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Implementation of an Agent-centric Planning of Complex Events as Objects of Pedagogical Experiences in Virtual World

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ABSTRACT

An agent-centric event planning method is proposed for providing pedagogical experiences in an immersed environment. Two-level planning is required at in a macro-level (i.e., inter-event level) and an intra-event level to provide realistic experiences with the objective of learning declarative knowledge. The inter-event (horizontal) planning is based on search, while intra-event (vertical) planning is based on hierarchical decomposition. The horizontal search is dictated by several realistic types of association between events besides the conventional causality. The resulting schematic plan is further augmented by conditions associated with those agents cast into the roles of the events identified in the plan. Rather than following a main story plot, all the events potentially relevant to accomplishing an initial goal are derived in the final result of our planning. These derived events may progress concurrently or digress toward a new main goal replacing the current goal or event, and the plan could be merged or fragmented according to their respective lead agents' intentions and other conditions. The macro-level coherence across interconnected events is established via their common background world existing a priori. As the pivotal source of event concurrency and intricacy, agents are modeled to not only be autonomous but also independent, i.e., entities with their own beliefs and goals (and subsequent plans) in their respective parts of the world. Additional problems our method addresses for augmenting pedagogical experiences include casting of agents into roles based on their availability, subcontracting of subsidiary events, and failure of multi-agent event entailing fragmentation of a plan. The described planning method was demonstrated by monitoring implementation.

***Key words**: Situated Learning, Cyber-world, Pedagogical Experience, Diversity of Situations, Event Planning, Agent, Simulation.*

1. INTRODUCTION

The diversity of situations is crucial for a cyber-world as a platform for computer-based immersed learning [1]-[3]. A situation refers to a part of this world that concerns a human agent therein at a given time. Such a situation functions as a semantic unit that could contextualize its activities. The events are the comprehensive elements of a situation in that they involve all kinds of elements of the world. It is all the more so since they often exploit as their means diverse phenomena, each complex in itself. Unless its goal is simple enough to be achieved in one step, an agent should plan for an event to achieve its goal.

As generic a term as it is, planning referring to any process of organizing the activities required to achieve a goal has long been a significant research issue with respect to practical planning methods and formalisms in a wide range of application areas [4]-[10]. Planning can be differently defined between application areas, even within an area depending on its purpose. Whereas planning in Interactive Storytelling (IS), for example, pursues coherent and interesting development of a story while allowing user interaction [8], [11], planning in simulated-world–based pedagogical systems strives to provide *realistic experiences in immersed environment* [12]-[14]. Of those pedagogical systems, ones teaching declarative domain knowledge such as mathematics and linguistics [1], [15], [16] may not appear to be as relevant to event planning as ones for procedural domain knowledge, (whose pedagogical targets are the procedure itself in the form of sequence of actions directly resulting from planning) [13], [17]. Still, declarative domains have good reason to share implicate events as effective learning stage for their corresponding simulation, in that numerous opportunities of pedagogical experience could be immersively embedded in progression of those events [13], [17], [18]. The extent and depth of the event plan determines the scope of pedagogical experience in situations unfolding through events and consequently the quality of learning in an Intelligent Tutoring System (ITS) based on simulated world.

To provide immersed pedagogical experiences to the learners [2], we aim to simulate diverse virtual situations, which would develop within and without events and in between them. Our simulation views a situation as an accumulated result of all the relevant historical occurrences thus far. This view is reminiscent of the stance of Situational Calculus, where a situation is defined not as a snapshot state but as a finite

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sequence of actions [19]. Conversely, a world each human agent sees unfolds through a series of relevant situations as a result of events occurring within the world. Our target learning content consists basically of declarative knowledge, while both procedural and declarative aspects [20] are intertwined to a greater or lesser degree as specific events unfold through its procedure [21] in different classes of ITSs [12]-[15]. Though more intricate and involving events are likely to offer all the more extensive and concrete chances of experience, such a complicated event tends to involve not only many agents interrelated a priori in their common background world but also many subsidiary events coupled to each other via physical and social conditions. As a consequence, the scope of planning for our event simulation is not confined to an individual event (or story) as in typical storytelling or computer game, but often spills over to other events via *multiplicity of an agent's roles* or other condition straddling events.

