Multiagent Systems: Spring 2006

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Preference Representation in Combinatorial Domains

The collective choices made in a MAS will be driven by the interests of individual agents. Agents must be able to *communicate preferences* (directly through full revelation, or indirectly via "moves" in a game).

- So far, we have treated this topic only very *abstractly*, by saying that agents "have" a utility function or "report" a valuation.
- In *combinatorial domains*, preference representation is not trivial:
  - for instance, negotiation over n goods requires expressing preferences over 2^n bundles
  - *also:* multi-criteria decision making; voting for assemblies; ...

  So far, we have ignored this *computational problem* in the course (as is common practice in the economics literature).
- In this lecture, we are going to review and compare different *preference representation languages*.

Plan for Today

- General *requirements* on preference representation languages
- Distinguish *cardinal* and *ordinal* preference structures
- Different *classes* of utility functions (cardinal preferences): monotonic, dichotomous, modular, concave utilities ...
- Review of languages for representing utility functions: *explicit form*, *k-additive form*, *weighted goals*, ...
- Discussion of properties of different representation languages: *expressive power* and *comparative succinctness*
- Review of languages for ordinal preference representation: *prioritised goals* and *ceteris paribus preferences*

Preference Representation Languages

The following questions should be addressed when you investigate a preference representation language:

- *Cognitive relevance:* How close is a given language to the way in which humans would express their preferences?
- *Elicitation:* How difficult is it to elicit the preferences of an agent so as to represent them in the chosen language?
- *Expressive power:* Can the chosen language encode all the preference structures we are interested in?
- *Succinctness:* Is the representation of (typical) preference structures succinct? Is one language more succinct than the other?
- *Complexity:* What is the computational complexity of related decision problems, such as comparing two alternatives?

We are going to concentrate on expressive power and succinctness.

Cardinal and Ordinal Preferences

A *preference structure* represents an agent's preferences over a set of alternatives $\mathcal{X}$. There are different types of preference structures:

- A *cardinal* preference structure is a (*utility* or *valuation*) function $u : \mathcal{X} \to \mathit{Val}$, where Val is usually a set of numerical values such as $\mathbb{N}$ or $\mathbb{R}$.
- An *ordinal* preference structure is a *binary relation* $\preceq$ over the set of alternatives, that is reflexive and transitive (and connected).

Note that we shall assume that $\mathcal{X}$ is finite.

Some Observations

- *Intrapersonal comparison:* ordinal and cardinal preferences allow for comparing the satisfaction of an agent for different alternatives
- *Interpersonal comparison:* ordinal preferences don't allow for interpersonal comparison ("Ann likes x more than Bob likes y")
- *Preference intensity:* ordinal preferences cannot express preference intensity; cardinal preferences can (subject to Val being numerical)
- *Representability:* a connected ordinal preference relation $\preceq$ is representable by a utility function u: $x \preceq y$ iff $u(x) \leq u(y)$
- *Cognitive relevance:* hard to make general statements, but at least ordinal preferences don't require reasoning with numerical utilities
- *Explicit representation:* the explicit representation of cardinal and ordinal preferences have space complexity $O(|\mathcal{X}|)$ and $O(|\mathcal{X}|^2)$, respectively (why?)

Preferences in Resource Allocation Scenarios

Let $\mathcal{R}$ be a finite set of indivisible *resources* (goods) with $|\mathcal{R}| = n$.

Assume there are *no externalities:* agent preferences only depend on their assigned bundle (not on the allocation as a whole or on any other outside factors) $\leadsto$ need to model preference structures over $\mathcal{X} = 2^{\mathcal{R}}$

Hence, the explicit representation has *exponential* space complexity.

Possible ways out:

- only consider *restricted classes* of preference structures, which may allow for a more concise representation; and/or
- consider (and compare) *different representation languages*.

We start with the case of utility functions ...

Classes of Utility Functions

Now a utility function is a mapping $u : 2^{\mathcal{R}} \to \mathbb{R}$.

- u is *normalised* iff $u(\{\,\}) = 0$
- u is *non-negative* iff $u(X) \geq 0$
- u is *monotonic* iff $u(X) \leq u(Y)$ whenever $X \subseteq Y$
- u is *dichotomous* iff $u(X) = 0$ or $u(X) = 1$
- u is *modular* iff $u(X \cup Y) = u(X) + u(Y) - u(X \cap Y)$
- u is *additive* iff $u(X) = \sum_{x \in X} u(\{x\})$

Important: for the above definitions, the respective (in)equations are understood to hold for *all* bundles $X, Y \subseteq \mathcal{R}$.

▶ What is the connection between modular and additive utilities?

