Integrated Task and Motion Planning

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Integrated Task and Motion Planning

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task and motion planning, robotics, automated planning, motion planning, manipulation planning

Abstract

The problem of planning for a robot that operates in environments containing a large number of objects, taking actions to move itself through the world as well as to change the state of the objects, is known as task and motion planning (TAMP). TAMP problems contain elements of discrete task planning, discrete–continuous mathematical programming, and continuous motion planning and thus cannot be effectively addressed by any of these fields directly. In this article, we define a class of TAMP problems and survey algorithms for solving them, characterizing the solution methods in terms of their strategies for solving the continuous-space subproblems and their techniques for integrating the discrete and continuous components of the search.

1. INTRODUCTION

Robots are playing an increasingly important role in society, and their range of applications is rapidly expanding. These applications have traditionally been in structured environments, such as factories, where the robot's interactions are limited and a behavior can be directly specified by a human. However, many of the most exciting potential applications of robots are in highly unstructured human environments such as homes, hospitals, or construction sites. In these applications, the robot will generally be tasked with a specific goal, such as cooking and delivering a meal to an elderly resident, but the actions necessary to achieve the goal will vary enormously depending on the state of the environment. For example, the robot might need to open cupboards and remove objects in order to retrieve a bowl that is necessary for preparing the meal (**Figure 1**). Directly specifying the full behavior policy for a robot operating in these unstructured environments is not practical because the required policy is too complex.

Since the earliest days of robotics, there has been an interest in automated planning, which involves developing algorithms for deciding what sequence of commands the robot should execute in order to accomplish some goal (2, 3). The first class of planning problems that arises is to move the robot from one state to another without colliding with objects in the world. This motion planning problem was formulated by Lozano-Pérez & Wesley (4) as a search for paths through the robot's configuration space (a space with dimensions representing the controllable joints of the robot) and has been the focus of a great deal of algorithmic development. The most effective methods are based on sampling (5, 6) or constrained optimization (7, 8).

Collision-free robot motion is important but does not enable the robot to alter the world. In order for the robot to, for example, move objects by picking them up and placing them, planning

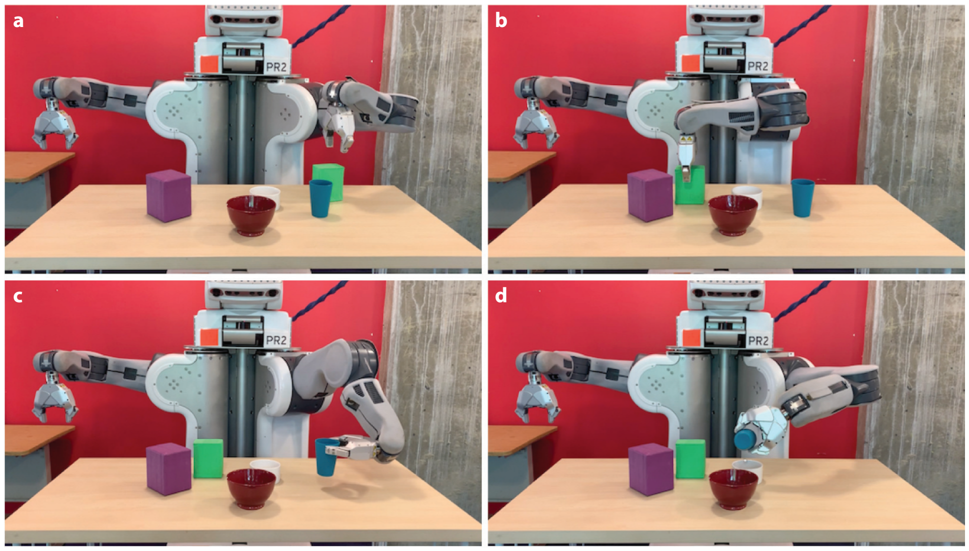

Figure 1

An example application of a task and motion planning algorithm. The specified goal is for the contents of the blue cup to end up in the white bowl. Because the green block obstructs reachable grasps for the blue cup, the algorithm automatically plans to relocate the green block before picking up the blue cup and pouring its contents into the white bowl. The images show (*a*) the robot reaching to pick up the green block, (*b*) the robot placing the green block, (*c*) the robot picking up the blue cup, and (*d*) the robot pouring the blue cup's contents into the white bowl. Figure adapted from Reference 1.

needs to consider a much larger space that encompasses the entire state of the world, which includes any objects the robot has grasped, the grasps it is using, and the poses of the other objects. Conceptually, it makes sense to try to directly extend motion planning methods to apply to entire world states, but this approach fails algorithmically. The entire world state, seen as a single kinematic system, is highly underactuated, in the sense that from any configuration, most of the degrees of freedom cannot be changed at will. The robot can change the position of an object only by moving over and touching it.

It is critical to understand the underlying topology of these spaces in order to plan in them. Alami et al. (9, 10), Branicky et al. (11, 12), and Hauser et al. (13, 14) have observed that the configuration space of the world has an important modal structure: Depending on where the objects are placed and how they are grasped, the legal changes to the world are in a different mode or feasible submanifold of the full space. Furthermore, it is possible to change modes only by moving to an intersection of the feasible space of the current mode and a new one, which is in general an even lower-dimensional subspace. For these reasons, planning is best viewed as a hybrid discrete–continuous search problem that involves selecting a finite sequence of discrete mode types (e.g., which objects to pick and place), continuous mode parameters (such as the poses and grasps of the movable objects), and continuous motion paths within each mode to a configuration that is in the intersection with the subsequent mode.

The AI community has addressed problems of planning in very large discrete domains (15). Their techniques derive leverage from factoring, a source of combinatorial structure in planning problems. Factoring is used to decompose the state space of the world into the Cartesian product of several subspaces, represented in terms of different state variables. Factoring enables a compact representation of the actions that can be performed on a state; these actions are generally described in terms of a small set of state variables that can be changed (while the others are held constant), as well as a condition on other variables that must be satisfied in order for the action to be executed. Furthermore, the AI planning community has developed a repertoire of highly effective, domain-independent search algorithms that exploit this type of action representation (16–18).

Research in task and motion planning (TAMP) seeks to combine AI approaches to task planning and robotics approaches to motion planning. A critical requirement for generality in approaches to TAMP actually lies between discrete high-level task planning and continuous low-level motion planning, at an intermediate level of selecting the real-valued mode parameters, such as how to grasp and where to place an object, which govern legal continuous motions of the system. This class of problems is computationally difficult in theory (19, 20) and requires algorithmic sophistication in practice.

1.1. An Example

An essential component of TAMP problems is the interdependence of the motion-level and task-level aspects of the problem. Approaches that treat these independently, without considering their complex interplay, are unable to solve the general class of problems. Consider a problem in which the robot's goal is for a particular pot (named `A`) to be placed on one of the burners of a stove. If the planner ignores the geometric aspects, it might select a high-level plan skeleton of the form

$$[\texttt{moveF}(q_0, \tau_1, q_1, p_0), \texttt{pick[A]}(q_1, p_0, g), \texttt{moveH[A]}(g, q_1, \tau_2, q_2), \texttt{place[A]}(q_2, p_1, g)],$$

where the `moveF` action involves robot movement when its hand is free, and the `moveH[A]` action involves robot movement when holding object `A`.[1] This plan skeleton has free parameters involving

[1]For a complete definition of these actions, see **Figure 7** in Section 3.1.

robot configurations (q_0, q_1, q_2), a grasp pose (g), placement poses (p_0, p_1), and paths (τ_1, τ_2). The skeleton imposes constraints on the choices of those values that will enable the plan to achieve the goal. Given this skeleton, it is now necessary to find values for all of these parameters that satisfy the constraints. It may be that there is no satisfying set of values; for instance, a kettle could be occupying the target burner, preventing any safe placement of the pot. In this case, a new skeleton is necessary: The robot will need to first move the kettle away and then place the pot on the stove. This example demonstrates a change in the high-level plan that is necessitated by the low-level geometry.

1.2. Scope

To keep the scope of this survey manageable, we limit the class of problems addressed, and discuss a variety of extensions in Section 4. In particular, we assume that actions are deterministic, the state of the world is completely known, the robot and every object in the environment are kinematic assemblies of rigid bodies with known shapes, the robot is holonomic, and the goal is specified as a set of requirements on the final robot configuration, object poses, and possibly other state variables, such as the cooked state of a dish. This class of problems encompasses several problems studied in the robotics community: pick-and-place planning (21), manipulation planning (22), navigation among movable obstacles (23), and rearrangement planning (24). An important related line of work uses linear temporal logic to provide high-level specifications for TAMP problems with temporally extended goals (25, 26), but this work is beyond the scope of this survey.

We begin with basic background in motion planning, multimodal motion planning (MMMP), and task planning (Section 2). Next, we draw from components of these fields in order to formalize TAMP in a manner that allows for many existing approaches to be studied (Section 3.1). We then describe a framework for understanding a broad class of TAMP algorithms in terms of combining (Section 3.3) a search over discrete plan structures with a search over continuous values satisfying constraints (Section 3.2) induced by the discrete structure. We conclude with a short discussion of a rich array of extensions and generalizations of this basic problem class and the approaches to solve them (Section 4).

2. BACKGROUND

TAMP rests on foundations in robot motion planning (Section 2.1), MMMP (Section 2.2), and AI task planning (Section 2.3). In this section, we give a compact overview of each of these planning problem classes.