As the common background for all the events and associated agents and conditions the world in our simulation has greater significance than ones as passive backdrops [5], [9], [11], [14]. In fact the background world and events therein are not separated from, but integrated with, each other. As a result, events regardless of being main or not and their environments are likewise parts of the unifying 'active' background world. A situation, a part of the background world, is precisely modeled in terms of Cartesian product between the pairs of *(entities, relations*) and (*existences, states*), and their *temporal change* [22]. These entities include agents as the most sophisticated entity type with belief, desire and intention (or volition) [23], and relationships include the fundamental relation of location as one of the two axes forming historical context. The agents, the dominant entity type in our planning, are designed to be *realistic* agents of all sorts encountered in the virtual world, including rational agents [13], [23]-[25] and believable agents [26]-[28], and agents not classifiable to stereotypical characters. All those agents inhabiting the world use their respective minds and beliefs to govern their (autonomous) behaviors, enabling multiple intentional events to develop *concurrently in an intertwined manner*. Each instance of event planning originates from some desire and subsequent intended goal [23], [25], [29] of one of those autonomous agents. The transition from desire to intention is modulated by some utility function to reflect subjective or social value [29] though our planning focuses on intention as the final attitude on event planning and execution. This individualization of the background world already sophisticated in itself further enhances the play affordance, an important factor in effective learning by playing or doing in situations [30], [31]. Any agent is modeled to be an autonomous entity type acting on intention and has its *own planning capability* toward a goal it independently sets (consequently proactivity as well), unlike the other entity types whose actions are purely conditioned with no regard to intention (these actions are called phenomena.)

Our event simulation as prescribed by our pedagogical objective focuses on planning of intricate events in a *macroscopic* level rather than in individual event level, and on interactions (including negotiation for casting) among *autonomous and independent* agents. It is macroscopic in the sense that each entire plan usually involves a number of interconnected events which each may be handled by different agents and comprises another set of subsidiary events and recursively. An autonomous agent with its own belief and desire at least attempts to achieve its goal, though it does not always behave rationally [25]. An independent agent is originally in a free or an available state as part of the background world and remains free (i.e., on its own volition) even when assigned or bound to a task or role (only less free while cast in a role.) Such an agent can become a candidate for an event role it believes itself to be qualified for, but its actual undertaking is to be determined by some social relationship (and its intention.)

The event, the exclusive element for progressing situations in our simulated world, is defined differently in several ways from other definitions. An event in our approach is composed in a recursive structure, i.e., an event in general is recursively composed of smaller events, so it could be as simple as walking into room and as complex as constructing bridge. This recursive composition serves a pedagogical demand that *every abstraction level* of event specification be a potential target of user experience, which is in contrast to providing encapsulation units subjectively determined by authors for facilitating authoring complex interactions between characters and objects [10], [32]. In practice, role casting itself, though stated in the context of substituting agents in roles [33], presents diverse chances of experience throughout its associated event planning and execution. Candidate agents for a role might be evaluated with respect, at least to their own time-varying conditions and to relationships with the casting agent beyond individual traits or capabilities [27], [33]-[35].

Coupling between events in our planning is made via the *preexisting background world* in terms of individual parametric elements (or overarching norms), rather than directly between events in terms of the binary relationship between their precondition and postcondition [35], [36]. This coupling is similar to rule chaining in the rule based system. Like past events of relevance, future events also could be coupled if only those couplings are anticipated or projected by their associated agents, which rendering agents not just reactive but proactive. In summary, not only current conditions within the perspective of the main goal but their associated *external causalities* and *historical contexts* also are considered in our planning.

The applicable types of association between events plays a crucial role in planning in that it determines the identifiable range of events relevant to a given goal and the order among those identified events. While search in planning for related actions or events in IS or other scenario-based systems is mostly based on narrative causality only [8], [14], [17] our search method diversifies the applicable association types between events to account for a wider range of physical phenomena and normative events beyond behavioral actions of characters under a plot. It could be viewed as a generalization of goal and normative types of influence [37] to an entire spectrum of physical and social impacts.

Though causality is the most fundamental type of association, its specific implication varies depending on how it is used. First, it can be used to identify what events need to be performed to trigger or execute a given event. Conversely, it can be used to identify what events might be subsequently started as a result of executing a particular event. An occurrence of an event may obligate occurrence of its associated event as stipulated by some regulation. This *deontic* type of association is specified between a pair of events with no regard to an overarching event. For example, if a crime is committed its corresponding punishment is prescribed to be imposed. In case it is a convention that a (social) event proceeds in a regular order of its subsidiary events, those subsidiary events are of *normative procedure* association type. For example, an ancestral rites proceed in lighting candles, bowing, filling cups with alcohol, bowing, and so on. This type of association is not actually specified between events at the same level, e.g., lighting candles, bowing etc., but the order (or association) between these events are merely a consequence of arrangement by their overarching event, e.g., ancestral rites. Conversely a sequence of events of this association type constitute an overarching event, which can only be reasoned by case-based planning [20], [38] when their order is known to the planner. All the events judged to be relevant in terms of these four association types would be merged into the plan if they have reasonable chances of occurrence.

