Temporal Planning with Preferences and Uncertainty

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Coordinated Observation Scheduling Problem

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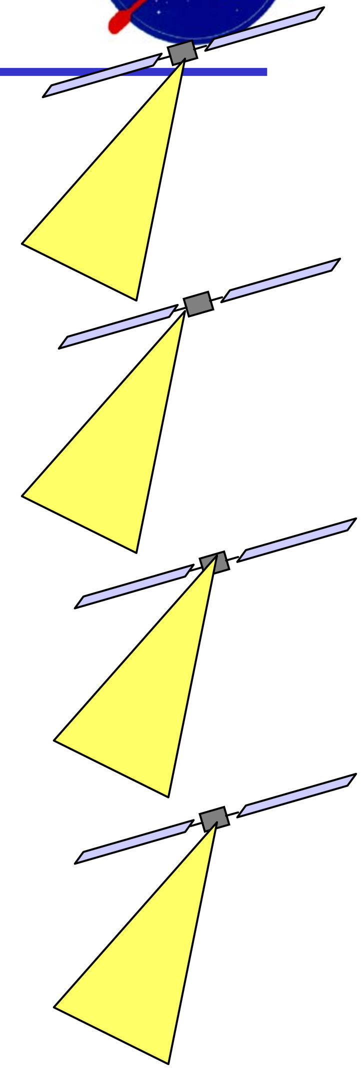