Modular and Additive Utilities

Modularity and additivity are really just two different names for the same thing (well, almost):

Proposition 1 *A utility function is additive iff it is both modular and normalised.*

Proof: "$\Rightarrow$": obvious ✓

"$\Leftarrow$": Let $X \subseteq \mathcal{R}$, $x \in X$.
From modularity, we get $u(X) = u(X \setminus \{x\}) + u(\{x\}) - u(\{\,\})$.
As u is normalised, we obtain $u(X) = u(X \setminus \{x\}) + u(\{x\})$.
If we iterate this step $|X|$ times, we get $u(X) = \sum_{x \in X} u(\{x\})$. $\square$

More Classes of Utility Functions

A few more commonly used classes of utility functions:

- u is *submodular* iff $u(X \cup Y) \leq u(X) + u(Y) - u(X \cap Y)$
- u is *supermodular* iff $u(X \cup Y) \geq u(X) + u(Y) - u(X \cap Y)$
- u is *concave* iff $u(X \cup Y) - u(Y) \leq u(X \cup Z) - u(Z)$ for $Y \supseteq Z$
  - Intuition: marginal utility (of obtaining X) decreases as we move to a better starting position (namely from Z to Y)
- u is *convex* iff $u(X \cup Y) - u(Y) \geq u(X \cup Z) - u(Z)$ for $Y \supseteq Z$

Note: sub(super)modular functions are also called sub(super)additive; different authors may or may not assume functions to be normalised.

Observations

The following relationships amongst some of these classes of utility functions are easily checked:

- submodular $\cap$ supermodular $=$ modular
- u submodular iff $-u$ supermodular
- u concave iff $-u$ convex
- concave $\subset$ submodular (Proof: set $Z = X \cap Y$)
- convex $\subset$ supermodular

Explicit Representation

The *explicit form* of representing a utility function u consists of a table listing for every bundle $X \subseteq \mathcal{R}$ the utility $u(X)$. By convention, table entries with $u(X) = 0$ may be omitted.

- the explicit form is *fully expressive:*
  any utility function $u : 2^{\mathcal{R}} \to \mathbb{R}$ may be so described
- the explicit form is *not concise:* it may require up to 2^n entries

Even very simple utility functions may require exponential space: e.g. the additive function mapping bundles to their cardinality (why?)

Remark: Of course, any additive utility function *could* be encoded very concisely: just store the utilities for individual goods + the information that this function is supposed to be additive $\rightsquigarrow$ linear space complexity. But this is *not* a *general method* (not fully expressive).

The k-additive Form

- A utility function is called *k-additive* iff the utility assigned to a bundle X can be represented as the sum of basic utilities assigned to subsets of X with cardinality $\leq k$ (*limited synergies*).
- The *k-additive form* of representing utility functions:

$$u(X) \quad = \quad \sum_{T \subseteq X} \alpha^T \qquad \text{with } \alpha^T = 0 \text{ whenever } |T| > k$$

Example: $u = 3.x_1 + 7.x_2 - 2.x_2.x_3$ is a 2-additive function

- That is, specifying a utility function in this language means specifying the *coefficients α^T* for bundles $T \subseteq \mathcal{R}$.
- In the context of resource allocation, the value α^T can be seen as the additional benefit incurred from owning the items in T *together*, *i.e.* beyond the benefit of owning all proper subsets.

Expressive Power

The k-additive form is *fully expressive*, if we choose k large enough:

Proposition 2 *Any utility function is representable in k-additive form for some $k \leq |\mathcal{R}|$.*

Proof: For any utility function u, we can define coefficients α^X:

$$\begin{aligned} \alpha^{\{\,\}} &= u(\{\,\}) \\ \alpha^X &= u(X) - \textstyle\sum_{T \subset X} \alpha^T \quad \text{for all } X \subseteq \mathcal{R} \text{ with } X \neq \{\,\} \end{aligned}$$

Hence, $u(X) = \sum_{T \subseteq X} \alpha^T$, which is k-additive for $k = |\mathcal{R}|$. □

The k-additive form allows for a *parametrisation* of synergetic effects:

- 1-additive = modular (no synergies)
- $|\mathcal{R}|$-additive = general (any kind of synergies)
- ... and everything in between

Comparative Succinctness

If two languages can express the same class of utility functions, which should we use? An important criterion is *succinctness*.

Let L and L' be two languages for defining utilities. We say that L' is at least as succinct as L, denoted by $L \preceq L'$, iff there exist a mapping $f : L \to L'$ and a *polynomial* function p such that:

- $u \equiv f(u)$ for all $u \in L$ (they represent the same functions); and
- $size(f(u)) \leq p(size(u))$ for all $u \in L$ (polysize reduction).