Our event planning is two dimensional, i.e., horizontal and vertical. The horizontal planning is an inter-event process based on search, while the vertical planning is an intra-event process based on hierarchical decomposition. Our planning first searches the world knowledge of a lead agent to identify the *entire* range of potential events and consequences derivable via the four association types starting from an initial goal set by that agent (in contrast to optimal or conditional searches [33], [39].) Each event that has been identified in this horizontal planning phase is recursively decomposed until the resulting subsidiary events all reduce to the primitive events of actions. A primitive event refers to a (simple) event that can be performed only by continuation or iteration of an action. Notice that *each* of these derived events in any planning phase is subject to another full-blown planning instance with that event as the initial event. In consequence the planning could be compounded by diverse exogenous events, which may have to be added to augment the 'skeletal' plan without contribution to achieving the main (or initial) goal. To sum up, the resulting plan comprises derived events in addition to the main event for the initial goal, forming a graph of events interconnected via their common conditional factors [40] or other types of association between events. A plan if successfully derived through the two phases is still in its schematic form, which is to be further elaborated in terms of quantitative aspects against relevant world states. These aspects include the existential properties of amount and count, the spatial relationships of location, and the spatio-temporal parameters of speed, duration, etc. [36]. All these quantitative aspects are formalized in spatio-temporal space [22].

The plot coherence in our approach is achieved in two levels: in an event level and in a macro-level. The event-level coherence is basically maintained by the conventional means of hierarchical decomposition of each event in a derivative of HTN planning while story variations are attained by means of search-based planning [8] with respect to external conditions of each event and meaningful types of association, respectively. The macro-level coherence across interconnected events is established *via their common background world* existing a priori. (It is reminiscent of the perspective any pairwise causality is only an intermediate one in an infinite chain of causalities.) The two-dimensional event planning and the inter-event planning together generate a semantically-rich and fine-grained event space from which numerous interesting situations could be derived through different courses of events or actions, which is an essential nature for high affordance of our simulated world. In fact, not only event failure itself but ensuing remedial actions [36] constitute another indispensable group of situations for pedagogical experience in the forms of alternative action, repair or withdrawal according to the event being essential or optional etc.

The planning and scheduling of a complex event could be further compounded in practice by many additional issues. Among them are the availability of candidate agents with respect to casting in its roles, disruption of occurrence due to failure of cast agent, subcontract and concurrent execution of its subsidiary events, critical path with respect to its minimum execution time, etc. Consequently its initial version based on the schematic knowledge is reified with respect to the particular agents cast in its associated roles and other initial conditions around. Thereafter, it is to be continuously revised according to its associated conditions including those agents' states varying incessantly through its execution. In case any essential precondition turns out to be unsatisfiable along its execution, the plan may need to be rescheduled or can be judged as infeasible at any point during its execution.

The paper is organized as follows. Section 2 describes related works and contributions of this paper. Section 3 presents planning of an intentional event. From a schematic planning it is elaborated with respect to several associations among events and situations. Section 4 describes how a schematic plan is modified and augmented in its execution according to ever-changing internal and exogenous conditions on cast agents and background world. Potential disruption during its execution and additional issues are discussed with respect to the agents involved therein. Section 5 demonstrates and discusses the viability of our planning method through an implementation. Section 6 draws a conclusion with future research.

2. RELATED WORKS AND OUR CONTRIBUTIONS

To plan an event an agent first needs a representation model for the background world, goals and actions. Many feature-centric and action-centric models have been developed and applied to automatic planning [4], [6]. Those models are oriented to logical reasoning to find a plan to achieve a goal from a given state [41], while composite events with a hierarchical structure in practice cannot be properly modeled just in terms of fragmentary predicates in logic. In contrast we pursue a maximum diversity of situations by elaborating a plan with respect to its subsidiary events and associated agents. Our planning is characterized to be agent-centric in that the agents play the pivotal roles in elaboration of basic plans beyond a main event or story. Our agent's composition is dichotomized into physical and mental parts. The physical part refers to the body or an actuator [42]. The mental part comprises sense, perception, emotion and social relationships [11] with belief (or knowledge) as its personal model of the background world [23]. This provides numerous internal and external factors by which the intention of an agent for an event could be diversified besides its basic driving forces [43]. Meanwhile, non-player characters (NPCs) have not generally been modeled in storytelling as independent agents unlike the player or lead character [44]. Those supporting agents are likely to be designed to act at best only reactively, and their personal conditions or belief are little considered in planning. Recently, the actors are generalized to include a few entities other than characters [35], and user model is used for implementing its proactivity [45]. We further these ideas by modeling an entity in general to have inherent (innate or acquired) capability of actions.