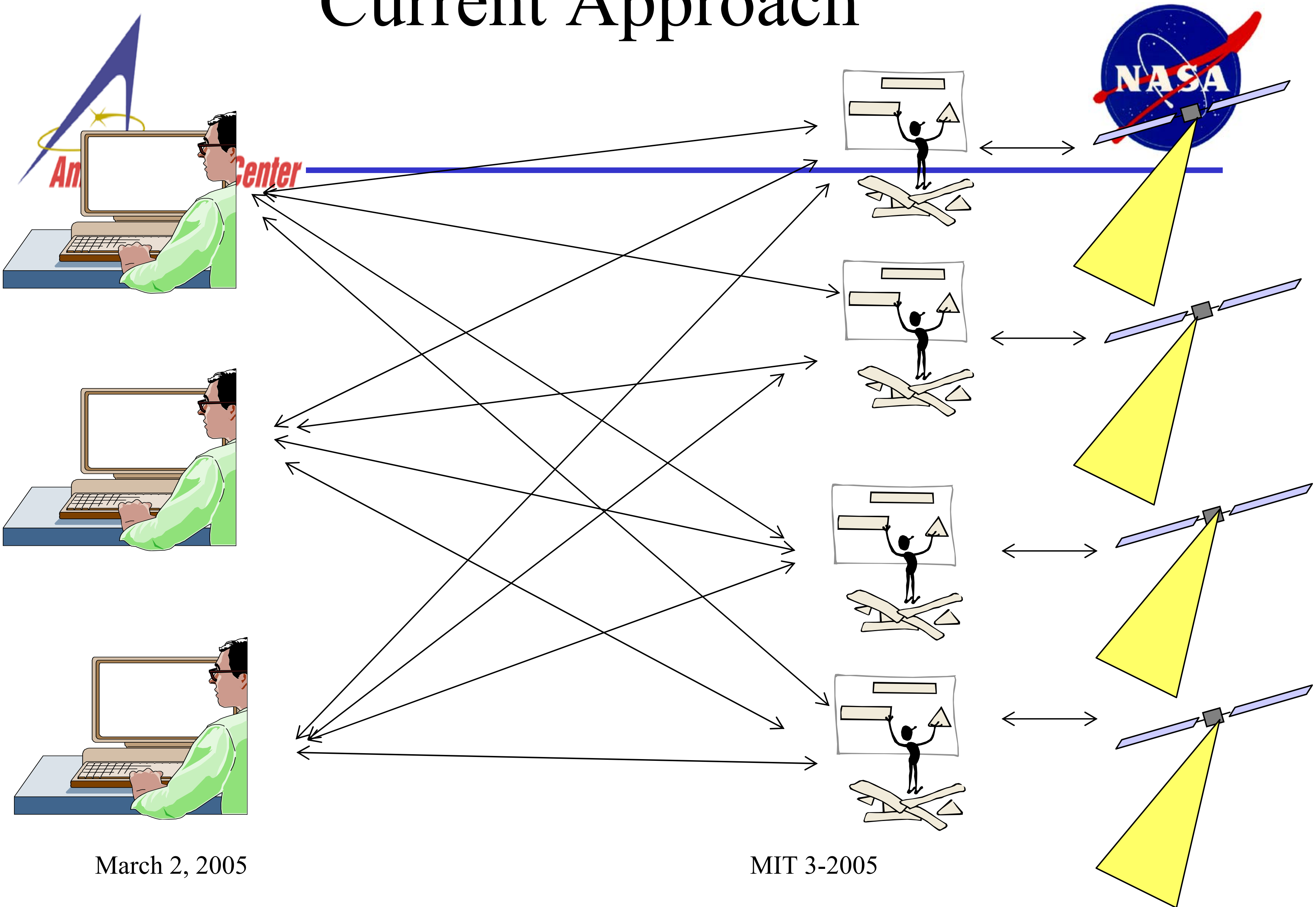
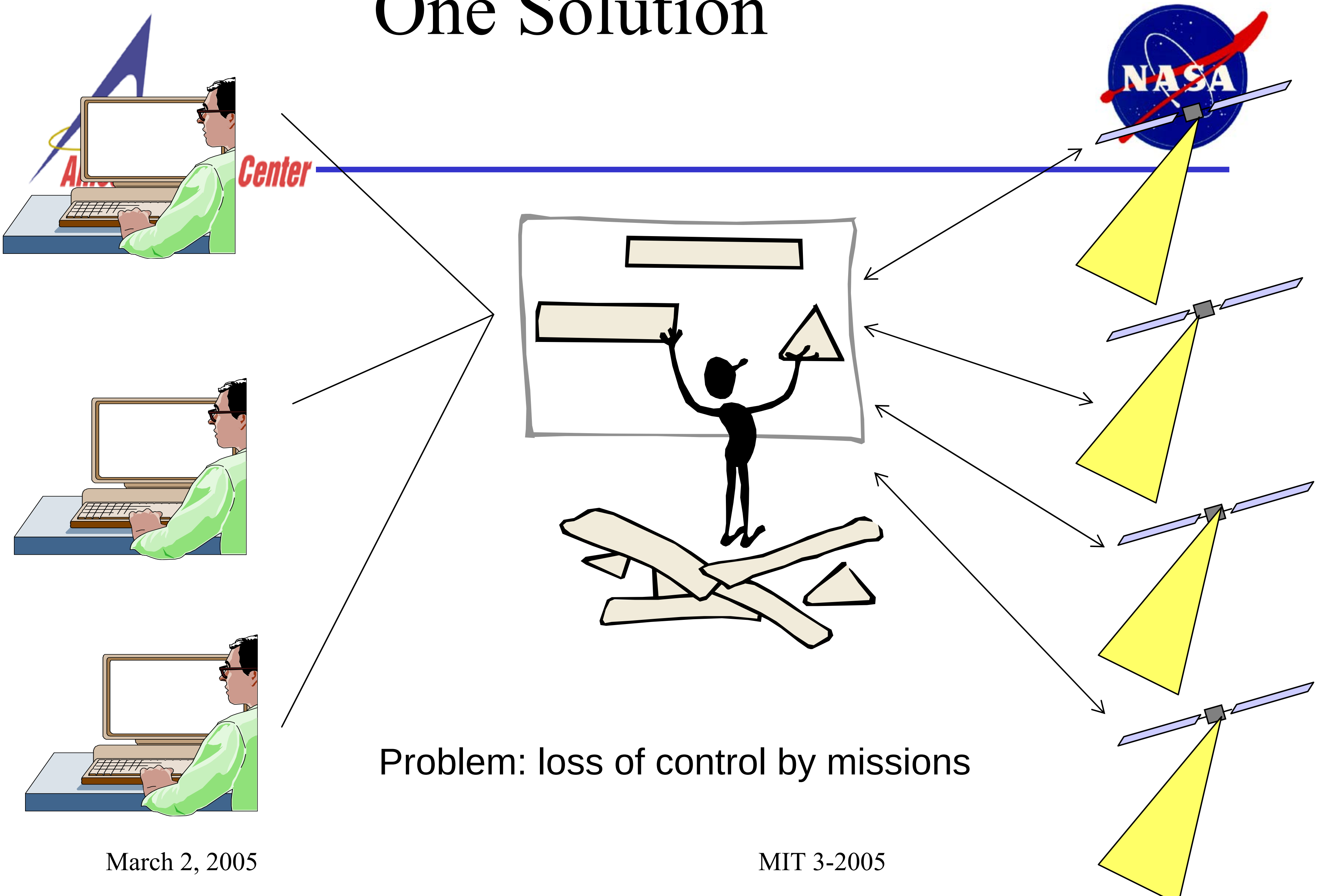
Earth scientists need access to multiple sensors to take a series of coordinated measurements.



