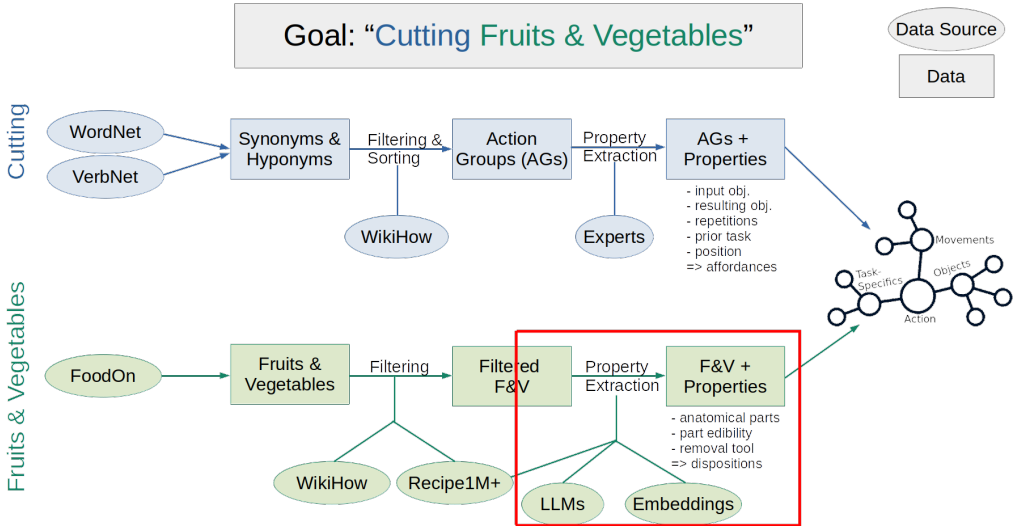
Fruits: 257 → 15

almond, apple, banana, cherry, coconut, lemon, lime, olive, orange, pepper, pineapple, pumpkin, squash, strawberry, tomato

Vegetables: 31 → 1

bean

Extraction of Object Knowledge



Extraction of Object Properties

Relevant Properties for *Cutting*

- **Anatomical parts**
  What parts that could potentially be removed exists? (e.g. peel, core, stem, shell)
- **Part edibility**
  Can an anatomical part be eaten, is it unpalatable or even poisonous?
- **Removal tool**
  What tool should be used to remove an unpalatable / poisonous anatomical part? (e.g. knife, peeler)

Using the Word Embeddings for Extracting Anatomical Parts

1. Take one of the three word embeddings (GloVe, NASARI or ConceptNet Numberbatch)
2. Iterate over all fruits and anatomical parts & calculate their embedding
3. Calculate the cosine similarity between the vectors
4. Compare the cosine similarity to a threshold

Word Embeddings for Extracting Anatomical Parts - Results

Method	Acc.	Prec.	Rec.	Spec.	F1	Threshold
CN Numberbatch	.788	.609	.636	.845	**.622**	Cossim $\geq$ 0.20
CN Numberbatch	**.825**	**1.00**	.364	**1.00**	.533	Cossim $\geq$ 0.30
GloVe	.550	.348	**.727**	.483	.471	Cossim $\geq$ 0.25
GloVe	.688	.435	.455	.776	.444	Cossim $\geq$ 0.40
NASARI	.750	.571	.364	.897	.444	Cossim $\geq$ 0.75
GloVe	.738	.533	.364	.879	.432	Cossim $\geq$ 0.50
NASARI	.500	.295	.591	.466	.394	Cossim $\geq$ 0.50

Using the Recipe Corpus for Extracting Anatomical Parts

Method 1 - Bigrams:

1. Provide a list of possible anatomical parts with their synonyms
2. Look for the co-occurrence of these terms with the fruit / vegetable by searching for their bigrams (*[fruit] [part]*)
   Example: Use a melon baller to dig out the **apple core**.
3. Compare the amount of co-occurrences to a threshold

Using the Recipe Corpus for Extracting Anatomical Parts

Method 1 - Bigrams:

1. Provide a list of possible anatomical parts with their synonyms
2. Look for the co-occurrence of these terms with the fruit / vegetable by searching for their bigrams (*[fruit] [part]*)
   Example: Use a melon baller to dig out the **apple core**.
3. Compare the amount of co-occurrences to a threshold

Method 2 - 2-Step Filter:

1. Provide a list of possible anatomical parts with their synonyms
2. Look for the co-occurrence of these terms with the fruit / vegetable by first searching for the fruit and then searching for the part in the results
   Example: Remove a 1 inch strip of **peel** around the middle of each **apple**.
3. Compare the amount of co-occurrences to a threshold