Compared to narrative worlds that usually are simplified in abstract forms or minimized in the forms of spatial configurations geared to serving as stage or environment for particular stories or behaviors in small domains [11], [14], [31], [5], [9], [10], [35], our full-blown virtual world, a sophisticated version of Working Memory [22], [40] is the central source of user experience as the common background stage for numerous events (or stories) to unfold in. To account for its complex nature the entire world is modeled in multiple layers, i.e., the reality composed of the physical and social worlds and thereover the conceptual worlds of its inhabitants or agents. An early agent model based on Time Tree with branching time future and a single past [23] lays down a formalism for virtual world model structured in many layers and facets. Rather than efficiency of its generation in constructing story world [14], [31], we pursue comprehensiveness and sophistication of the world composition. Specifically event in our simulation is roughly equivalent to plot point in [31], but world state specified in terms of NPCs, objects and places is generalized in our simulation into *time-varying situation* of entities and relationships. Still, our world model shares several basic elements with the problem domain definition in [10], only with some notable differences due to distinction in their target problem domains: such as *relationships* between entities being explicitly considered in our model as important elements of the domain or world as entities (roughly equivalent to objects and actors in [10]), and different agents having *different conceptual worlds* over the common background world (of reality.) Coupling between events through an autonomous and independent agent would have far-reaching implications not comparable with ones that coupling through an object (e.g., a diary or a key [10], [46]) might have. Their consequences would potentially reverberate as extensively as through the *entire* virtual world.

Whereas the development of narratives tends to be centered around the characters with other entities merely in supporting roles across character-based and plot-based storytelling [5], [37], [8], [44], [46], the other entities, e.g., props and organizations, are deemed not less significant elements than agents (or characters) in our planning either when those entities are linked with the agents or on their own, although believable agents [11], [26] being the key constituents of our realistic background world.

Once those independent agents have been cast into some event, they are likely to confront all the problems that are addressed by conventional planning methods in performing their roles *within* each of those events collectively comprising the world. In this respect, we can exploit diverse existing approaches, for example, to simulate interaction between agents or crowd of agents involved in an event [35], [36], [47]-[49] as the main mode for progression of multi-agent events [28] often identified in our planning. We expand the interaction patterns between agents from ones premised on spatial affinity [36] to include other types of relationships, for example, parties to a contract. As for allowing user intervention, existing techniques such as real-time search techniques [34] or re-planning [9] are applicable to our model while it is beyond our present scope.

Whereas terminal actions in IS and other computer-simulated systems [8], [13], [14], [46] are those actions to be animated in the presentation, the action as an atomic element of events along with the other element of collision in our planning refers to an inherent function of an entity regardless of its animation. That is, an action is a function that its 'host' agent is capable of performing only with her inherent parts (e.g., walk) or a phenomenon whose procedure and effect is confined within its 'host' entity (e.g., burn.) Notice that 'go to phone' (a terminal action from [46]) for example, would be regarded as an event to be performed by means of (the action of) 'walk' in our planning. While an action in a parameterized behavior tree (PBT) [33] is roughly equivalent to an action (sometimes a motion) in our model, our action is only potentiality with no substance in reality until instantiated in terms of duration or the number of iterations to form a primitive event with a concrete temporal span. Note the timing of elements is essential information for reifying into a schedule a schematic plan that has been obtained from the front phase of planning. For realistic simulation of detailed scenes, the solutions to 'bottom-up' situations under their top-down planner [36] are applicable to our approach (though those solutions are largely subsumed by autonomy nature of our agents [32], [43]) despite wide difference in ultimate objective, entertainment vs experience. Each action being executed in our simulation is instantiated incrementally (or tentatively [14]) in its associated historical context, and is continued or iterated according to the plan along the progression of the occurrence.

In a technical perspective our vertical planning is a recursive decomposition process generating a hierarchically organized plan of events sequenced in partial order, whose representation is framed on an AND/OR graph similar to Hierarchical Task Network (HTN) [44], [46], [50]. A major difference of our vertical planning from HTN-based planning is that the primitive actions in our planning refer to performance of an entity's innate capabilities instead of playable actions [8]. Another difference is that the durations of the identified events are further depicted on the timeline (i.e., a plan being elaborated to a schedule) [51] enabling their executability to be judged with respect to their associated agents' temporal availability [47].

The combinatorial optimization approach and the plot adaptation algorithm [14], [31] also are candidate approaches to selection of the best quality plans and to personify objective (or neutral) plans generated in the early stage of our macro-level planning. Branching in bridge [31] could be adopted for our planning to implement the optional precondition for executing events. While degree of real-time constraint varies depending on the application areas [13], [15], [35], it is partially applicable to our simulation. In parts of our planning where real-time performance are required we could adapt relevant approaches developed in IS, ITS and other story-based systems with stringent time constraints [5], [9], [10], [14], [35].