Current Approach

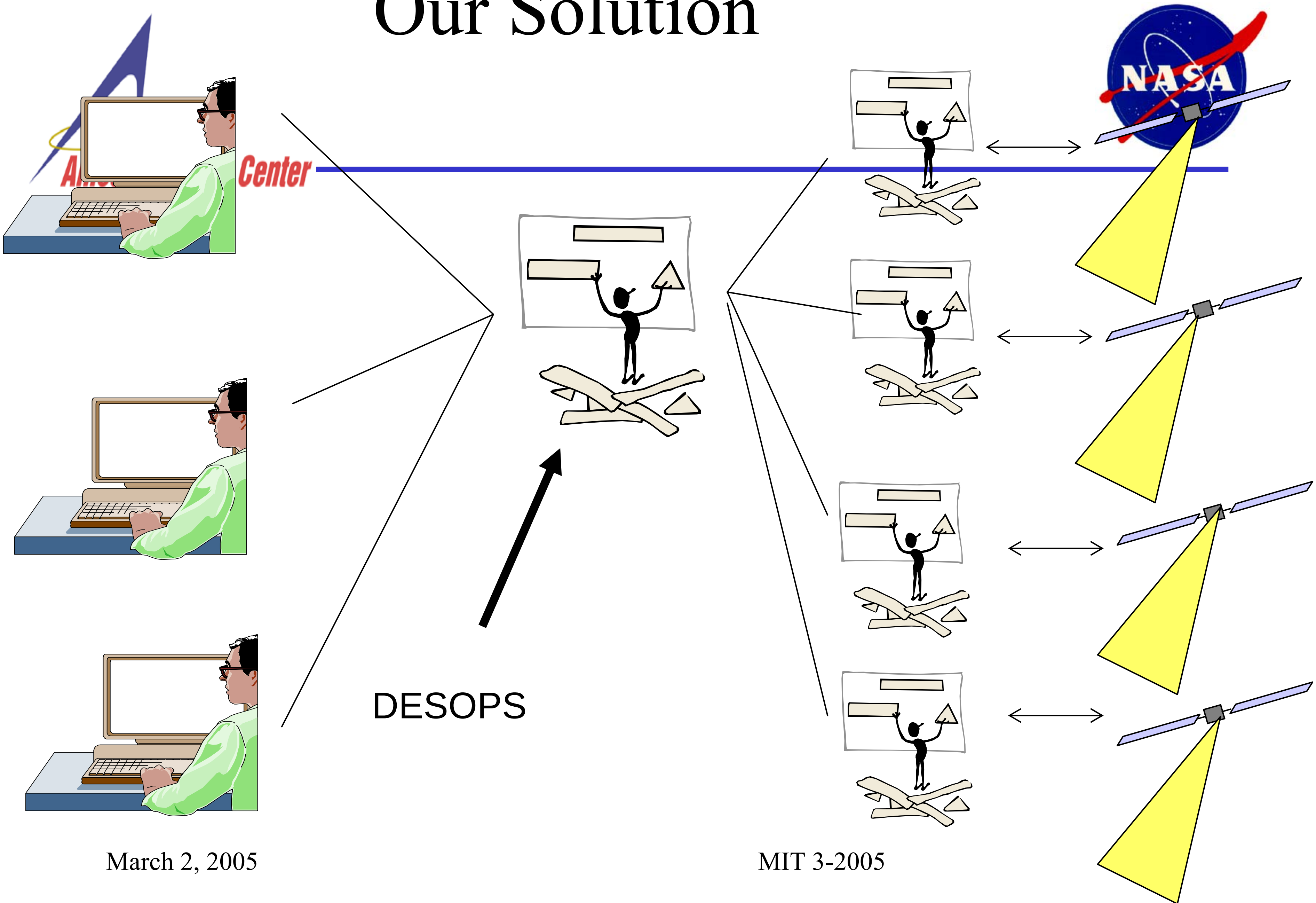


One Solution



Problem: loss of control by missions

Our Solution



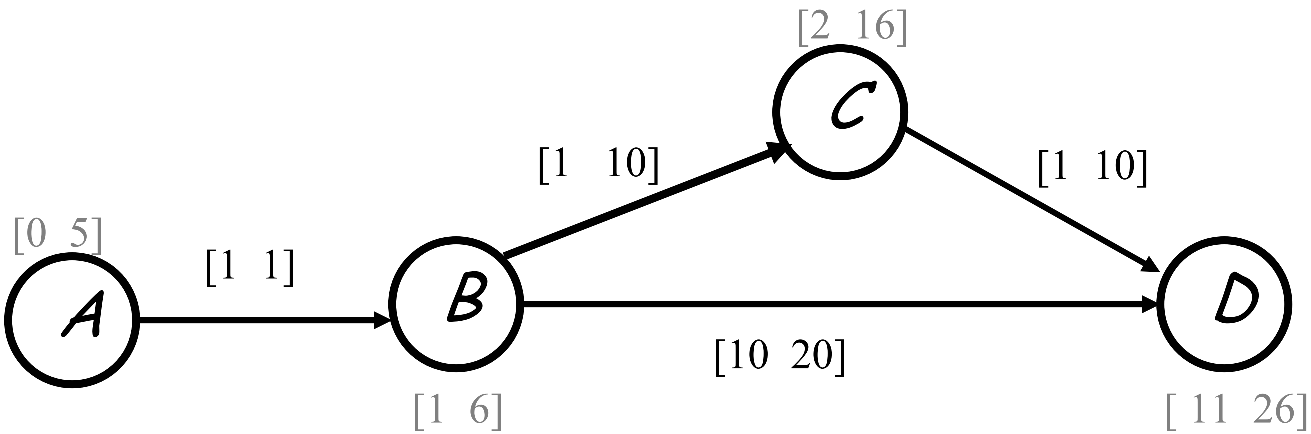
Example: Earth Observation Campaign Scheduling