Recipe Corpus for Extracting Anatomical Parts - Results

Method	Acc.	Prec.	Rec.	Spec.	F1	Threshold
2-Step Filter	**.863**	**.824**	.636	**.948**	**.718**	Occ. in $\geq 1\%$ of steps
Bigrams	.688	.463	**.864**	.621	.603	Occ. in any step
2-Step Filter	.738	.517	.682	.759	.588	Occ. in $\geq 0.5\%$ of steps
Bigrams	.788	.667	.455	.914	.541	Occ. in $\geq 0.1\%$ of steps

Prompting ChatGPT & GPT-4 for Anatomical Parts

System Message: Can you please answer the following question only with the existing parts and without any additional text.
User Message: Which of the following four food parts do you think are part of a `[fruit]`:
A core, a shell, a peel and a stem.

Comparing Different Methods for Extracting Anatomical Food Parts

Method	Acc.	Prec.	Rec.	Spec.	F1	Threshold
Recipe1M+ 2-Step	**.863**	.824	.636	.948	**.718**	Occ. in $\geq$ 1% of steps
ChatGPT	.775	.556	**.909**	.724	.690	-
GPT-4	.700	.476	**.909**	.621	.625	-
CN Numberbatch	.788	.609	.636	.845	.622	Cossim $\geq$ 0.20
Recipe1M+ Bigrams	.688	.463	.864	.621	.603	Occ. in any step
Recipe1M+ 2-Step	.738	.517	.682	.759	.588	Occ. in $\geq$ 0.5% of steps
Recipe1M+ Bigrams	.788	.667	.455	.914	.541	Occ. in $\geq$ 0.1% of steps
CN Numberbatch	.825	**1.00**	.364	**1.00**	.533	Cossim $\geq$ 0.30
GloVe	.550	.348	.727	.483	.471	Cossim $\geq$ 0.25
GloVe	.688	.435	.455	.776	.444	Cossim $\geq$ 0.40
NASARI	.750	.571	.364	.897	.444	Cossim $\geq$ 0.75
GloVe	.738	.533	.364	.879	.432	Cossim $\geq$ 0.50
NASARI	.500	.295	.591	.466	.394	Cossim $\geq$ 0.50

Food Part Edibility Using LLMs

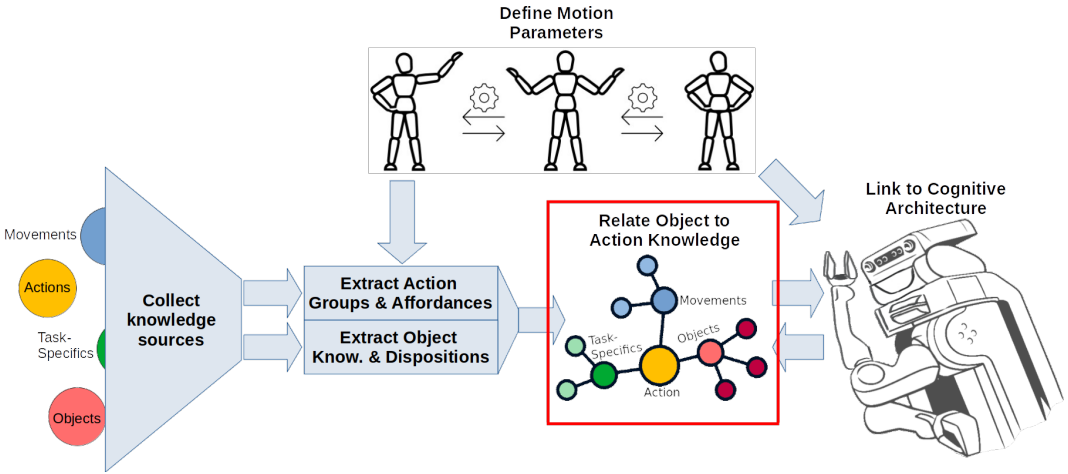
System Message: Can you please answer the following question only with the chosen edibility and without any additional text.
User Message: What is the edibility for the `[part]` of a/an `[fruit]`?
You can choose between three possibilities: Edible, Must Be Avoided or Should Be Avoided

Food Part Edibility Using LLMs

System Message: Can you please answer the following question only with the chosen edibility and without any additional text.
User Message: What is the edibility for the `[part]` of a/an `[fruit]`?
You can choose between three possibilities: Edible, Must Be Avoided or Should Be Avoided

Method	Prec.	Rec.	F1
GPT-4	**.613**	**.542**	**.410**
ChatGPT	.195	.444	.253

Knowledge Engineering Methodology: Step 4



Knowledge Engineering Methodology: Step 4

Connect affordances to dispositions in the TBox using `affordsTask`, `affordsTrigger` and `hasDisposition` relations introduced in the SOMA ontology:
Disosition: Cuttability of an apple

hasDisposition some
(*Cuttability*
and (*affordsTask some CuttingAction*)
and (*affordsTrigger only* (*classifies only Knife*)))