2.1. Motion Planning

The problem of planning motions for a robot with d degrees of freedom can be framed as finding a trajectory for a point representing the robot's configuration through a d-dimensional configuration space. More formally, a motion planning problem is specified by a configuration space $\mathcal{Q} \subset \mathbb{R}^d$, a constraint $F : \mathcal{Q} \to \{0, 1\}$, an initial configuration $q_0 \in \mathcal{Q}$, and a goal set of configurations $Q_* \subseteq \mathcal{Q}$. The feasible configuration space is a subset of $\mathcal{Q}$ that satisfies the constraint $Q_F = \{q \in \mathcal{Q} \mid F(q) = 1\}$. The objective is to find a continuous path $\tau : [0, 1] \to \mathcal{Q}$ such that $\tau(0) = q_0$, $\tau(1) \in Q_*$, and $\forall \lambda \in [0, 1]\ \tau(\lambda) \in Q_F$. The simplest motion planning problems involve free-space motion, in which the robot simply needs to move through space without colliding with anything. Given a set of objects, defined by their shapes and poses in the world, the constraint $F(q)$ requires that the robot not collide with any object.

Motion planning is PSPACE-hard, but there are exact algorithms that leverage algebraic geometry to solve problems using only polynomial space (proving motion planning is

PSPACE-complete) (27). Nevertheless, the two most widely used approaches are sampling-based motion planning (5, 6) and trajectory optimization (7, 8). Both of these classes of algorithms are useful in practice but are not complete, because they cannot identify infeasible problems. Under some robustness conditions, however, many sampling-based motion planning algorithms can be shown to be probabilistically complete, meaning that the probability that they will fail to find a solution, if one exists, converges to zero as the running time increases. LaValle (28) provided a comprehensive overview of motion planning algorithms.

2.2. Multimodal Motion Planning

MMMP extends the problem space of planning to include changing the state of other objects in the world (13, 14, 29, 30). To formalize MMMP problems, we need to model changes in the kinematics of the system, extend motion planning to handle constraints beyond collision avoidance, and integrate these components.

2.2.1. Kinematic graphs. One way to represent the geometric state of many environments is to encode the state variables collectively as a kinematic graph (28), which makes their dependencies explicit. In a kinematic graph, vertices represent bodies and the robot's controllable joints, and edges represent attachments. Each edge has an associated relative transformation between the child body and parent body, which is a pose in SE(3). If each body is connected to at most one parent body and the graph is acyclic, then this is a kinematic tree, for which the full state of the world can be derived from just the joint values of the robot q through forward kinematics. The attachments can be of several kinds. The most straightforward is a rigid attachment, which models an object resting stably on a surface or a robot grasping an object in a fixed grasp.

Figure 2 shows a kinematic tree for an example kitchen environment that contains a robot manipulator with two joints (j_1, j_2), a fixed `Table` and `Stove`, and movable objects `Plate`, `Pizza`, and `Book`. Initially, the `Pizza` rests on the `Plate`, which itself rests on the `Table`. When the robot

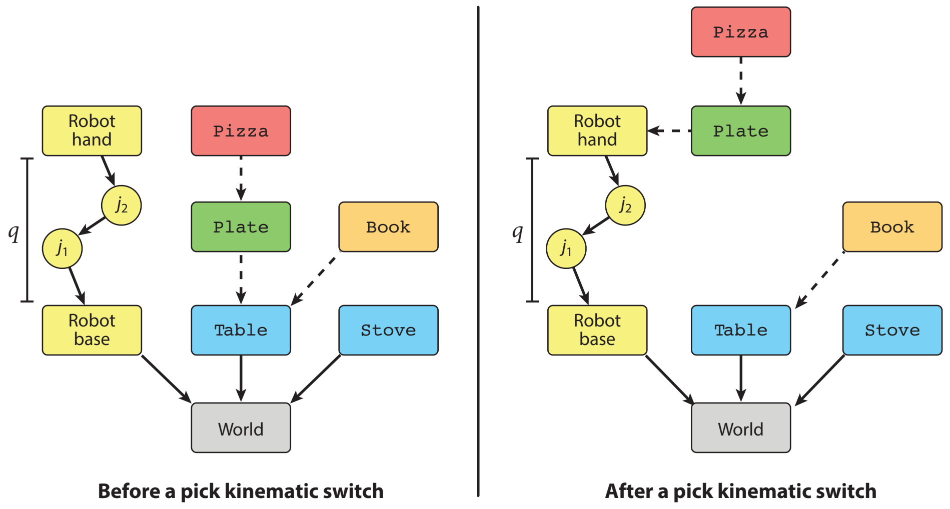

Figure 2

The change to a kinematic tree that results from picking up the `Plate`. Rectangular nodes are bodies, and round nodes are robot joints. Lines encode attachments; solid ones are fixed, and dotted ones may be changed. The robot has two joints (j_1, j_2), whose current state is given by configuration q.

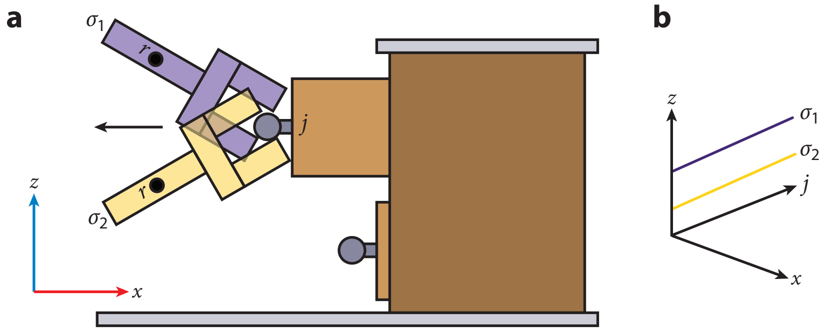

Figure 3

Constrained motion planning for a system in which a gripper pulls a drawer. (*a*) The gripper and the drawer. The pose of the gripper relative to the drawer handle induces the 1D mode constraints σ_1 and σ_2. (*b*) The combined configuration space and the feasible spaces $\mathcal{W}_{F_{\sigma_1}}$ and $\mathcal{W}_{F_{\sigma_2}}$ (*lines*). The modes σ_1 and σ_2 allow the gripper to move along different 1D lines in this 3D space, depending on the grasp of the drawer handle.

picks up the `Plate`, it also transitively picks up the `Pizza`. This change in the kinematic graph is referred to as a kinematic switch, which is a type of mode switch. After the switch, as the manipulator moves, the poses of both the `Plate` and the `Pizza` change with respect to the world; we move through this mode using the same actuators as before, but the feasible configuration space has changed.

2.2.2. Constrained motion planning. When the robot interacts with objects in the world, the effective configuration space is no longer the degrees of freedom of the robot: It corresponds to the state of the whole system, a space we denote as $\mathcal{W}$. This state can be described by the discrete structure encoded in a kinematic graph, as well as continuous values of the transformations on the edges, which encode static relationships. However, these systems are generally underactuated, meaning that they cannot be locally controlled in arbitrary directions, because we can only directly actuate the robot's degrees of freedom. However, we can indirectly manipulate these objects by controlling the robot.

We begin by considering a simple single-mode problem in which the kinematic graph is fixed. **Figure 3*a*** illustrates a robot gripper pulling a drawer, where the gripper pose is fixed relative to the drawer. Although normally the gripper can translate generally in x, z, the drawer has only a single degree of freedom, denoted by joint j. The combined configuration space of the gripper and the drawer is a 3D space with coordinates $\langle x, z, j \rangle$, but they are constrained by the need to keep the gripper attached to the drawer.

In this and many other manipulation problems, the constraint function $F(w)$, which now applies to the whole-world configuration $w \in \mathcal{W}$, includes both the collision-free constraint and a kinematic constraint, which causes $\mathcal{W}_F$, the subspace of $\mathcal{W}$ for which F holds, to be lower dimensional than $\mathcal{W}$. As a result, sampling $\mathcal{W}$ randomly will have zero probability of producing a sample in $\mathcal{W}_F$, rendering standard sampling-based motion planning methods ineffective. This difficulty of sampling motivated the development of constrained motion planners, which explicitly take these constraints into account and plan within the low-dimensional space $\mathcal{W}_F$.

Dimensionality-reducing constraints are often expressed using a mode parameter σ, a fixed value that affects the constraint $F_\sigma(w)$. In general, σ is real valued. Here, we illustrate the effect of two different choices of this value, σ_1 and σ_2. Each stipulates a different rigid attachment pose between the gripper and the drawer handle. **Figure 3*b*** illustrates the combined configuration space and the feasible spaces $\mathcal{W}_{F_{\sigma_1}}$ and $\mathcal{W}_{F_{\sigma_2}}$.

The most general approach for constrained motion planning defines sampling and connecting operations that project values onto the constraint surface. This is typically done by starting at a sampled point $\mathcal{W}$ and performing local descent on the constraint violation until convergence. Because this is a numeric optimization, the constraint will generally never be exactly satisfied, but the samples can get ϵ-close to the surface for any $\epsilon > 0$. Several approaches have provided probabilistically complete methods for constrained motion planning using projection (31, 32) and atlas-based techniques (33–35). Kingston et al. (36, 37) have provided comprehensive surveys of these techniques.

When the kinematic graph is a tree, the planning problem is much easier. The set of pairwise rigidity constraints specifies all poses of objects relative either to the world frame (fixed objects) or to the robot (grasped objects). This collection of poses collectively constitutes a mode σ. We can sample full configurations for the system that exactly satisfy these constraints by simply sampling the robot's degrees of freedom q and performing forward kinematics to derive the full configuration w.