- **Science goal:** Validate a emissions model predicting the aerosols released by wildfires.
- **Measurement types:**
  - Moisture content
  - Aerosol concentration
  - Vegetation type
  - Burned area
  - Fire temperature
- **Constraints on measurements:**
  - Location
  - Temporal ordering *(preferences for some times over others)*
  - Sensor capabilities
- **Other constraints on problem:**
  - Campaign cost

Temporal CSPs

- Temporal CSP [Dechter, et. al.'91]
  - **Variables** representing events.
  - **Domains** representing times associated with events.
  - Binary **constraints** specify allowed ranges for durations between events:
    - Each is a set of expressions of the form : $a \leq Y - X \leq b$
  - **Solution** to a TCSP is a complete assignment of domain elements to variables that satisfy all the constraints.
  - Simple Temporal Problem (STP) is one where each constraint consists of single interval.
- STPs can be solved using shortest path algorithms.

STP as Network

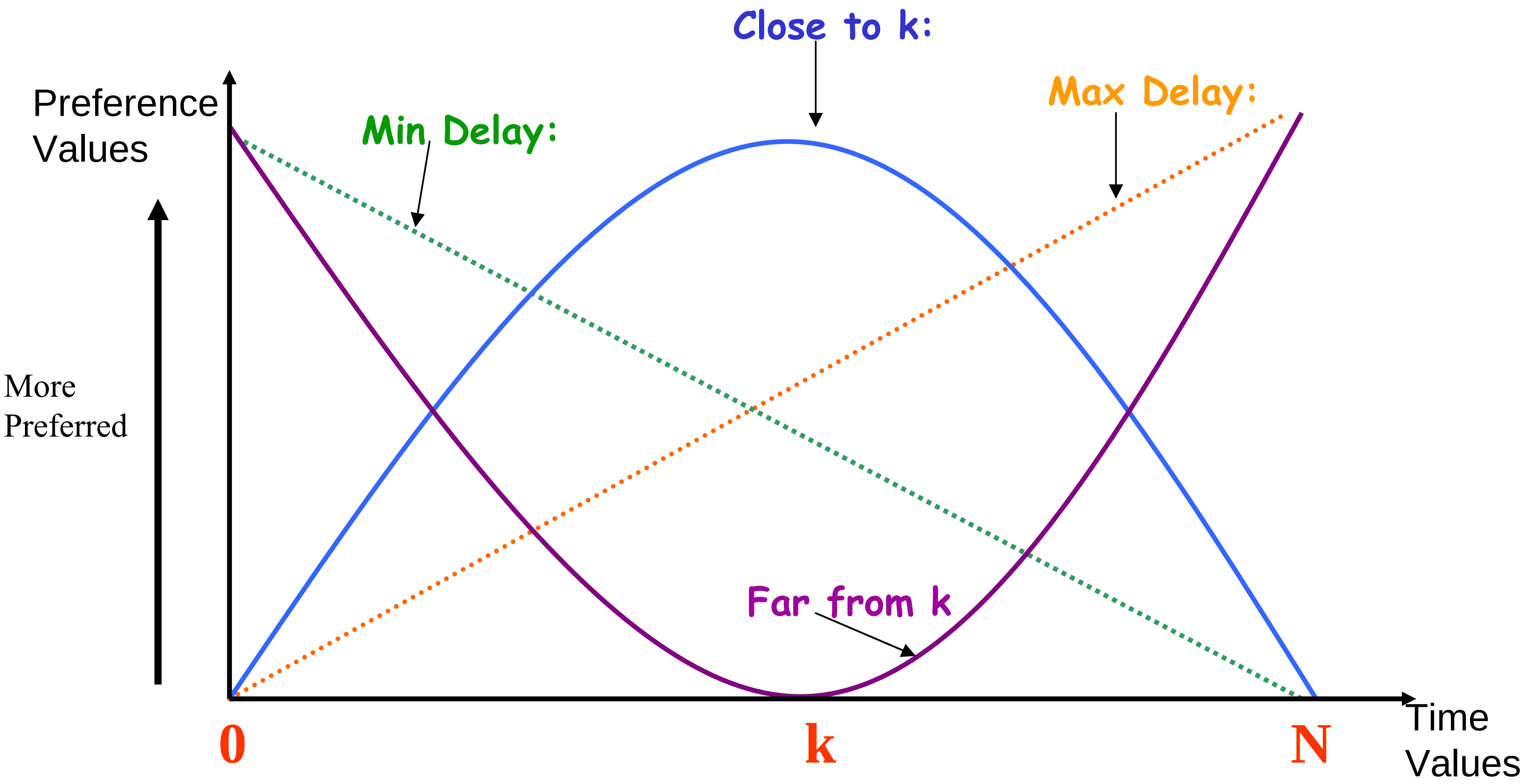


Solution1: (A,B,C,D)=(0,1, 2,11)
Solution2: (A,B,C,D)=(0,1, 6,11)
Solution3: (A,B,C,D)=(0,1,11,18)
...etc.

TCSP with Preferences (TCSPP)

- Generalization of TCSP by assigning a preference function to each constraint.
- A **soft temporal constraint** is a pair <I,f> where
  - I is a set of intervals and
  - f: U{I} → A is a function (A is a set of preference values).
- A **solution** to a TCSPP will satisfy all the interval constraints, and a **preferred solution** will be one which selects the preferred values based on the *f*s.

Simple Preference Functions