Write $L \prec L'$ (strictly less succinct) iff $L \preceq L'$ but not $L' \preceq L$.

Two languages can also be *incomparable* with respect to succinctness.

Explicit vs. k-additive Form

Proposition 3 *The explicit and the k-additive form of representing utility functions are incomparable with respect to succinctness.*

Proof sketch: The following two functions can be used to prove the mutual lack of a polysize reduction:

- $u_1(X) = |X|$: representing u_1 requires $|\mathcal{R}|$ non-zero coefficients in the k-additive form (*linear*); but $2^{|\mathcal{R}|} - 1$ non-zero values in the explicit form (*exponential*).
- $u_2(X) = 1$ for $|X| = 1$ and $u_2(X) = 0$ otherwise: requires $|\mathcal{R}|$ non-zero values in the explicit form (*linear*); but $2^{|\mathcal{R}|} - 1$ non-zero coefficients in the k-additive form (*exponential*), namely $\alpha^T = 1$ for $|T| = 1$, $\alpha^T = -2$ for $|T| = 2$, $\alpha^T = 3$ for $|T| = 3$, $\ldots$

Y. Chevaleyre, U. Endriss, S. Estivie, and N. Maudet. *Multiagent Resource Allocation with k-additive Utility Functions*. DIMACS-LAMSADE Workshop 2004.

Weighted Propositional Formulas

An alternative approach to preference representation is based on weighted propositional formulas . . .

Notation: finite set of propositional letters PS (representing goods); propositional language $\mathcal{L}_{PS}$ over PS can describe requirements.

A *goal base* is a set $G = \{(\varphi_i, \alpha_i)\}_i$ of pairs, each consisting of a consistent propositional formula $\varphi_i \in \mathcal{L}_{PS}$ and a real number α_i. The utility function u_G generated by G is defined by

$$u_G(M) \quad = \quad \sum \{\alpha_i \mid (\varphi_i, \alpha_i) \in G \text{ and } M \models \varphi_i\}$$

for all models $M \in 2^{PS}$. G is called the *generator* of u_G.

▶ If we restrict goals to *conjunctions of atoms* (of at most length k), then this corresponds directly to the *k-additive form*.

Weighted Conjunctions of Literals

Proposition 4 *The language of weighted conjunctions of literals is more succinct than the k-additive form.*

Proof sketch: Every conjunction of atoms is also a conjunction of literals, so the latter at *at least* as succinct as the k-additive form. ✓
To separate the two consider $u(\{\,\}) = 1$ and $u(X) = 0$ for $X \neq \{\,\}$: u is generated by $G = \{(\neg p_1 \wedge \cdots \wedge \neg p_n, 1)\}$ (linear), but requires exponentially many coefficients in the k-add. form: $\alpha^T = (-1)^{|T|}$. ✓

Y. Chevaleyre, U. Endriss, and J. Lang. *Expressive Power of Weighted Propositional Formulas for Cardinal Preference Modelling*. Proc. KR-2006.

Weighted Conjunctions of Literals (cont.)

Proposition 5 *The language of weighted conjunctions of literals is at least as succinct as the explicit form.*

Proof: Let u be any utility function given in explicit form. For each bundle X with $u(X) \neq 0$ add the following goal to your goal base:

$$\left(\left(\bigwedge_{p \in X} p\right) \wedge \left(\bigwedge_{p \notin X} \neg p\right), u(X)\right)$$

That is, the cardinality of the goal base is equal to the number of non-zero values in the explicit form, and each goal has length n. $\Box$

So this may seem the "best" language. But:

- some (simple) utilities may take *more space* than in the explicit or k-additive form (albeit not exponentially more)
- now representations are *not unique* anymore

Program-based Representations

Yet another approach to representing preferences would be to define utilities in terms of a *program:* input bundle, output utility value. But not just any program will do. Requirements:

- it must be possible to efficiently validate that a given string constitutes a *syntactically correct program*; and
- we have to have an effective method of *computing the output* of the program for any given input.

Dunne *et al.* (2005) propose such a program-based approach based on so-called *straight-line programs* (warning: this is rather technical).

One result says that any function computable by a deterministic Turing Machine in time T is representable by an SLP with $O(T \log T)$ lines.

P.E. Dunne, M. Wooldridge, and M. Laurence. *The Complexity of Contract Negotiation*. Artificial Intelligence, 164(1–2):23–46, 2005.

Ordinal Preferences

Next we are going to look into different languages for representing *ordinal* preference structures.

Recall that an *explicit representation* of an ordinal preference relation $\preceq$ over 2^n alternatives requires space up to $O(2^n \cdot 2^n)$: for each pair of bundles, say which one is preferred.