The aspects in which the planner is interested, of props or roles other than the protagonist, e.g., roses or a flower pot [46] [33], are usually confined to those directly relevant to the main story plot, e.g., (existence of) roses or price of pot. In contrast any of their general aspects is a potential source of a new event in our planning, which could lead the story to digress off the main plot (though no digression in our perspective), e.g., the flower pot might turn out to be a smuggled antique treasure prompting (a complicated event of) police investigation to proceed in parallel with or in place of the main event. While side-quests or digressions may well be strictly restricted or supported externally to main storyline in [31], [46], our planning not only regards those side storylines as an inherent part of a plan due to branching via causality or the other (real-life) association types but also exploits them as another path to promote play affordance (or narrative interests) of the simulated world all the stories unfold in. As a consequence, a (main) goal in our planning is not fixed but variable according to how the situation progresses, to be exact the conventional concept of main goal or event being inapplicable to, or to be modified for, our model. In effect, a narrative goal is no more than a 'square one' or 'flash point' providing a clue for planning of relevant events. Incidentally, a domain by which a goal (or the precondition and postcondition) of an event can be specified is formed by all the possible situations in the world, which is a generalization of goal specification in [10]. Further generalization is possible in terms of its procedure [28] and other aspects [43] beyond mandatory execution of event [10].

While most narrative systems apply causality to identify what events might subsequently be started as a result of executing an event [8], [14], [17] and goal-directed search is often used in planning for parts of a plot [8], [10], [46], narrative causality between actions or events is not precisely specified. Our planning formalizes both backward and forward usages of causality to find the *prerequisite* events and the *ensuing* events, respectively. We further elaborate on the association via causality with respect to entities and relationships as condition parameters for event occurrences.

In most interactive narratives, actions are uninterruptible or atomic [20] and their sequential order with respect to their entireties is the only way they are related to each other. Coupling between actions is rationalized by parameterizing behavior tree [33], mainly for code reuse in the context of a single event rather than interplay between independent events. While integration of independent behaviors of characters is considered in case of their spatial affinity [36], our model monitors and considers assorted spatial relationships among entities beyond spatial affinity [52]. In reference to the simplifying assumptions [20] our planning can be evaluated with respect to its practicality, for example, the atomic time assumption is lifted, i.e., concurrent execution of actions is allowed [51] execution of an action is rendered interruptible; and its intermediate states are made visible and of concern to the planner. Consequently the roles progressing *any* event in our model are played by entities that *happen to be cast* from the background world instead of entities that are prepared specifically for particular event as in typical narrative systems. (Notice those agents cast in the roles *preexist in the background world* independently of those roles.) As a natural consequence, those background entities function as junctions for coupling events that are previously independent into events that concurrently interact in an intertwined manner via individual entities cast in *multiple roles (or props)* across those concurrent events.

Unlike in typical interactive narratives [8], [37] story plot in our system is not strictly controlled in a global perspective, but dynamically controlled (with no fixed global goal other than initial goal) as long as it is not detrimental to overall pedagogical objective. That is, plot control could be transferred onto another overarching event into which the story progresses (i.e., digresses) from the currently main event according to the user's choice or pedagogical needs. To enhance play affordance, narrative interests such as failure of plan [23] and competing plans [8] are further augmented by additional aspects like inexistence (constituting absence, nonfeasance, avoidance, etc.) of entities, relationships or occurrences [23], [29], [36].

Contributions: We propose a two-level event planning, *in a macro-level (i.e., inter-event level*) and in an intra-event level, for providing pedagogical experiences with an objective of learning declarative knowledge, which is different from ones many conventional planning methods attempt to pursue. Rather than events following a main story plot, *all* the events potentially relevant to accomplishing an initial goal are derived in planning. Coupling between independent events is based on an agent's *multitude of roles (or props)* across concurrent events. These events in a plan may progress *concurrently or digress* toward a new main goal replacing the current goal or event, and the plan could be merged or fragmented according to their respective lead agents' intentions. As the pivotal source of event concurrency and intricacy the agents are modeled as not just autonomous but *independent* types, i.e., entities with their own beliefs and goals (and subsequent plans) in their respective parts of world.

Events in our model are integrated as parts of the unifying background world and conversely they collectively form the world. All the relationships including event occurrences are coupled with each other via their preexisting common background world. A full-blown virtual world is the central source of user experience as the common background stage for numerous concurring events to unfold in. For a precise description of its complexity and intricacy of events therein, the entire world is modeled in terms of entities and their interrelationships in multiple layers in a historical (time-varying) context. *Coherency among events* (loosely coupled by entities) is established *via their common background world*, which is contrast to pre-authored scenario prescribing intra-event coherency [8].

Our planning method proposes *additional types of association* between events besides the conventional causality. The association via causality is formalized in both directions, i.e., from causing event to affected event, and from requiring event to satisfying event, and further elaborated with respect to entities and relationships as condition parameters for event occurrences. In a social event, a regular order of its subsidiary events is dictated by the *normative* procedure type of association. The *deontic* type of association is specified between a pair of events with no regard to an overarching event.