Preference Values Structured as Semirings

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- **A C-Semiring** [Bistarelli, Montanari, Rossi, '95] is a structure $\langle A, +, \times, 0, 1 \rangle$, where
  - A is a set containing 0, 1.
  - $+$ is commutative, associative, idempotent (i.e., a+a =a), 0 is unit element (i.e., $a + 0 = a$);
  - $\times$ is associative, distributes over $+$, 1 is unit, 0 is absorbing (i.e., $a \times 0 = 0$).
- Partial order relation $\leq$ for comparing values:
  - $a \leq b$ "b is better than a".
  - $\langle A, \leq \rangle$ is a complete lattice.

Examples

- Fuzzy: $\langle [0,1], \max, \min, 0, 1 \rangle$
  - Preference values between 0 and 1.
  - Value of any tuple is minimum of values of sub-tuples.
  - Preferred solutions are ones with the greater overall preference value.
- Classical CSP: $\langle \{false, true\}, \vee, \wedge, false, true \rangle$
  - Preference function: $f: X \to \{false, true\}$
  - Ordering: "true is better than false"

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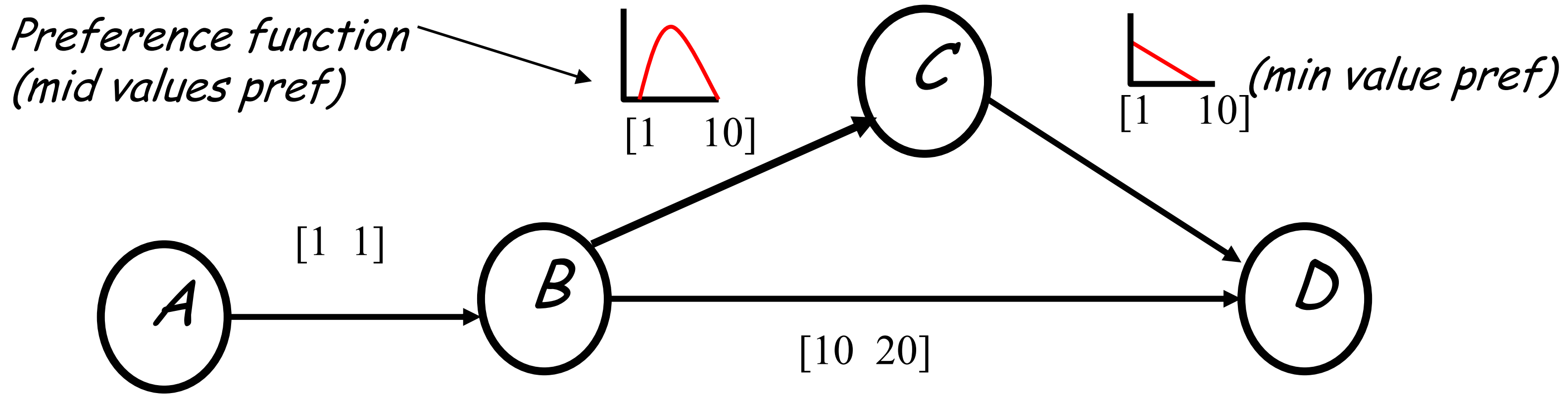
Formalization of TCSPP

- A **TCSPP** consists of
  - **Variables** $X = \{x_1, x_2 \cdots x_n\}$
  - Associated **Domains** $D_i = \{v_{i1}, v_{i2} \cdots v_{im}\}$
  - A set of soft binary **constraints** $\{T_{ij}\}$ over distances $v_j - v_i, v_j \in D_j, v_i \in D_i$, where $T_{ij} = \langle I_{ij}, f_{ij} \rangle$, and $f_{ij} : \bigcup I_{ij} \to A$.
  - A **Semiring** $S = \langle A, +, \times, 0, 1 \rangle$
- An **STPP** (Simple Temporal Problem with Preferences) is a TCSPP where each T_{ij} consists of a single interval.