2.2.3. Multimodal motion planning. Constrained motion planning provides a framework for reasoning about systems with many degrees of freedom but few actuators. However, it assumes that the constraints themselves remain constant, and therefore it is not expressive enough to model multistep manipulation problems in which the robot must make and break contact, changing the kinematic graph and thus the active constraints on its motions. To model such problems, we must allow the mode to undergo discrete changes (13, 14, 29, 30). The state of the system is $s = \langle w, \sigma \rangle$, where we can think of $w \in \mathcal{W}$ as the collective configurations of the robot and all other objects or mechanisms in the environment and σ as the additional mode information, indicating, for example, which objects are currently attached to which others. The control theory community analyzes reachability for a similar class of hybrid systems, except that they typically address problems with a finite set of modes but more complex continuous-time dynamics (38–40). For the most common cases of MMMP, we can refactor this representation so that $s = \langle q, K \rangle$, where $q \in \mathcal{Q}$ is the robot configuration and K is a kinematic graph that contains the mode information and implies the poses of all the bodies in the system, but we will make our general presentation in terms of $\langle w, \sigma \rangle$.

More formally, an MMMP problem consists of a finite set $\{\Sigma_1, \ldots, \Sigma_m\}$ of mode families, each of which has a real-valued parameter vector θ. Associated with each mode $\sigma = \Sigma(\theta)$ is a constraint function F_σ on full system configurations. At any given time, the system state $\langle w, \sigma \rangle$ is in a single mode σ, but whenever $w \in F_{\sigma'}$, the system may execute a mode switch, typically represented by a change to the kinematic tree, into mode σ'. The goal of an MMMP is typically a set of full system configurations $\mathcal{W}_*$, and a solution has the form $[\sigma_0, \tau_0, \sigma_1, \tau_1, \ldots, \sigma_k, \tau_k]$, where $s_0 = \langle w_0, \sigma_0 \rangle$ is the initial state of the system, τ_i is a trajectory in F_{σ_i}, $\tau_0(0) = w_0$, $\tau_i(0) = \tau_{i-1}(1)$ for $i \in \{1, \ldots, k\}$, and $\tau_k(1) \in \mathcal{W}_*$.

As an example, we model pick-and-place tasks in this framework. Modes in which the robot is not grasping any objects are transit modes, and modes in which the robot is holding an object are transfer modes (9, 10, 22). For a robot with a single gripper, there is a transit mode family for free motion and a transfer mode family for each object that it can grasp. In the transit mode family, the mode parameter comprises the fixed world poses of every movable object. In the transfer mode family for a particular object, the mode parameter contains the grasp pose as well as the fixed world poses of every other movable object. Thus, although the system can only operate according to a single mode at a time, the mode parameter is high dimensional because it contains constraints involving every movable object. For interactions with cyclic kinematic graphs, such as

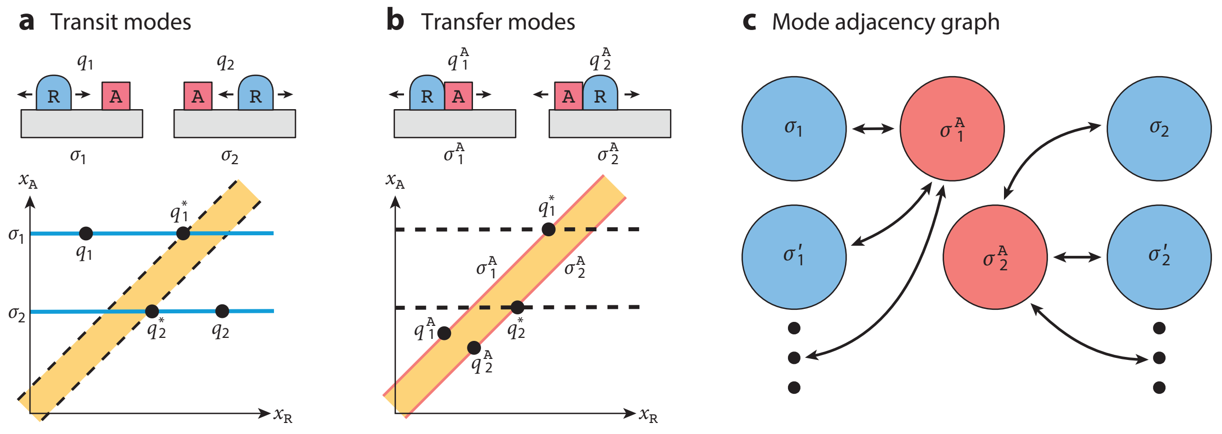

Figure 4

The feasible configuration space for two transit modes (σ_1 and σ_2) and two transfer modes ($\sigma_1^{\mathtt{A}}$ and $\sigma_2^{\mathtt{A}}$). Mode switches $\sigma_1 \leftrightarrow \sigma_2^{\mathtt{A}}$ occur at configuration q_1^*, and mode switches $\sigma_2 \leftrightarrow \sigma_2^{\mathtt{A}}$ occur at configuration q_2^*. (*a*) The robot moving during a transit mode. The two 1D blue lines indicate the space for which the system can change, which depends on the current mode σ_1 or σ_2; these modes correspond to different placements of the movable object, which remains constant. The yellow region corresponds to infeasible states where the robot and the object are in collision. Because the object can be placed anywhere on the interval, there are infinitely many possible transit modes. (*b*) The robot and object moving during a transfer mode. Because the robot can attach itself to either the left or right side of the object, there are two possible transfer modes, $\sigma_1^{\mathtt{A}}$ and $\sigma_2^{\mathtt{A}}$, indicated by the 1D red lines. The relative pose between the robot and object remains constant during a transfer mode, and the robot can switch between transit and transfer modes at a 0D (point) intersection between both lines (configurations q_1^*, q_2^*). (*c*) Legal mode transitions as a directed graph. The transit modes $\{\sigma_1, \sigma_1', \ldots\}$ correspond to the robot being on the left of the object, whereas the transit modes $\{\sigma_2, \sigma_2', \ldots\}$ correspond to the robot being on the right of the object. To switch to a new transit mode, the robot must first enter the appropriate transfer mode. Note that the graph is disconnected because the robot is unable to move to the other side of the object.

manipulating a drawer or opening a door, a constrained motion planner (Section 2.2.2) is generally required in order to plan within the mode.

A key challenge in multimodal motion planning is identifying configurations that are in the intersection of the constraint sets for two modes and thus allow the system to switch between them. This intersection is often lower dimensional than the feasible space Q_{F_σ} of either mode. In a pick-and-place domain, in order to perform a kinematic switch between a transit and transfer mode, the robot's gripper must be in contact with the involved object at a particular pose. This requirement imposes six constraints on the robot's configuration, and as a result, the set of solutions is $(d-6)$-dimensional. Fortunately, solutions can often be found using inverse kinematics, either by projecting random samples into the constraint set using optimization (41) or by analytically solving for the solutions to a reparameterized set that captures its underlying dimensionality (42). **Figure 4** illustrates a 1D robot (`R`) acting in the presence of a single movable object (`A`).

2.3. Task Planning

Within the AI community, there has been a long-standing focus on planning in discrete domains, generally with very large state spaces, which are made tractable by using representations and algorithms that exploit underlying regularities in the structure of the domain. Ghallab et al. (15) provided a comprehensive discussion of task planning from the AI perspective, and Karpas & Magazzeni (43) surveyed task planning for robotics.

The simplest formalization of AI planning is to specify a set of states (state space) $\mathcal{S}$, a set of transitions $\mathcal{T} \subseteq \mathcal{S} \times \mathcal{S}$ that describe legal changes to the state, an initial state $s_0 \in \mathcal{S}$, and a set of goal states $\mathcal{S}_* \subseteq \mathcal{S}$. Each directed transition $t = \langle s, s' \rangle \in \mathcal{T}$ moves the system from state s to state s'.

The objective for a planner is to find a plan π, a sequence of transitions, that advances the initial state s_0 into a goal state $s_* \in S_*$. This problem can be reduced to a graph traversal problem, where the vertices are states and directed edges are transitions, and solved using standard graph-search algorithms. However, the state spaces considered are very large, so it is critical to use a functional representation of $\mathcal{T}$ to reveal states incrementally—for example, by working forward from the initial state.

The first step toward compact representations and efficient algorithms is to factor the state representation into a collection of state variables. More formally, states can be represented using a set of variables $\mathcal{V} = \{1, \dots, m\}$, each of which has a finite domain $\mathcal{X}_v$. States are assignments of values $x_v \in \mathcal{X}_v$ for variables $v \in \mathcal{V}$. This induces a state space $\mathcal{S} = \mathcal{X}_1 \times \cdots \times \mathcal{X}_m$ that is the Cartesian product of each variable's domain. Consider a variation on the example in **Figure 2**, involving a single robot, a movable pizza, and a movable book. Each state specifies the locations of the robot, the pizza, the book, and the object that the robot is holding (or `None`), as well as whether the pizza has been cooked. The set of possible locations consists of `Box`, `Plate`, `Table`, and `Oven`. The robot can move between any pair of locations, pick up an object at the robot's current location if it is not holding anything, and place an object at the robot's current location. We can describe a state as an assignment of values to the variables `atRob` (four possible values), `at[Pizza]` (five domain values), `at[Book]` (five domain values), `holding` (three domain values), and `cooked[Pizza]` (two domain values). A state in this domain can then be defined as

{`atRob=Plate`, `holding=None`, `at[Book]=Table`, `at[Pizza]=Box`, `cooked[Pizza]=False`}.