Prioritised Goals

Again, associate goods with propositional letters in PS and bundles with models $M \in 2^{PS}$. *Goals* can be expressed as formulas in the propositional language $\mathcal{L}_{PS}$.

Instead of weights, we now have a *priority relation* over goals. Assuming this priority relation is a total order, it can be represented by a function $rank : \mathbb{N} \to \mathbb{N}$ mapping each (index of a) goal to its rank. By convention, a *lower rank* means *higher priority*.

A *goal base* is now a finite set of goals with an associated rank function: $G = \langle \{\varphi_1, \ldots, \varphi_m\}, rank \rangle$.

▶ Ideally, all goals will get satisfied. But if not, how can we extend the priority relation over goals to a preference relation over alternatives?

Combining Priorities

There are several options (convention: $\min(\{\,\}) = +\infty$):

- *Best-out ordering*:

  $M \preceq M'$ iff $\min\{\mathit{rank}(i) \mid M \not\models \varphi_i\} \leq \min\{\mathit{rank}(i) \mid M' \not\models \varphi_i\}$

  That is, preference depends (only) on the rank of the most important goal that is being violated.

- *Discrimin ordering*:
  Let $d(M, M') = \min\{\mathit{rank}(i) \mid M \not\models \varphi_i$ and $M' \models \varphi_i\}$ be the rank of the most important goal "discriminating" the alternatives.

  $$M \preceq M' \text{ iff } d(M, M') \leq d(M', M) \text{ or}$$
  $$\{\varphi_i \mid M \models \varphi_i\} = \{\varphi_i \mid M' \models \varphi_i\}$$

Combining Priorities (cont.)

- *Leximin ordering:*
  Let $d_k(M) = |\{\varphi_i \mid M \models \varphi_i \text{ and } rank(\varphi_i) = k\}|$ be the number of goals of rank k that are satisfied by alternative M.

$M \preceq M'$ iff (1) for all k: $d_k(M) = d_k(M')$ or

(2) there exists a k such that $d_k(M) < d_k(M')$

and for all $j < k$: $d_j(M) = d_j(M')$

Properties

- None of the three variants of combining prioritised goals leads to a *fully expressive* preference representation language.
- The *best-out ordering* and the *leximin ordering* result in *connected* preference relations, but the *discrimin ordering* typically does not.
- For the *strict* preference relations we have:
  - *best-out preference* entails *discrimin preference*; and
  - *discrimin preference* entails *leximin preference*

Ceteris Paribus Preferences

In the language of *ceteris paribus* prefernces, preferences are expressed as statements of the form $C : \varphi > \varphi'$, meaning:

> *"If C is true, all other things being equal, I prefer alternatives satisfying $\varphi \wedge \neg\varphi'$ over those satisfying $\neg\varphi \wedge \varphi'$."*

The "other things" are the truth values of the propositional variables not occurring in φ and φ'. A preference relation can be constructed as the transitive closure of the union of individual preference statements.

Discussion: interesting from a *cognitive* point of view (close to human intuition), but of rather *high complexity*.

An important sublanguage of *ceteris paribus* preferences, imposing various restrictions on goals, are *CP-nets*.

C. Boutilier *et al.* *CP-nets: A Tool for Representing and Reasoning with Conditional Ceteris Paribus Preference Statements*. JAIR, 21:135–191, 2004.

Summary

- Preference representation is relevant to MAS, because agents need to communicate their interests to make collective decisions.
- We have emphasised *expressive power* and *succinctness:*
  - expressive power should be *appropriate*; note that many game-theoretical results presuppose that agents can express *any* preference structure (e.g. whatever your true valuation, you should be able to communicate it to the auctioneer)
  - succinctness is crucial in *combinatorial domains* (such as resource allocation)
- Languages considered (there are many more):
  - *cardinal:* explicit form, k-additive form, weighted goals, and program-based representations of utility functions
  - *ordinal:* prioritised goals and ceteris paribus statements

References

For a concise overview and for a discussion of the role of preference representation in the context of multiagent resource allocation, consult:

- Y. Chevaleyre *et al*. Issues in Multiagent Resource Allocation. *Informatica*, 30:3–31, 2006. Section on Preference Representation.

For an in-depth survey of logic-based languages for representing preferences, refer to:

- J. Lang. Logical Preference Representation and Combinatorial Vote. *Annals of Mathematics and Artificial Intelligence*, 42(1):37–71, 2004.

What next?

Next week, we are going to continue discussing issues related to preference representation, but we are going to focus specifically on languages developed for combinatorial auctions:

- *Bidding Languages for Combinatorial Auctions*