Simple Temporal Problems with Preferences (STPP)

- TCSPP in which I is restricted to be a single interval.

Example:

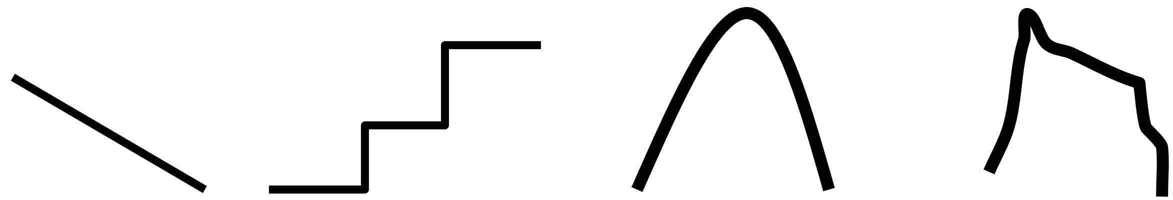


Evaluating Solutions in a TCSPP

- Let s = (v_1, …, v_n) be a solution to a TCSPP, where each v_i is the assigned time value to x_i
- Let $s \downarrow x_i, y_j = (v_i, v_j)$ be the projection of s to the values of the variables x_i, y_j.
- Let $\prod\{f_1, f_2, \ldots f_n\}$ abbreviate $f_1 \times f_2 \times \ldots \times f_n$.
- Define
  - $Val(s) = \prod\left\{ f_{ij}(v_i, v_j) \mid (v_i, v_j) = s \downarrow x_i, x_j \right\}$
- *Val* provides the "global" preference for a solution.

Semi-Convex Functions

- Any horizontal line drawn in the Cartesian plane is such that the set of values f(x) not below the line forms a single interval.
- Closed under intersection and composition.
- Examples:

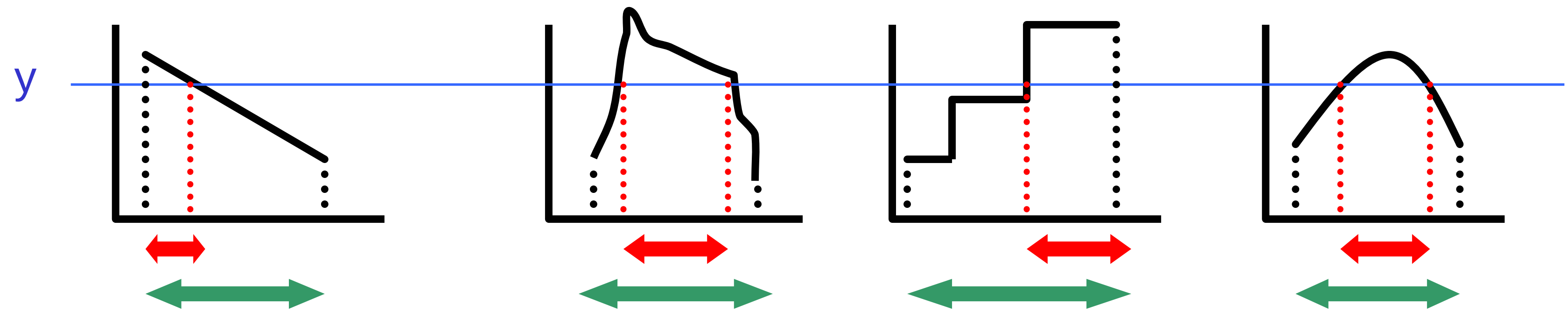


Tractability Result

- Any STPP with soft constraints each with a semi-convex preference function over a totally ordered semiring with $\times$ idempotent is such that finding an optimally preferred solution is tractable.
- The proof requires "chopping" each semi-convex preference function at some level y.
- The interval above a chop point y defines the constraint for a Simple Temporal problem, STPy.

Example of Chopping

- Soft constraint of STPP: <$[a_i, b_i]$,fi>
- Induced constraint of STPy: $[a_i', b_i']$



Any solution to the STP_{opt}, with opt the largest y with STPy solvable, is an globally preferred solution to the original STPP.
Since STPs are tractable, so are (this breed of) STPPs.