By complete *separation of roles from candidate agents* our planning is expanded to include, as an integral part a plan, a potentially lengthy and complicated event of casting in terms of availability of agents, subcontracting etc. In addition, abnormal termination of plan execution due to unforeseen changes in agents' individual conditions is formulated with respect to fragmented sub-plans.

3. PLANNING OF INTENTIONAL EVENT

Our event planning is conducted in two dimensions, horizontal and vertical, toward a given goal. The horizontal planning is an inter-event process based on search, while the vertical planning is an intra-event process based on hierarchical decomposition. In a horizontal planning phase, the world knowledge of a lead agent is searched via the four association types for all the events relevant to achieving an initial goal set by that agent. Each event that has been identified in this horizontal planning phase is recursively decomposed until all the resulting subsidiary events reduce to the primitive events of actions. Meanwhile, each of these derived events in any planning phase is subject to another general planning instance with that event as the initial event. To sum up, the resulting plan comprises derived events in addition to the main event identified for the initial goal, forming a graph of events interconnected via their common condition factors or other types of inter-event association. The horizontal planning in practice cannot be completed until its corresponding vertical planning is completed, and vice versa, unless the agent (unrealistically) has perfect knowledge of the event under planning. In effect these two phases of planning proceed in an interleaved manner [53] or the drawn plan may subject to proper modifications for elaborations or corrections.

By the execution time, any event in the plan eventually is to be decomposed and prepared in terms of the actions (and collisions.) The action plays a role analogous to a (primitive) action or operator described in domain theory in generative planning [20]. Those actions include agents' inborn faculties and acquired motions (e.g., human's smell and infant's toddle), machine's facility (e.g., run of automobile), and phenomena on substances (e.g., rust of iron.) Their actual occurrences (of the action type) are realized in terms of its iteration or continuation. Of various action types we focus on agents' actions, which may involve tools, or merely trigger a phenomenon as a whole. An event in general refers to an activity that involves multiple agents assuming their respective roles therein. Each such role is designated to perform one or more actions for the event. An event is eventually carried out by performing those actions required of the agents cast in its associated roles. An action-type occurrence in effect constitutes a primitive event. Those action occurrences are to be properly arranged into a plan with respect to their global goal. This (initial) schematic plan derived through the two phases of planning is to be further elaborated in terms of quantitative aspects against relevant world states. These aspects include the existential properties of amount and count, the spatial relationships of location, and the spatio-temporal parameters of speed, duration, etc. as formalized in spatio-temporal space. In particular durations of occurrences are formulated in terms of duration along the timeline.

An instance of planning is initiated only if, given a goal, the lead agent is already aware of an event suitable for achieving the goal with respect to at least its effect and precondition. Unless the event is routine, generative planning [20] is to be performed from the goal. The vertical planning is based on case-based search, while the horizontal planning is based on generative search against its associated ontology [54]. The routine events range widely in their extent and nature according to knowledge and experience of the planner, e.g., from inborn ability of cry to acquired social activity of purchase. The routine events or actions identified as relevant plan fragments in case-based search are assembled (after necessary revisions [55]) into the main plan.

3.1 Schematic planning for events

A part of the background world relevant to an example situation is schematically described as follows. It is composed basically of entities (including human instances), relationships and events. The actions as primitive elements of event occurrences are specified on their associated entities. Linkage between events are indicated if they are in association with each other, such as deontic (below denoted by |→) and customary (by →). To briefly introduce some notations, the concept preceding entity instances grouped in [ ] denotes entity class, bold-type and underline for entities indicate system and region, respectively; name() denotes action and event with ';' delimiting its parts; < > inside an event delimit its procedure part, and | partitions alternative path set, and roles (and props) are indicated by Italic type; { } enclose action set of entity class or instance; ≪≫ denotes action occurrence.

Human.{walk(), speak(), see()} [Human1, Human2, …], Wallet1, Book1, Cash:Bill1, Metro1, Station1, House1, Cosmetics1, Suit1; Siblings(Human1, Human2), Friends(Human3, Human5), Friends(Human1, Human2), Friends(Human2, Human4), Own(Human1, House1);

date(date[Human], place[];), theft(target[])|→penalize(<Miranda-notify()→handcuff()→ >;), dress-up([cosmetics, suit];), cash-withdraw(subject-agent; [teller-machine]; ; [cash]), go(source[place], destination[place]; <≪walk()≫| mass-transit() | drive-car()>;), job-seek(), purchase()

Though agent's epistemic aspect in planning is a significant issue with respect to incomplete information, partial observability, etc. [5], [44], [45] we here take an omniscient view on the agents' world knowledge. Against this background world, (schematic) events are instantiated into historical occurrences advancing the world forward. In general, some of alternative solutions toward a given goal are immediately executable under the current condition and the others require additional events (mere waiting considered an event as well) to be performed to satisfy their preconditions. When appointed to go to a place, for example, alternative procedures (each comprising events) might be evaluated to select the best one based on conditions and traits. That is, between taking metro (still may need walk to a station as a premise) or driving to the appointed place depending on, say, time constraint and disposition on walking.