Although in total the variables have 19 possible values, there are 600 possible states resulting from the possible combinations of variable values. Generally, the size of the state space grows exponentially with the number of variables.

Next, we need to encode the set of transitions compactly. In many domains, due to locality of effect or other underlying domain properties, transitions change the value of only a small number of the state variables at a time, which allows us to describe large sets of transitions compactly using a single action that encodes the difference between the two states. These changes can be described by a set of effects `eff:` $\{v_1 \leftarrow c_1, \dots, v_k \leftarrow c_k\}$ that list the variables that are modified $(v_1, \dots, v_k)$ and their resulting values $(c_1, \dots, c_k)$. This set of effects describes a large set of state pairs in the transition: one corresponding to each possible assignment to the values of the unchanged variables.

Another structural property of many domains, which can be used to more compactly express legal transitions, is that each action may be correctly executed only in certain states. For example, a `pick` action cannot be performed if the robot is already holding an object. We can express this by specifying, for each action, a set of preconditions `pre:` $\{x_{v_1}{=}c_1, \dots, x_{v_k}{=}c_k\}$ that describe the set of states in which that action can be executed in terms of values of some of the state variables.

One final important structural property is an object-centric abstraction: In most problems, the state variables correspond to properties of objects in the domain (e.g., the location or color of a particular cup) or relations among them (e.g., whether a particular cup is inside a particular box). We can describe the possible actions of a domain generically, via templates that are parameterized by a choice of particular objects that are present in a domain instance. This form of abstraction allows the size of the domain description to be independent of the number of state variables in the domain.

We illustrate the basic principles of task planning via an example in **Figure 5**, which specifies the preconditions and effects of the `moveF`, `moveH`, `pick`, `place`, and `cook` actions. This specification needs to be coupled with a listing of the actual entities in any domain instance, such as the names of objects (`Pizza` and `Book`) and locations (`Box`, `Plate`, `Oven`, and `Table`), to yield a complete transition-system specification. The state variables are then `holding` and `atRob`, along with

```
moveF[loc1,loc2]
 pre: atRob=loc1
  eff: atRob←loc2
moveH[loc1,loc2]
 pre: atRob=loc1, holding=obj
  eff: atRob←loc2
pick[obj,loc]
 pre: atRob=loc, holding=None, at[obj]=loc
  eff: at[obj]←None, holding←obj
place[obj,loc]
 pre: atRob=loc, holding=obj
  eff: at[obj]←loc, holding←None
cook[obj]
 pre: at[obj]=Stove
  eff: cooked[obj]←True
```

Figure 5

A template specification of the `moveF`, `moveH`, `pick`, `place`, and `cook` actions.

`cooked[obj]` and `at[obj]` for each actual object name `obj`. Similarly, the actual possible actions are generated by substituting all combinations of object and location constants for the template variables. For example, with two objects and four locations, there are eight instances of the `place` action.

To clarify the use of template variables, note the `pick` action description: This is a template describing a finite number of action instances, one for each discrete value of `obj` and `loc`. But note that these two variables play different roles. As the number of possible values of `obj` increases, the dimensionality of the state of the problem (characterized by the number of state variables) increases; as the number of possible values of `loc` increases, the domain of discourses of the `at[obj]` variables increases, but the number of variables does not.

The final component of a planning problem is a description of the set of goal states, which has the same form as an action precondition, as a conjunction of values of some state variables, where all unmentioned state variables may have any arbitrary value. For example, the following goal description encodes the entire set of states in which the pizza is cooked and on the plate: {`at[Pizza]=Plate`, `cooked[Pizza]=True`}. The solution to a task planning problem is a sequence of action instances $a_1, \dots, a_k$, which induces a state sequence $s_0, \dots, s_k$, where each s_i is a state expressed as an assignment of values to state variables, s_0 is the initial state of the planning problem, s_i satisfies the preconditions of a_{i+1}, s_{i+1} is the result of executing a_i in s_i, and s_k satisfies the goal conditions.

To finish our example, let the initial state be

s_0={`holding=None,atRob=Table,at[Pizza]=Box,at[Book]=Table,cooked[Pizza]=False`}.

Solving this task requires first placing the pizza in the oven to cook it and then relocating it to the plate:

$$\pi = [\texttt{moveF[Table,Box],pick[Pizza],moveH[Box,Oven],place[Pizza],}$$
$$\texttt{cook[Pizza],pick[Pizza],moveH[Oven,Plate],place[Pizza]}].$$

One focus of AI planning has been to define languages for specifying planning problems. The one shown in **Figure 5** is similar to a lifted version of simplified action specification (SAS$^+$) (44). The most widely-used formalism is PDDL (Planning Domain Definition Language) (45), which can be seen as a transition system where state variables are Boolean facts. The AI planning community has developed domain-independent algorithms that can operate on any problem written in a planning language, without any additional information about the problem. A factored planning representation enables efficient heuristic search algorithms that estimate the distance to a goal state by solving relaxed problems (simplified versions of the original problem).

Finally, there are several extensions to the basic task planning formalism (46–48) that are relevant to TAMP. One of these is numeric planning, which involves planning with real-valued variables such as time, fuel, or battery charge. Recent approaches support planning with convex dynamics (49) and nonconvex dynamics by discretizing time (50). Although these methods have many use cases, they currently cannot be directly applied to most TAMP problems because they assume the set of actions is finite.

3. TASK AND MOTION PLANNING

To find solutions to TAMP problems, we need to integrate aspects of motion planning, MMMP, and task planning. In this section, we introduce a framework for describing TAMP problems and algorithms that allows us to describe most of the broad range of existing methods within a unified framework, which we hope elucidates the modeling and algorithmic trade-offs among them. We begin by providing a formalism for describing TAMP problems, then characterize solution methods in terms of their strategies for sequencing actions, selecting their continuous parameters, and integrating these methods.

3.1. Task and Motion Planning Problem Description

Informally, TAMP problems use compact representational strategies from task planning to describe and extend a class of MMMP problems. TAMP is an extension of MMMP in that there may be additional state variables that are not geometric or kinematic, such as whether the lights are on or the pizza is cooked. We begin by articulating a generic MMMP, using an extension of a task planning formulation, in **Figure 6**. There are two extensions of the task planning formalism visible here. First, there are continuous action parameters. Second, in addition to preconditions and effects, we have a new type of clause, called `con`, for constraint. This clause is a set of constraints that all must hold true among the continuous parameters of the action in order for it to be a legal specification of a transition of the system.

This formulation does not extend to the basic formulation of MMMP, but it provides a clear articulation of the overall system dynamics. In a domain with a large number of objects, there will be a large number of mode families, each of which requires specifying a constraint on a very-high-dimensional world configuration space. What TAMP adds is the ability to unpack the entities in the problem description into subparts that are simpler to describe and that reveal substructure in

```
moveWithin[i]($\theta$,$w$,$\tau$,$w'$)
 con: $\tau$(0)=$w$, $\tau$(1)=$w'$, ($\forall t \in$[0,1]$F_{\Sigma_i(\theta)}$($\tau$($t$)))
 pre: mode=$\Sigma_i$($\theta$), conf=$w$
  eff: conf$\leftarrow w'$
switchModes[i,j]($w$,$\theta$,$\theta'$)
 con: $F_{\Sigma_i(\theta_1)}$($w$), $F_{\Sigma_j(\theta_2)}$($w$)
 pre: mode=$\Sigma_i$($\theta_1$), conf=$w$
  eff: mode$\leftarrow\Sigma_j$($\theta_2$)
```

Figure 6

A formalization of multimodal motion planning in the style of task planning. There is a `moveWithin` action for each mode family Σ_i and a `switchModes` action for each mode family pair Σ_i, Σ_j.

```
moveF($q$,$\tau$,$q'$,$p^A$,...,$p^E$)
 con: Motion($q$,$\tau$,$q'$), CFreeW($\tau$), CFreeA($p^A$,$\tau$), ..., CFreeE($p^E$,$\tau$)
 pre: holding=None, atRob=$q$, atA=$p^A$, ..., atE=$p^E$
  eff: atRob$\leftarrow$$q'$
moveH[obj]($g$,$q$,$\tau$,$q'$,$p^A$,...,$p^E$)
 con: Motion($q$,$\tau$,$q'$), CFreeW[obj]($g$,$\tau$),
      CFreeA[obj]($p^A$,$g$,$\tau$), ..., CFreeE[obj]($p^E$,$g$,$\tau$)
 pre: holding=obj, at[obj]=$g$, atRob=$q$, atA=$p^A$, ..., atE=$p^E$
  eff: atRob$\leftarrow$$q'$
pick[obj]($q$,$p$,$g$)
 con: Stable[obj]($p$), Grasp[obj]($g$), Kin[obj]($q$,$p$,$g$)
 pre: holding=None, atRob=$q$, at[obj]=$p$
  eff: holding$\leftarrow$obj, at[obj]$\leftarrow$$g$
place[obj]($q$,$p$,$g$)
 con: Stable[obj]($p$), Grasp[obj]($g$), Kin[obj]($q$,$p$,$g$)
 pre: holding=obj, atRob=$q$, at[obj]=$g$
  eff: holding$\leftarrow$None, at[obj]$\leftarrow$$p$
cook[obj]($p$)
 con: Stable[obj]($p$), OnStove[obj]($p$)
 pre: at[obj]=$p$
  eff: cooked[obj]$\leftarrow$True
```

Figure 7

One formalization of task and motion planning for an environment that contains the movable objects A, B, C, D, and E. Actions now have real-valued parameters and constraints on these parameters.

the problem that enables algorithmic insights. We will illustrate this process in a TAMP generalization of the cooking domain from Section 2.3 using one particular formalization style, shown in **Figure 7**.