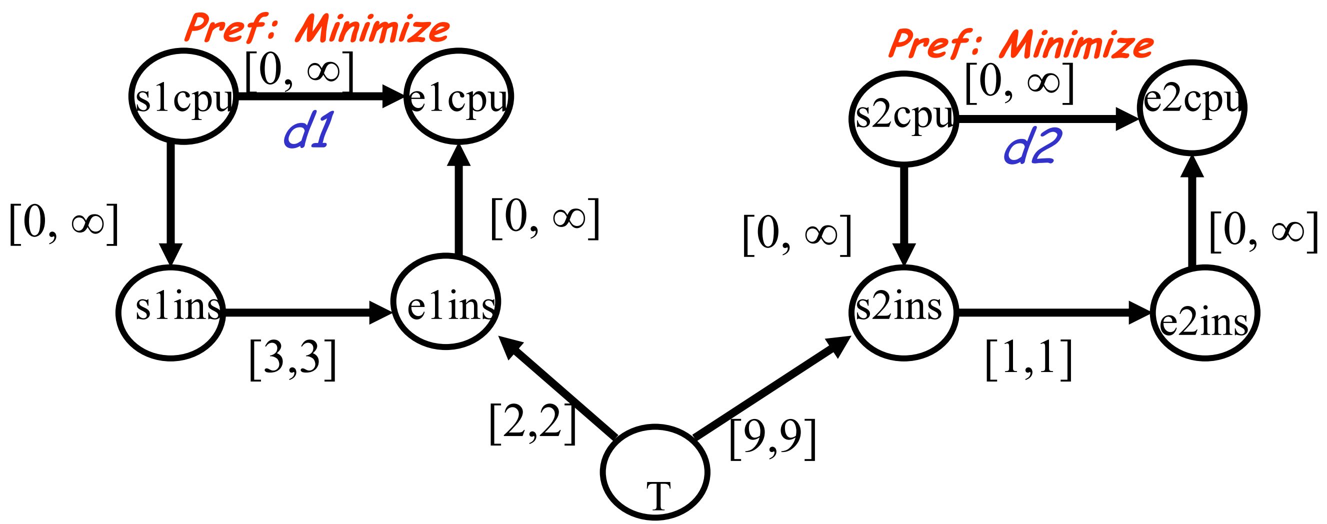
Search for Optimal Solution

- First step: find chop point.
  - If semiring has finite number of elements, then using binary search, the number of choice points examined will be polynomial.
- Second step: solve the induced STPy.
  - Can be performed effectively using shortest path algorithms.
- The output of this algorithm is a flexible plan consisting of the set of all "weakest link-optimal" (WLO) fixed-value solutions.

Global Preference Criteria

- *Weakest Link (WL)*: Maximize the preferences of the individual that is worse off.
- *Pareto*: Maximize according to the principle: the community becomes better off if one or more individuals become better off and none become worse off.
- *Utilitarian:* Maximize the overall preferences of all the individuals.

Limitation of WLO: The "Drowning Effect"



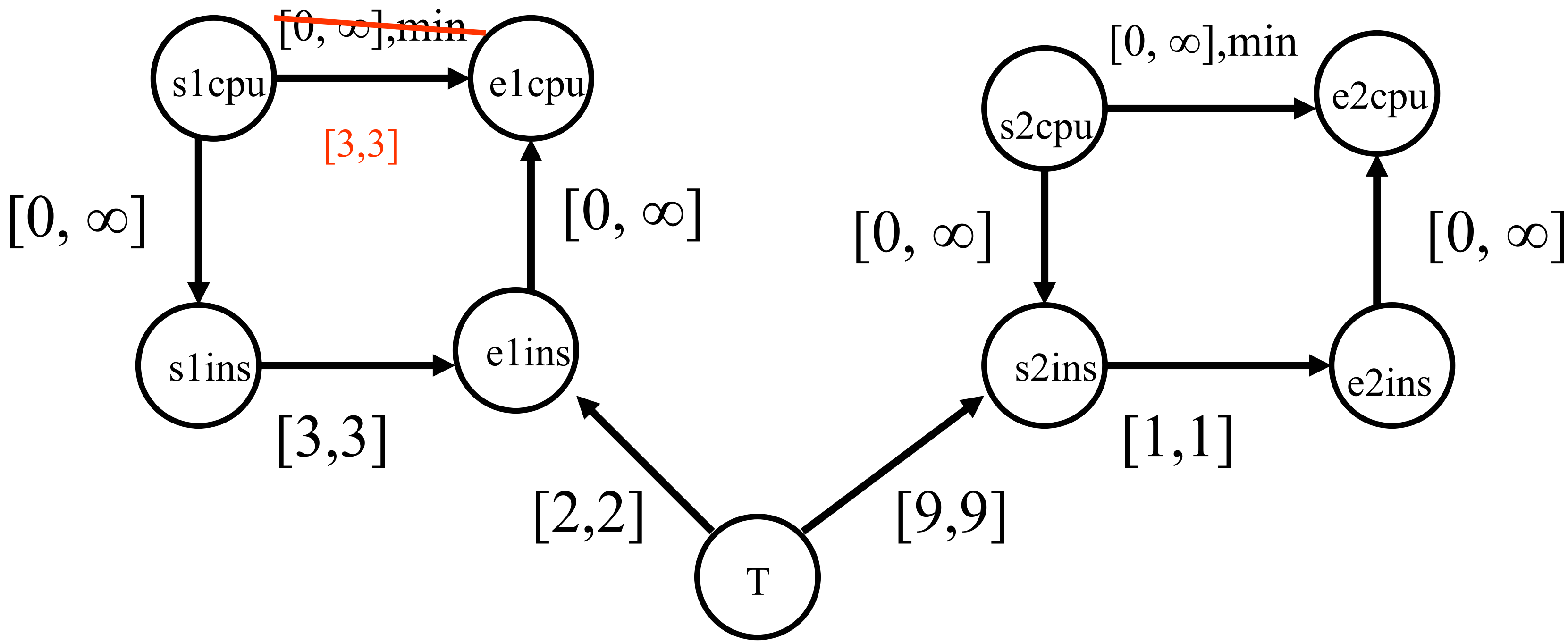
Values for (d1,d2) in all WLO optimal solutions are: (3,1), (3,2), and (3,3).