A goal is a situation an agent intends to be in to fulfill her wish or obligation. The goal situation could be one that is newly created or preserved as it is. Unless such a goal is satisfied with the given conditions some event needs to be performed against the given condition in order to achieve the goal. Such an event in general is complex enough to demand a deliberate planning with smaller events selected by its agent. Initially a plan is drawn up based on a schematic knowledge. Specifically a schematic planning proceeds along several threads of reasoning, vertical and horizontal, via diverse candidate paths possible in a graph of events as illustrated in Fig. 1. The relevant events are successively identified starting from an event able to immediately satisfy the goal as exemplified by a sequence ③→②→① for a goal (situation) SG in Fig. 1 according to the functional association such that the Effect of an event produces a part of Precondition of another event. This horizontal identification process first proceeds backward over the set of available events or their composites until the Precondition of each event so far identified can be fully satisfied exclusively with the given background conditions [40], [56]. Once identified in the horizontal planning, each selected event is vertically analyzed with respect to its hierarchical composition. An identified event may require other events to be added to the plan according to their association (to be detailed in 2.3.) For example, the original event A2 is premised on A1 indirectly through background conditions as led by ③&② chain, and legally entails A3 following link ④ as illustrated in Fig. 1. These derived events A1 and A3 are to be added to the original event A2. Two subsidiary events in A3 are identified by a case-based search and their order is accordingly determined, and the planning with A32 is similar to that with A2. These identified events in the corresponding order constitute a plan in a schematic form, which is subject to elaboration. The resulting plan would be arranged to form a partially ordered set of events, denoted by $\prod_k(A_k)$, with the 'last' event (one with its Effect ⊇ goal) as the only greatest element [56].

In general, any partially ordered set of functionally interrelated events could be defined as a (composite) event, a clue leading to a layered organization of the event. Such a set forms a tree rooted at the event whose effect represents the overall function of the associated composite event. Each leaf node of the tree corresponds to an action [56].

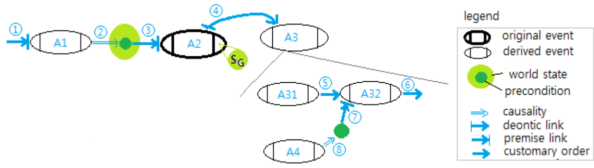

Fig. 1. Different threads of reasoning for schematic planning

(Procedure of) an event in general, *A*, could be formulated as,

$A() ::= \langle\langle a_i \rangle\rangle \mid \prod\{\langle\langle a_i \rangle\rangle, A\}$, where denotes a schematic action, ≪≫ indicates the repetition or continuation, and ∏{} denotes a partially-ordered set with respect to 'precedes' [56]

Definition

For A_i, A_j, $A_k \in$ {Event}, A_i precedes A_j if S_F^i partially satisfies S_P^i and A_i precedes A_k if A_i precedes A_j and A_j precedes A_k.

Theorem

The precedence between events in the plan is a partially ordered relation.

proof)

Let *T*(A)=t1, *T*(B)=t2, *T*(C)=t3, where *T*(x) denotes the occurrence time of event x.

reflexivity: (The definition is extended from < to ≤ to include A precedes A.)

A≤A means that A<A or A=A, and A=A is always true.

transitivity: If A<B and B<C, t2 = t1+Δt1, t3 = t2+Δt2, (where Δt1, Δt2≥0)

t3 = (t1+Δt1)+ Δt2 = t1 (Δt1+Δt2) > t1 ⇒ A<C.

anti-symmetry: Suppose A and B are events such that A ≤ B and B ≤ A.

t2 = t1+Δt1, t1 = t2+Δt2, (where Δt1, Δt2≥0)

t2 = (t2+Δt2)+ Δt1 ⇒ Δt2+Δt1=0 ⇒ Δt2=Δt1=0 ⇒ A=B

An event proceeds only forward along the timeline, so there can be no loop.