Consider an example that has five movable objects, A through E. We decompose the system configuration w into state variables `atRob`, `holding`, `at[A]`, `at[B]`, `at[C]`, `at[D]`, and `at[E]`. The discrete state variable `holding` can take values ranging over {None, A, B, C, D, E} and specifies the current mode family Σ. The variable `atRob` is now a robot configuration, and `at[obj]` is the pose of object `obj` relative to either the world coordinate frame (when `holding` $\neq$ `obj`) or the robot hand coordinate frame (when `holding` $=$ `obj`).

The `moveF` (move while the gripper is free) and `moveH` (move while the gripper is holding) actions describe transit and transfer motion within modes. The `pick` action corresponds to a switch from a transit mode to a transfer mode, while the `place` action corresponds to a switch from a transfer mode to a transit mode.

The sparsity of effect of planning action descriptions is a good match for articulating which state variables are changed (and, implicitly, which ones stay the same). We can see that, in each action description, the **`eff:`** clause indicates only the variables that change. When the preconditions involve discrete constant values (such as None), they are being used to specify the mode family of the initial state of the transition. The advantage of being able to use templates is apparent: The `moveH` action has a template parameter `obj`, meaning that there is a mode family for each object being held.

Just as we have decomposed the configuration and the mode, we can decompose constraints, expressing them as conjunctions of constraints with smaller arity. For example, the `pick` action has the constraint `Kin[obj]`(q, p, g). For any particular value of `obj`, representing an actual object in the domain, this represents a kinematic constraint, saying that if the robot is in configuration q and holding object `obj` in grasp g, then `obj` will be at pose p. In `moveF` and `moveH`, the `Motion`(q, τ, q')

constraint specifies the relationship between a trajectory τ and two robot configurations, asserting that $\tau(0) = q$, $\tau(1) = q'$, and τ is continuous. Notice that the trajectory τ appears in neither the preconditions nor the effects of these actions; they are auxiliary parameters that describe motion within the modes. The `Stable[obj]`(p) constraint requires that p be a pose representing a stable placement for object `obj` on a static object in the world. Similarly, the `OnStove[obj]`(p) constraint requires that p be a stable placement where `obj` is specifically on a stove. The `Grasp[obj]`(g) constraint defines stable grasp poses (transforms between the hand frame and object frame) g for object `obj`. This set may be finite if there are only a few known grasps but could be uncountably infinite in general. The collision-free constraint `CFreeA[obj]`(p, g, τ) asserts that if object `A` is at pose p, the robot is holding `obj` in grasp g, and it executes trajectory τ, no collision will occur. The constraint `CFreeW[obj]`(g, τ) is defined similarly except that it involves the fixed objects in the world (indicated by the abbreviation `W`). Finally, although not pictured, because the $p^{\mathtt{A}}, \ldots, p^{\mathtt{E}}$ parameters in the `moveF` and `moveH` actions are each mentioned only in a single constraint and precondition, they can be compiled away using state constraints (51) or inference rules (axioms) (52), resulting in these action templates being independent of the number of objects in the problem instance.

In preparation for studying algorithms for solving TAMP problems, it is useful to examine the form of a solution, which is a finite sequence of action instances $\pi = [a_1, \ldots, a_k]$, where each a_i includes assigned values for all parameters that satisfy that action's constraints. These actions induce a state sequence $[s_0, s_1, \ldots, s_k]$, where each s_i is a state expressed as an assignment of values to state variables, s_0 is the initial state of the problem, s_{i-1} satisfies the preconditions of a_i, s_i is the result of executing a_i in s_{i-1}, and s_k satisfies the goal conditions. Selecting the action templates and values for the template variables specifies the form of a solution, which we call a plan skeleton. If the skeleton is fixed, then the set of variables for which values must be selected is determined, and the problem that remains is one of selecting those values so that the constraints of the actions in the skeleton are satisfied.

Consider a TAMP problem with a single movable object `A`. Suppose the initial state is $s_0 =$ {`atRob`=$\mathbf{q_0}$, `at[A]`=$\mathbf{p_0}$, `holding=None`, `cooked[A]=False`}, where the bold mathematical symbols $\mathbf{q_0}$ and $\mathbf{p_0}$ are real-valued constants. The set of goal states can be defined using conditions and constraints, such as `cooked[A]=True`. One possible plan skeleton is

$$\pi = [\texttt{moveF}(\mathbf{q_0}, \tau_1, q_1), \texttt{pick[A]}(q_1, \mathbf{p_0}, g_2), \\ \texttt{moveH[A]}(q_1, \tau_3, q_3), \texttt{place[A]}(q_3, p_4, g_2), \texttt{cook[A]}(p_4)], \quad 1.$$

where $q_1, \tau_1, g_2, q_3, \tau_3$, and p_4 are the free parameters. Plan skeletons can be visualized graphically by enumerating the sequence of $|\pi| + 1$ values of each state variable, as well as the motion parameters τ_1 and τ_3, and associating the constraints of the ith action with the appropriate $i - 1$ and i state variables. **Figure 8** illustrates this plan skeleton in the form of a dynamic factor graph (53).

3.2. Hybrid Constraint Satisfaction

Finding an assignment of values to the parameters of a plan skeleton that satisfies the associated constraints is a hybrid constraint satisfaction problem (H-CSP). Although many parameters are inherently continuous, some may have discrete domains. For example, there might be a finite set of stable resting surfaces for a particular object. **Figure 9** compresses the plan skeleton in **Figure 8** into a constraint network (a bipartite graph from parameters to constraints) by removing redundant constraints, constants, and parameters (54). Although TAMP is decidable via computational-geometry algorithms, just as in motion planning, most practical approaches use optimization or

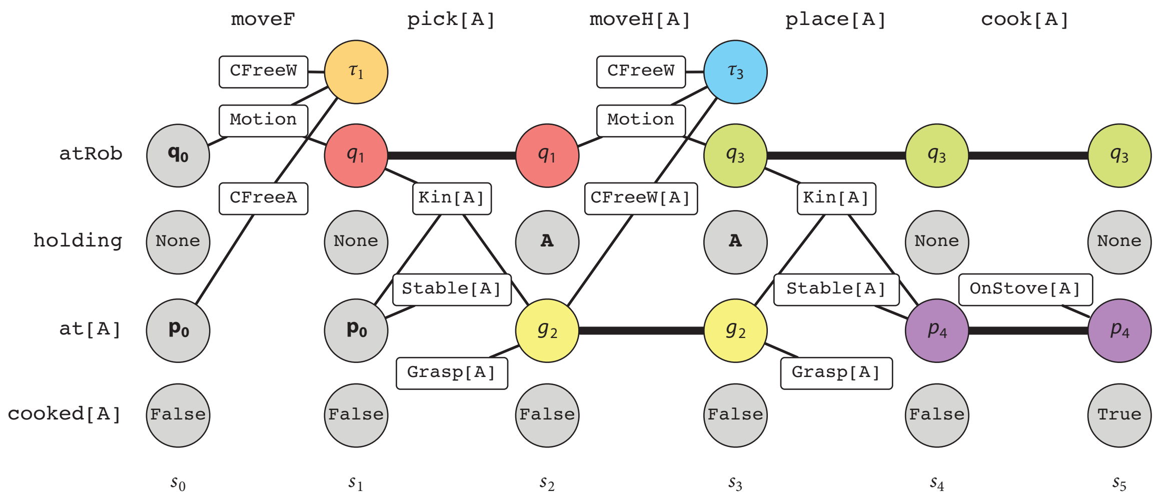

Figure 8

The plan skeleton from Equation 1. Round nodes represent state variables, and rectangular nodes represent constraints. Gray nodes have constant values, and colored nodes represent variables. Thick black lines display equality constraints that persist over time. Each vertical column corresponds to a state; the actions in the skeleton, which are responsible for the state changes, are shown between the state columns, at the top. Multiple nodes of the same color represent a single variable that is constrained to maintain its current value across multiple steps of the plan. Each constraint is connected to the variables it constrains. Any assignment of values to the variables that satisfies all the constraints fills out the skeleton into a complete legal plan that is guaranteed to achieve the goal; however, it may be the case that no satisfying assignment exists.

sampling to solve the underlying H-CSPs. Another dimension of variability in solution approaches is whether the method attempts to satisfy the entire constraint set at once: Methods vary dramatically in their high-level control structure for handling the search over skeletons and parameter values, and they make different demands on constraint satisfaction methods.

3.2.1. Joint satisfaction. The most straightforward strategy for approaching an H-CSP is to reduce it to a constrained mathematical program and solve for the values for all the free parameters at once. Although there is a vast literature on mathematical programming, solving programs corresponding to TAMP H-CSPs is often very difficult due to the high dimensionality in continuous parameter space, the inclusion of discrete parameters, and the nonconvexity of the constraints. Although there is no efficient, general solution method for these mathematical programs, there are some approaches of practical value.