Knowledge Engineering Methodology: Step 4

Connect affordances to dispositions in the TBox using `affordsTask`, `affordsTrigger` and `hasDisposition` relations introduced in the SOMA ontology:
Disosition: Peelability of a banana

hasDisposition some
(*Peelability*
and (*affordsTask some Peeling*)
and (*affordsTrigger only* (*classifies only Hand*)))

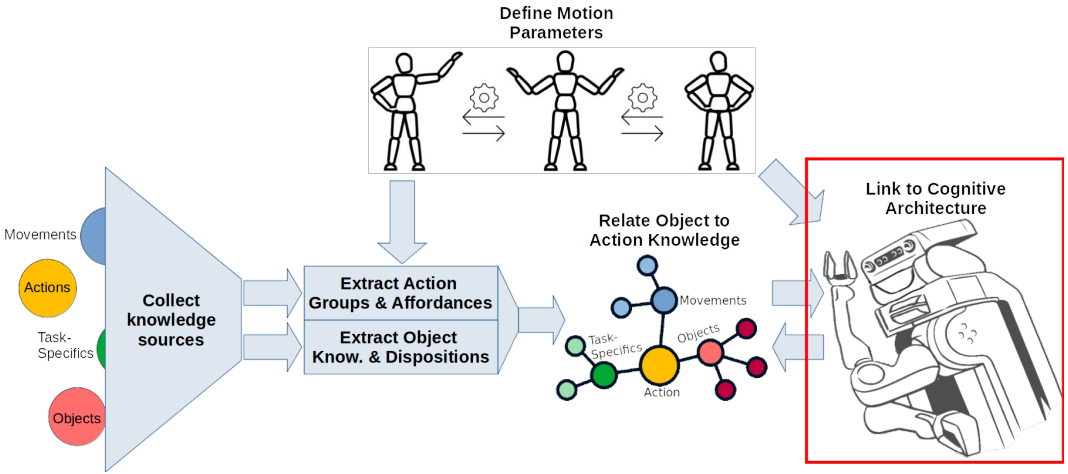
Knowledge Engineering Methodology: Step 4

Affordance and Disposition

- Link a food object to a disposition
- Dispositions can afford different tasks and tools

hasDisposition some
(*Peelability*
and (*affordsTask some Peeling*)
and (*affordsTrigger only* (*classifies only Hand*)))

Knowledge Engineering Methodology: Step 5



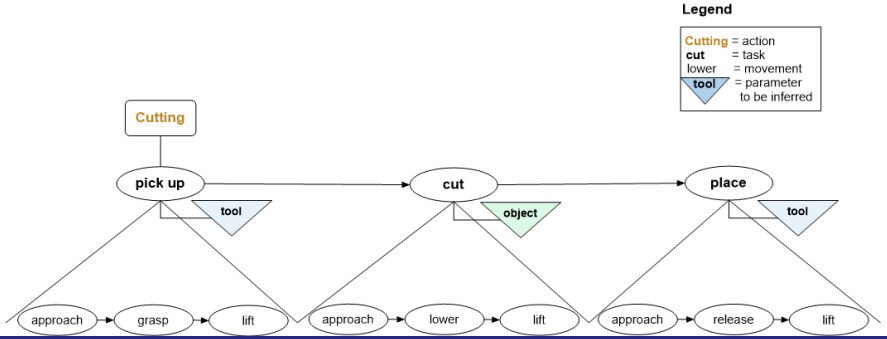
Knowledge Engineering Methodology: Step 5

Inspect Action Plan

With the given plan

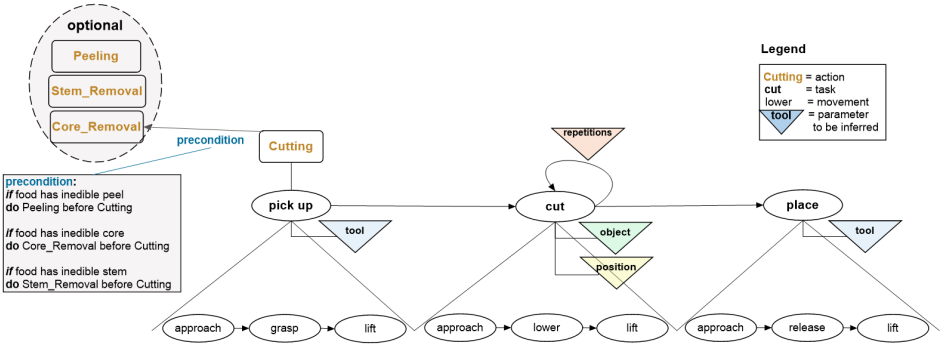
- a robot can cut a given object once at a set position