But (3,1) intuitively "better" than (3,2) and (3,3)

Beyond WLO

- The tractability of solving using WLO has been demonstrated, but WLO has limitations.
- Either PO or UT might be considered "better" (more discriminating) as an optimization policy.
- We can approximate the behavior of a PO solver by an iterative process of solving using WLO and transforming the problem.
- We refer to this algorithm as WLO+.

WLO+ in action



A "weakest link constraint" is the one in which the preference value of its duration in all WLO solutions is the same as the "chop level" of the original STP using the WLO strategy.

WLO+ generates Stratified Egalitarianism (SE)-optimal solutions

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- Using an economic metaphor, a "society" is SE-improved if some members below the poverty line are improved while none dropped below the poverty line.
- SE solutions are a subset of Pareto Optimal solutions.
- WLO+ Returns exactly the Stratified Egalitarian Solutions.

Global Preferences criterion: Utilitarian Optimality (UT)

- The global value of a solution is the sum of local values.
- Finding a single UT optimal solution is tractable when all local preference functions are convex and piecewise linear.
  - A UT optimization problem can be reduced to a Linear Programming Problem (LPP).
- The set of *all* UT optimal solutions of a STPP **P** can be represented as the solutions to a STP that results from adding constraints to the STP underlying **P**.
  - Set of all solutions to an LPP coincides with one of the faces of the polyhedron that defines the solutions to the LPP.
  - Faces are found by changing some inequalities to equalities, an operation that corresponds to adding constraints to an STP.
  - Solving the dual to the LPP determines the changes.

Extensions to Uncertainty Temporal Planning

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- The field of decision theory has explored issues related to the value of decisions in the face of uncertainty.
- One domain relevant to planning or scheduling for which results from decision theory would benefit is time.
- The goal in this expanded work is to devise systematic methods for exploring the interactions between temporal preferences and uncertainties.

Summary

- STPPs: framework for generating "globally preferred" solutions to temporal reasoning problems.
  - Useful in a variety of planning and scheduling applications
  - Introduction and comparison of distinct global preference criteria: WLO, SE, Pareto, Utilitarian.
  - Utilitarian optimality can be obtained tractably, under certain conditions, when solved as an LPP.
- Extensions to handle uncertainty (STP^3)
  - Can be used to systematically examine interactions between preferences and probabilities dealing with time.

Extensions and Applications

- Dynamic Execution Strategies
  - What happens to preferences over time as observations of natural events occur?
- Current and future applications
  - Earth science observation scheduling
    - Integration into DESOPS system for distributed observation scheduling
  - Rover science planning
    - Integration into MAPGEN

Related Work

- **STPUs:**
  - I. Tsamardinos, M. E. Pollack, and S. Ramakrishnan. Assessing the probability of legal execution of plans with temporal uncertainty. In Proc. of ICAPS'03 Workshop on Planning Under Uncertainty and Incomplete Information.
- **Uncertainty CSPs**:
  - H. Fargier, J. Lang, R. Martin-Clouaire and T. Schiex. A constraint Satisfaction Framework for Decision-Making under uncertainty. UAI-95.
- **Planning with uncontrollables**:
  - N. Muscettola, P. Morris, and I. Tsamardinos. Reformulating temporal plans for efficient execution. Proceedings of KR'98.
- **Multi-criteria optimization**:
  - Ulrich Junker. Preference-based search and multi-criteria optimization. In Proceedings of AAAI-02. AAAI Press, 2003.