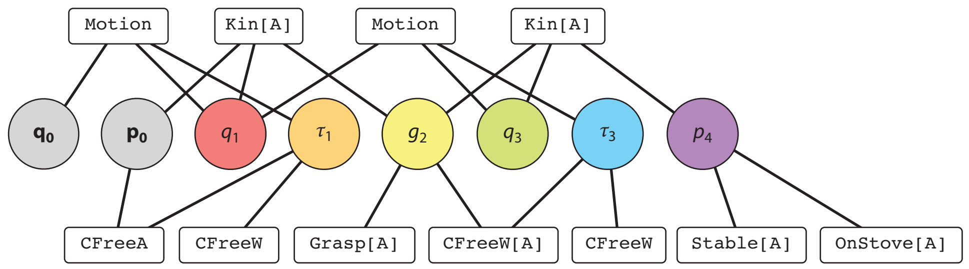

Figure 9

The constraint network for the plan skeleton in **Figure 8**.

When all decision variables are real valued, a common solution strategy is to minimize an objective function, which incorporates both the hard constraint violation and any soft action cost penalties, using local-descent methods, though these are guaranteed to reach only a local optimum of the objective function, which may not satisfy the constraints. The following mathematical program corresponds to the constraint network in **Figure 9**:

$$\begin{aligned}
\underset{q_1,\tau_1,g_2,q_3,\tau_3,p_4}{\text{minimize}} \quad & \sum_{t=1}^{T} f_{\texttt{moveF}}(\tau_1[t],\tau_1[t-1]) + \sum_{t=1}^{T} f_{\texttt{moveH[A]}}(g_1,\tau_3[t],\tau_3[t-1]) \\
\text{subject to} \quad & g_{\texttt{Grasp[A]}}(g_1)=0,\ g_{\texttt{Stable[A]}}(p_4)=0,\ h_{\texttt{OnStove[A]}}(p_4)\leq 0 \\
& g_{\texttt{Kin[A]}}(q_1,\mathbf{p_0},g_2)=0,\ g_{\texttt{Kin[A]}}(q_3,p_4,g_1)=0 \\
& h_{\texttt{Motion}}(\tau_1[t],\tau_1[t-1])\leq 0,\ h_{\texttt{Motion}}(\tau_3[t],\tau_3[t-1])\leq 0 && \text{for } t\in[T] \\
& h_{\texttt{CFreeW}}(\tau_1[t])\leq 0,\ h_{\texttt{CFreeA}}(\mathbf{p_0},\tau_1[t])\leq 0 && \text{for } t\in[T] \\
& h_{\texttt{CFreeW}}(\tau_3[t])\leq 0,\ h_{\texttt{CFreeW[A]}}(g_1,\tau_3[t])\leq 0 && \text{for } t\in[T] \\
& \tau_1[0]=\mathbf{q_0},\ \tau_1[T]=\tau_3[0]=q_1,\ \tau_3[T]=q_3.
\end{aligned} \qquad 2.$$

The trajectories τ_1 and τ_3 are approximated as a sequence of robot configurations $\tau[0], \tau[1], \ldots, \tau[T]$, where T is a hyperparameter. Each constraint is associated with a real-valued (and often once- or twice-differentiable) function, which is expressed in either an equality [$g(\ldots)$] or inequality [$h(\ldots)$] constraint for the mathematical program. Although it is not a focus of this survey, optimization can also fluidly incorporate action costs, enabling it to identify a solution that is not only feasible but also low cost. For example, Equation 2 minimizes the combined cost of moving through a `moveF` mode [$f_{\texttt{moveF}}(\ldots)$] and a `moveH[A]` mode [$f_{\texttt{moveH[A]}}(\ldots)$], each of which is the sum of a function defined on adjacent configurations that comprise the trajectory parameter τ_1 or τ_3. More generally, mixed-integer programming techniques are required. One prominent algorithm for solving mixed-integer programs is branch-and-bound, which performs a discrete search over assignments to the integer variables; then, conditioned on an assignment for each integer variable, the resulting mathematical program is real valued and can be addressed by descent.

3.2.2. Individual satisfaction. An alternative approach to solving H-CSPs is to generate small groups of parameter values that satisfy a single constraint or a small set of constraints and then combine them. A sampler takes one or more constraints and generates a sequence of assignments of values to the free parameters, where each assignment that is generated is guaranteed to satisfy the constraints.

A challenge when designing samplers is dealing with constraints whose set of satisfying values has lower dimension than the combined domains of the free parameters. For example, the `Stable[obj]`(p) constraint requires object `obj` to rest perpendicular to a 2D plane within a 3D pose space, so this constraint lies in SE(2) despite the set of object poses being in SE(3). The rejection-sampling strategy of sampling at random from a bounded region of SE(3) will have zero probability of producing a value satisfying this constraint. However, samples can be produced by directly sampling `Stable` rather than SE(3). Low-dimensional constraints remain problematic when attempting to produce values that also satisfy other constraints. For example, consider solving for values of q, p, and g that satisfy both `Stable[obj]`(p) and `Kin[obj]`(q, p, g). Here, the difficulty is finding a pose p that satisfies `Stable` while also admitting values of q and g that satisfy `Kin`. One solution is to explicitly design samplers that operate on larger collections of constraints; this approach generally reduces to the joint satisfaction approach (Section 3.2.1).

Alternatively, one can design conditional samplers that take in input values for some of the parameters in the constraint(s) and produce satisfying output values for the rest of the parameters. Intuitively, these samplers consume values already known to satisfy some constraints and find completing values that are compatible for additional constraints. In the above example, a conditional

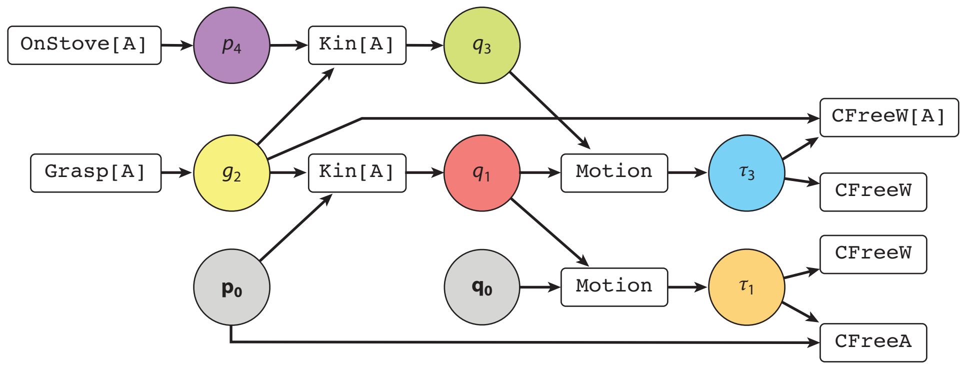

Figure 10

A sampling network for the constraint network in **Figure 9**.

sampler for `Kin[obj]` that takes in p and g as inputs can consume a placement pose sampled by `Stable[obj]` and produce configurations q by finding inverse kinematics solutions. In the event that no such solution exists, the conditional sampler returns an empty sequence, effectively rejecting the input values. Boolean tests for a constraint can also be represented within this framework as degenerate samplers that perform a check on the input values but do not generate any output values. For example, the collision-free constraints `CFreeW`, `CFreeA`, and `CFreeW[A]` can be evaluated by querying a collision checker. In some applications, it may be beneficial to specify several conditional samplers for an individual constraint, which represent different partitions into input and output parameters. For example, an alternative sampler for `Kin[obj]` takes in q and g and performs forward kinematics to produce a pose for `obj` that satisfies the constraint.

More generally, several conditional samplers can be composed to form a sampling network (55), a directed acyclic graph defined on free parameters and conditional samplers. A directed edge from a parameter to a sampler indicates that the parameter is an input to the sampler. A directed edge from a sampler to a parameter indicates that the parameter is an output of the sampler. Each parameter is required to be the output of exactly one sampler. This process is similar in spirit to converting a factor graph (constraint network) into a directed acyclic Bayesian network (53). **Figure 10** gives an example sampling network for the factor graph in **Figure 9**.

3.2.3. Comparison.

There are trade-offs involved in satisfying constraints individually as opposed to satisfying them jointly. Individual satisfaction allows particular constraint types to be addressed using a special-purpose procedure that is well equipped for that constraint and provides a framework for modularly combining them. For example, efficient algorithms for inverse kinematics and motion planning can be used to generate robot configurations and trajectories, respectively. Often, values generated in an attempt to satisfy one H-CSP can be reused in other, related H-CSPs. In fact, values can even be usefully generated without a particular H-CSP in mind, as shown in Section 3.3.2.

When jointly solving the complete set of constraints for a plan skeleton, only a single solution is required because, by construction, it has satisfied all relevant constraints. In comparison, when constructing samplers and conditional samplers, it is important that they, in the limit as the number of samples goes to infinity, cover the complete space of feasible solutions, because some samples may be ruled out by other constraints in the problem. Another advantage of joint satisfaction is that constraints on one parameter can transitively influence the selection of values for other parameters, directing the search. Many methods for joint satisfaction require the constraints to be made available in analytic form, enabling fast and accurate computation of derivatives used in descent methods. However, some constraints, such as collision constraints, are difficult to define in a differentiable form. In such cases, sampling, which only requires black-box access to the constraint for use in rejection sampling, can be a more effective strategy, although its success is strongly dependent on the volume of solutions within the sampled space.

Finally, although we contrast these techniques, one can integrate both strategies. For example, an algorithm could use individual sampling to generate values that satisfy `Stable[A]`, `Grasp[A]`, and `Kin[A]` but use joint satisfaction to solve for trajectories τ that satisfy `Motion`, `CFreeW`, `CFreeA`, and `CFreeW[A]`.