→ Use action groups and analyzed action parameters to modify action plan



Knowledge Engineering Methodology: Step 5

Adapted action plan:



Knowledge Engineering Methodology: Step 5

- Map concepts in the generalised plan to their representation in the ontology
- Ground objects & their properties in the perception system
- Cognitive architecture needs to be able to query the ontology to gather specific parameterisations at runtime

Knowledge Engineering Methodology: Step 5

A look at action designator refinement

Refining an object type through known parameters/variables (here :knife)

```
(an object
   (type :knife))
```

Knowledge Engineering Methodology: Step 5

A look at action designator refinement

Refining an action type through known parameters/ variables (here :cutting)

```
(an action
   (type :cutting))
```

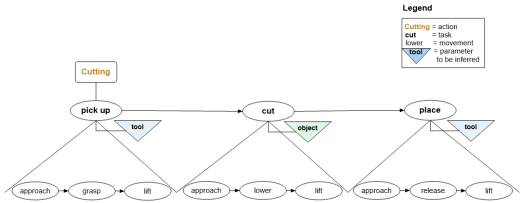
Knowledge Engineering Methodology: Step 5

A look at action designator refinement
Refining an action type through queryable parameters/ variables (here ?navigation-goal, set in code)

```
(let ((?navigation-goal (make-pose "map" '(0.0 1.0 0.0) '(0.0 0.0 (* pi 0.0)))))
 (perform (an action
    (type :going)
    (target (a location
      (pose ?navigation-goal)))))))
```

Knowledge Engineering Methodology: Step 5

Initial cutting action designator




```
(perform
  (an action
      (type :cutting)
      (?object_acted_on (an object (type :food) (pose ...) ...))
      (?object (an object (type :tool) (pose ...) ...))
      (?arm (a body_part (type :arm) (pose ...) ...))
      (?arm (a body_part (type :arm) (pose ...) ...))
      (?goal (:success (:cutting (on :food))))))
```

Knowledge Engineering Methodology: Step 5

```
(perform
  (an action
      (type :cutting)
      (?object_acted_on (an object (type :food) (pose ...) ...))
      (?object (an object (type :tool) (pose ...) ...))
      (?arm (a body_part (type :arm) (pose ...) ...))
      (?arm (a body_part (type :arm) (pose ...) ...))
      (?goal (:success (:cutting (on :food))))))
```

- for all queryable variables (e.g. **?object_acted_on**)
- first try to resolve internally (if used before)
- then query knowledge base for info
- try to resolve through sensors
- assign

Knowledge Engineering Methodology: Step 5

Adapted cutting action designator

```
(perform
  (an action
      (type :cutting (?repetitions (:boolean)))
      (?prior_action (an action (type :preparing)))
      (?depends_on_task (an action (type :cutting)))
      (?object_acted_on (an object (type :food) (pose ...) ...))
      (?object (an object (type :tool) (pose ...) ...))
      (?arm (a body_part (type :arm) (pose ...) ...))
      (?arm (a body_part (type :arm) (?position (on :food)) ...))
      (?goal (:success (:cutting (on :food))))))
```

Knowledge Engineering Methodology: Step 5

```
(perform
  (an action
      (type :cutting (?repetitions (:boolean)))
      (?prior_action (an action (type :preparing)))
      (?depends_on_task (an action (type :cutting)))
      (?object_acted_on (an object (type :food) (pose ...) ...))
      (?object (an object (type :tool) (pose ...) ...))
      (?arm (a body_part (type :arm) (pose ...) ...))
      (?arm (a body_part (type :arm) (?position (on :food)) ...))
      (?goal (:success (:cutting (on :food))))))
```

Things to query from the knowledge base

- **?repetitions**
- **?prior_action**
- **?depends_on_task**
- **?position**, i.e. cutting position

Knowledge Engineering Methodology: Step 5

Prior to action execution, the robot will pose these queries:

- What tool shall be used? (unless already known)
- **?prior_action**: Are prior actions (e.g. peeling) required?
- **?depends_on_task**: Does the task depend on tasks that need to executed (e.g. halving before quartering)?
- **?repetitions**: How many repetitions of this task need to be performed?

Knowledge Engineering Methodology: Step 5

Before cutting motion execution, the robot will pose these queries:

- **?position**: What is the needed cutting position (center or end)?
- **?object**: What is the input object to cut (whole food or food part)?
- What is the result object? This is needed to determine successful action execution

Knowledge Engineering Methodology: Step 5

Let us now look at the queries in the last jupyter notebook

Thank you for your attention!

Questions?

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