3.3. Combining Action Sequence and Parameter Search

We now have the tools to search for action sequences (Section 2.3) and to solve H-CSPs (Section 3.2). In this section, we discuss strategies for combining them into integrated TAMP algorithms. We would like to order the decision-making in a way that minimizes the overall runtime of the algorithm for a problem distribution. There are several intuitive principles for organizing the search, which sometimes conflict with one another. One way to reduce search effort is to prune infeasible decision branches as quickly as possible [sometimes called failing fast (56)]. We would also prefer to postpone expensive computations until most of the rest of a potential solution has been found. For example, in many manipulation applications, collision checking is expensive, due to the geometric complexity of 3D meshes and the need to check at a fine resolution to ensure safety, so we might wish to lazily postpone this operation (57, 58). At the same time, we would like to balance the computational effort spent on each component—for example, by not spending too much time trying to satisfy the H-CSP associated with a single skeleton or even a single constraint, in case it is unsatisfiable. Additionally, information gained in one branch of a high-level search, such as the solution or infeasibility of a subproblem, can often be reused to make another branch of the search more efficient.

We begin by focusing on the overall control flow of TAMP algorithms, which determines the relative ordering of action sequencing and H-CSP solving. There are three predominant classes of strategies: sequence before satisfy, in which we find whole plan skeletons and then try to satisfy all of their constraints; satisfy before sequence, in which we find sets of satisfying assignments for individual constraints and attempt to assemble actions that use those values into complete plans; and interleaved, in which actions are added to the plan and additional constraints are satisfied incrementally. We conclude by addressing an important aspect of making these approaches efficient, which is to take advantage of previous subproblem assignments or failures, in order to avoid readdressing related subproblems. **Figure 11** illustrates the first two classes of TAMP strategies as flowcharts.

Throughout the discussion of control structures, it is important to remember that sampling and optimization techniques are typically only semicomplete, in that they are not able to certify that a problem instance is infeasible—they simply fail to find a solution in the time available to them. Even for feasible H-CSPs, these algorithms may need to run for an extremely long time if, for example, a feasible problem admits only a tiny volume of solutions. Handling this is complicated by the fact that we might be forced to consider a possibly unbounded number of H-CSPs simultaneously. To simplify the discussion, we can think about this process happening nondeterministically, where intuitively a separate thread is created for each H-CSP. We can always simulate

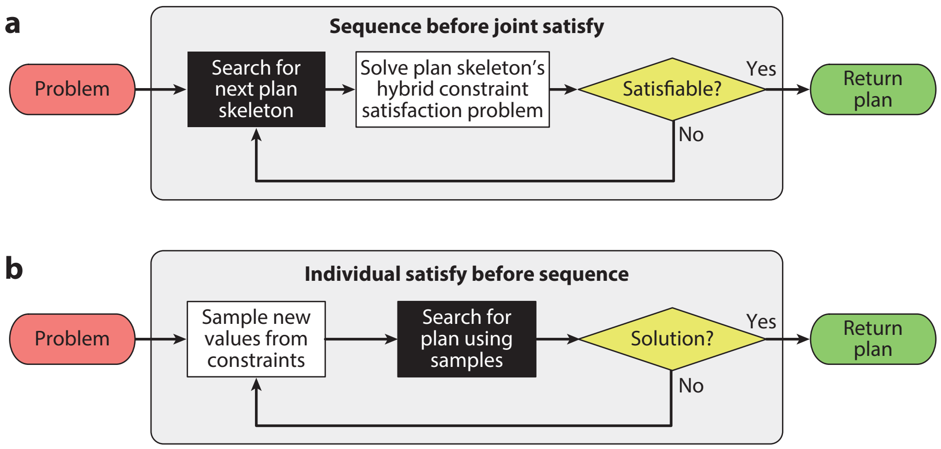
a
Sequence before joint satisfy
Problem
Search for next plan skeleton
Solve plan skeleton's hybrid constraint satisfaction problem
Satisfiable?
Yes
No
Return plan
b
Individual satisfy before sequence
Problem
Sample new values from constraints
Search for plan using samples
Solution?
Yes
No
Return plan

Figure 11

Flowcharts for two representative task and motion planning algorithms. (*a*) An algorithm that iteratively searches in the space of unbound plans and jointly satisfies the set of constraints (Section 3.3.1). (*b*) An algorithm that iteratively performs individual sampling before searching in the space of fully bound plans (Section 3.3.2).

this behavior in a single process by appropriately revisiting the threads, making sure that none are starved.

3.3.1. Sequencing first. The earliest algorithms for TAMP committed to a strict hierarchy of first finding an action sequence and then finding continuous parameter values. For example, Shakey the robot (3) performed STRIPS (Stanford Research Institute Problem Solver) planning over high-level abstract actions, such as which room to move to, and then planned low-level motions that realized the high-level plan, with no mechanism for finding an alternative high-level plan if the lower-level motions were not possible. Shakey therefore aggressively assumed that problems satisfy the downward refinement property. More formally, a two-level hierarchy satisfies the downward refinement property if every solution to the high level can be refined into a solution at the low level (59). When this property holds, problems can be completely disentangled into separate task planning and motion planning problems, so an algorithm that strictly determines a plan skeleton based on values of discrete template arguments before solving the associated constraint-satisfaction problem is complete. In TAMP problems in practice, downward refinement rarely holds. As soon as geometric or kinematic considerations make some high-level plans infeasible (because, for example, three objects do not actually fit into the box we planned to put them in, or the grasp needed to remove an object from a shelf will not work to place it on the stove and there is no surface available to use for regrasping), we cannot inflexibly commit to any abstract plan without knowing its geometric and kinematic feasibility.

However, even when downward refinement does not hold, a top-down problem decomposition can be very effective, as long as there is a mechanism for backtracking and trying alternative high-level plans when the lower-level solver fails (55, 60, 61). **Figure 11*a*** illustrates this approach, in which there is an outer loop representing a search over legal plan skeletons. For each plan skeleton, we attempt to solve the associated H-CSP; if we succeed, we return the complete solution, and if not, we return to the outer loop and try another skeleton. In many everyday TAMP applications, action sequencing is relatively inexpensive, making it advantageous to find a plausible action sequence before satisfying constraints. Furthermore, solving H-CSPs can be computationally expensive, so by only attempting to solve H-CSPs that correspond to viable plan skeletons, we can potentially save substantial computation time.

3.3.2. Satisfaction first. An alternative strategy is motivated by the fact that task planning in finite domains can often be highly efficient even in very large problem instances, and this strategy therefore seeks to reduce the hybrid problem of TAMP to one or more discretized planning problems by generating values of continuous quantities, such as poses and configurations, and computing in advance which constraints they satisfy (14, 21, 22, 55). For example, one might sample, for an environment with some fixed support surfaces, a set of values p_i such that `Stable[A]`(p_i) holds. Approaches that perform satisfaction first almost always use individual satisfaction (Section 3.2.2), which is typically implemented using sampling because these approaches aim to generate values that are useful for a variety of plan skeletons. A single round of sampling will generally not suffice. When the discrete planning problem given a particular set of values is infeasible, it is necessary to generate more samples and try again, as illustrated in **Figure 11*b***.

Satisfying before sequencing is advantageous when the computational effort of repeatedly sequencing and failing to satisfy the associated H-CSP outweighs the computational effort of eagerly generating values that satisfy constraints up front. This often is the case when one or more of the following are true: (*a*) Sampling is efficient and does not result in a combinatorial explosion of sampled values, (*b*) each discrete action sequencing search has nonnegligible overhead, and (*c*) sampled values are unlikely to satisfy critical constraints.

3.3.3. Interleaved. There are many ways to interleave the searches for the action sequence and parameter values. In some cases, we would like to presample state variable values, such as robot configurations and object poses, but defer the computation of motion parameter values, such as collision-free trajectories between two robot configurations. In this case, the domains of the state variables have already been discretized. Conditioned on an assignment of values to every nonmotion parameter (state variable) for an action instance, each motion parameter is affected only by the constraints of that particular action, which means that the problem of finding satisfying values for its parameters is independent of finding parameters for other actions. Thus, the existence of a satisfying assignment to the motion parameters can be evaluated online during action sequencing in order to compute only values for action instances encountered during the search. The strategy was first applied to TAMP under the name of semantic attachments (62–64). Although this strategy limits the amount of interleaving that is possible, it is appealing in that the state space is fixed during sequencing; it only identifies that some transitions are infeasible.

Interleaved action and parameter search can also aid the search for plan skeletons when sequencing first. One source of search control is to observe that, in order for a plan skeleton to admit a satisfying assignment, all of its subsequences must also have satisfying assignments. Thus, a partial plan skeleton can be pruned from the search if its H-CSP is infeasible. Some approaches even solve relaxations of the induced H-CSPs that omit certain constraints, such as motion constraints with many decision variables, which are often satisfiable and thus are uninformative (61, 65–69).

A more general control structure is to perform a tree search, with layers alternating between selecting an action template and sampling parameter values for that action that satisfy the partial skeleton constraints. A substantial difficulty in this approach is that tree nodes may have infinitely many successor nodes due to the possibly infinitely many satisfying parameter values and action instances that could be performed. Thus, it is important that the search be persistent (70, 71), in the sense that it will revisit previous search nodes indefinitely in order to generate additional samples for continuous parameters.

3.4. Communication Between Subproblems

TAMP strategies require solving multiple H-CSP subproblems. These problems often have a shared substructure that can be exploited, resulting in substantial reductions in computation. The primary algorithmic question is whether to share information about sets of constraints that can be satisfied (positive) or about sets of constraints that cannot be satisfied (negative). Algorithms that satisfy constraints individually typically take the positive approach, and algorithms that satisfy constraints jointly typically take the negative approach. Although we will discuss these approaches separately, it is possible to develop algorithms that use both, possibly to handle different types of constraints.

3.4.1. Positive methods. Positive methods are straightforward: Whenever an H-CSP is solved, regardless of whether it contains one or many constraints, they add each constraint in the H-CSP, along with its satisfying assignment, to a database of constraint elements (i.e., known solutions to constraints). For methods that satisfy before sequencing (Section 3.3.2), this database is used to instantiate action instances before sequencing. If action sequencing fails to find a solution, then the feedback is that the current database is insufficient and more values must be sampled. Some methods that sequence before satisfying (Section 3.3.1) also use positive feedback. The focused algorithm presented by Garrett et al. (55, 72, 73) plans using a mixed set of sampled values and free parameters (optimistic values), which represent values that are not yet available but might potentially be generated by a sampler.

3.4.2. Negative methods. Alternatively, instead of recording solutions to constraints, an algorithm could identify unsatisfiable counterexample H-CSPs. Because any H-CSP that contains an unsatisfiable subproblem is itself unsatisfiable, any H-CSP that contains a recorded counterexample can be pruned; this can, in turn, prevent action sequencing from exploring plan skeletons that have not yet been explored but have the same failure case as a previously explored skeleton. Since most H-CSP solvers are only semidecision procedures, they can never determine with certainty that a problem is infeasible. One way to handle this problem is to assume unsatisfiability initially but (as discussed in Section 3.3) allocate a thread to each H-CSP that continually searches for a solution in case one exists. If one of these threads returns with a solution, the H-CSP is removed from the counterexample set.

A key algorithmic concern here is identifying informative counterexamples. The smaller a counterexample is, the more H-CSPs and thus plan skeletons it can prune. For example, consider the constraint network in **Figure 9** and suppose that placement $\mathbf{p_0}$ is on a tall shelf that the robot cannot reach. If we could isolate constraint `Kin[A]`$(q_1, \mathbf{p_0}, g_2)$ as the bottleneck, rather than the full H-CSP, then any plan skeleton that attempts to pick `A` at its initial placement will be pruned, informing the planner that `A` cannot be manipulated.

The problem of identifying small counterexamples can itself be time-consuming, requiring the original H-CSP to be decomposed into smaller H-CSPs, each of which is individually tested for unsatisfiability. Several TAMP approaches have proposed heuristic methods for diagnosing failure and repairing the problem (60, 74–76). There are also several good domain-independent strategies. For problems in which the state variables are presampled (Section 3.3.3), the remaining H-CSP is often disconnected, and thus each unsatisfiable connected component can be independently added as a counterexample (77–79). There are methods from the Boolean satisfiability problem literature that, for unsatisfiable propositional formulas, identify unsatisfiable cores (80)—small subsets of constraint that cause unsatisfiability. These ideas can be extended to

Table 1 Multimodal motion planning (MMMP) and task and motion planning (TAMP) approaches (listed roughly chronologically within each cell), based on how they solve hybrid constraint satisfaction problems and how they integrate constraint satisfaction with action sequencing

	Pre-discretized	Sampling	Optimization
Satisfaction first	Ferrer-Mestres et al. (84, 85)[b]	Siméon et al. (22)[a] Hauser et al. (13, 14, 29)[a] Garrett et al. (21, 86)[b] Krontiris et al. (87, 88)[a] Akbari & Rosell (89)[b] Vega-Brown & Roy (90)[a]	
Interleaved	Dornhege et al. (62, 63, 91)[b] Gaschler et al. (92–94)[b] Colledanchise et al. (95)[b]	Gravot et al. (96, 97)[b] Stilman et al. (23, 98, 99)[a] Plaku & Hager (100)[a] Kaelbling & Lozano-Pérez (101, 102)[b] Barry et al. (30, 103, 104)[a] Garrett et al. (70, 71)[b] Thomason & Knepper (105)[b] Kim et al. (106, 107)[b] Kingston et al. (108)[a]	Fernández-González et al. (109)[b]
Sequencing first	Nilsson (3)[b] Erdem et al. (74, 75)[b] Lagriffoul et al. (65–67)[b] Pandey et al. (110, 111)[b] Lozano-Pérez & Kaelbling (112)[b] Dantam et al. (77–79)[b] Lo et al. (113)[b]	Wolfe et al. (114)[b] Srivastava et al. (60, 76)[b] Garrett et al. (55, 73)[b]	Toussaint et al. (61, 68, 69)[b] Shoukry et al. (81–83)[b] Hadfield-Menell et al. (115)[b]

[a]Approaches for MMMP.
[b]Approaches for TAMP.

continuous mathematical programs, where real-valued constraint violation feedback can improve the efficiency of the search for counterexamples (81–83).

3.5. Taxonomy

Table 1 shows a representative set of MMMP and TAMP algorithms, categorized in terms of how they solve for continuous parameter values and how they combine searching for the mode family or task-level structure of a plan with searching for continuous values. This table is meant to provide broad coverage but is not exhaustive. Each row lists one of three strategies for integrating constraint satisfaction and action sequencing: satisfaction first (Section 3.3.2), interleaved satisfaction and sequencing (Section 3.3.3), and sequencing first (Section 3.3.1). Each column lists one of three strategies for performing constraint satisfaction: assuming the state variables are pre-discretized and solving for motion parameters, individual sampling (Section 3.2.2), and joint optimization (Section 3.2.1).

4. EXTENSIONS

There are many ways to extend the basic TAMP problem class and associated algorithms; below, we describe areas of current active research and future interest.

4.1. Kinodynamic Systems

In this review, we have focused on domains with quasi-static dynamics (after the robot executes an action, the objects end in a stable configuration that persists until the robot's next action) and simple rigid-body kinematics. Extending TAMP to handle deformable objects and liquids as well as to full dynamics, such as throwing, is an important direction. Several TAMP approaches have already demonstrated the ability to plan for kinodynamic systems (68, 69, 100).

4.2. State and Action Uncertainty

Uncertainty is a critical issue when acting in the real world. In the presence of future-state uncertainty, a planning algorithm might need to take into account multiple possible outcomes of an action and ensure that there are actions it can take in response, to avoid unlikely but disastrous outcomes. More difficult, but pervasive, is uncertainty about the present state. In this case, the problem can be treated as a belief-space planning problem, in which the planner reasons explicitly about the agent's state of information about the world and takes actions both to gain information and to drive the world into a desired belief state. Several approaches for deterministic observable TAMP have been extended to handle these challenges (102, 116–118).

4.3. Planning and Learning

A critical question is where TAMP models come from. Most work in TAMP assumes perfect observability, control actuation, and knowledge of the kinematics and shapes of objects. Machine learning methods can help with the process of acquiring models in nonideal domains as well as speeding computation. In particular, learning methods can improve TAMP in several ways:

- Learning models: Given a controller, whether acquired via learning or hand built, the constraints that allow us to characterize successful executions for the TAMP planner may not be obvious, but they, too, can be learned from experience (1).
- Learning search guidance: Classic task planning algorithms derive domain-independent search heuristics from the action descriptions, but there are also opportunities to automatically learn domain-dependent search heuristics (119, 120), in the form of policies or value function estimates (121) or action orderings (122). Learning search guidance has been hugely influential in games such as Go (123). In TAMP problems, it is more difficult because it is much less clear how to encode the state of the problem (object shapes and poses) in a way that affords generalization from current function approximation methods, and because the goal must be encoded into the prediction as well, but there is initial progress in this area (106, 124, 125).
- Learning sampling guidance: As we have seen, many TAMP planners use conditional samplers as part of their strategy for solving underlying H-CSPs. Learning can make sampling much more effective in two different ways: one in which the learning happens during a single search process and one in which the learning happens across problem instances. In the forward-search algorithms that interleave selection of action and parameters, we can derive inspiration from Monte Carlo tree search (126, 127), in which experience with trying to expand nodes in a branch of the tree is used to form local estimates of the likelihood that a solution lies along that branch. Sampling for continuous parameter values can itself be similarly guided, using techniques for optimistic global optimization (107, 128). Samplers can also be learned from previous experience using generative models such as generative adversarial networks (129).

SUMMARY POINTS

1. Task and motion planning (TAMP) selects the sequence of high-level actions that the robot should take, the hybrid parameter values that determine how the action is performed, and the low-level motions that safely execute the action.
2. TAMP approaches build on research in motion planning, multimodal motion planning, and task planning.
3. Many TAMP approaches can be seen as integrating a search over plan skeletons (partially specified plans) and the satisfaction of constraints over hybrid action parameters.
4. Existing approaches can be usefully categorized according to how they address and integrate these two types of decisions.

FUTURE ISSUES

1. Further investigation is needed of strategies that combine sampling and optimization approaches to TAMP.
2. TAMP methods should be extended to plan in more realistic environments that, for example, involve deformable objects, time, dynamics, liquids, and other agents.
3. Uncertainty is central to all real-world robot applications; future TAMP methods should consider both future-state and present-state uncertainty.
4. Incorporating learning-based methods into planning will enable planners to reason with learned action models, requiring less human-provided domain knowledge.

DISCLOSURE STATEMENT

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