3.2 Background world in terms of entities and relationships

The background world and events therein are integrated with each other. That is, events regardless of being main or not and their environments are likewise parts of the unifying 'active' background world, consequently the world being the sum of events a_i throughout the historical time or $\psi = \cup a_i$. To account for its complex nature the entire world is modeled in multiple layers, i.e., the reality composed of the physical and social worlds and thereover the conceptual worlds of its inhabitants or agents. World = <R, {C_i}> where R denotes the reality; i=1,2,3,…, # of agents; Agent i's conceptual world C_i = M_i(R), i.e., R as modeled by its modeling function M_i, and $C_k \in R$ for all k≠I (of self), which is described in detail in [22].

A part of the background world that concerns an agent therein at a given time is defined as a situation. Such a situation functions as a semantic unit that could contextualize events occurring there. Our simulation views a situation as an accumulated result of all the relevant historical occurrences thus far. Conversely, a world each agent sees unfolds through a series of relevant situations as a result of events occurring within the world. The background world, and situations as its parts, are uniformly described in terms of Cartesian product between the pairs of entities and relations and existences and states, along with their temporal change. These entities include agents as the most sophisticated entity type, and relationships include the fundamental relation of location as one of the two axes forming historical context. All the possible situations in the world form a domain by which the precondition and postcondition of event, or goal is specified. The background entities function as junctions for coupling events that are previously independent into concurrent events via individual entities in multiplicity of roles (or props) across those concurrent events.

The entities provide the foundation of the situations considering the fact a relation also can exist only on top of their associated entities. Especially the autonomous entities of humans function as the agents of the intentional events to move those situations forward. Together with the entities their interrelations constitute the Precondition and Effect Parts of an event. On the other hand, the existence of some relation between entities implies a possibility they could affect each other across their associated events. A relation can be physical, social or psychological. Among numerous physical relations, locational adjacency between entities is a fundamental physical relation, which is a necessary condition for any interaction to occur between them in a physical event. No physical entity on the earth can stay unless it is supported by another in a spatial dependency relation with it. Social relations are exemplified by ownership and kinship.

3.3 Association types between situations and events

Considering that situations are changed by events and conversely events can be characterized in terms of situations, the associations between situations and events provide a key to logical deduction of relevant events in planning for a goal involving many events. We consider four types of associations between situations and events. That is, causality denoted by S1⇒A1, premise relation (causality in inverse direction) denoted by S2→|A2, deontic connection denoted by A3|→A4, customary order denoted by A5→A6, where Si and Ai denote situations and events, respectively. These associations dictate how the events are semantically interconnected, whereby a plan could be augmented to a more comprehensive one.

The (forward) causality relation S1⇒A1 denotes the development of a phenomenon, that is, A1 occurs if only the precondition S1 is satisfied. A1 can be connected with A7 only indirectly in case the effect of A7 produces S1. The premise relation S2→|A2 can be realized only if its agent's associated intention is established besides the precondition S2 [23], [29]. That is, in order for A2 to occur, the associated agent needs to pursue its execution with S2 satisfied as its premise. The deontic connection A3|→A4 refers to a relation where A4 ought to be performed if A3 has occurred. From the viewpoint of A4, A3 is merely a condition which the execution of A4 depends on. If any event in a plan is found to be the antecedent condition in a deontic regulation, its associated consequent event must be added to the plan. Any newly added event may require an additional planning of its own. The customary order A5→A6 indicates a stipulated precedence between two events, say, to proceed from A5 to A6. This precedence need not be an inevitable association, but may result from a discretionary choice. Hence the precedence could not be used as a basis to logically deduce A5 from A6 or vice versa. Rather it should only be excerpted as a whole for planning, i.e., 'A5 precedes A6' in their fixed order, from their overarching composite event comprising several subsidiary events in sequence.

The search for events to be added goes forward for the causality type and backward for the premise type though both types being based on causality with different usages, while it goes forward for the deontic type and the customary order type. The first two association types subsume a connection from the precondition to its associated event. As a result, such a type of connection by itself is sufficient for planning on those events. For the other types, however, their associated precondition needs to be separately identified in addition to the given connection. That is, these types specify connections between events, not between individual conditions parameters in terms of entities and relationships. Incidentally, while a connection not based on causality may not be exploited for a goal-oriented deduction of an associated antecedent from a consequent in planning, it could provide useful information for an ex-post reasoning as in a police investigation in a scope of its overarching event. Though it could be further abstracted in terms only of the precedent and antecedent corresponding to its Precondition and Effect respectively, an event notably a physical event always has a procedure spanning over the time unlike a deduction rule in the logical domain. Just like an assertion is deemed to be a special case of a rule [39], i.e., an unconditional rule, a situation specified for the Effect can by itself be regarded as a special case of an event.

3.4 Detailed schematic planning in steps

As for goal state S_G, the schematic planning would proceed in several phases such as:

1) Finding an event with the goal in its effects.
2) Decomposing the found event into subsidiary events recursively until all its subsidiary events are of an action type.
3) Augmenting the plan to include exogenous events found to be associated with each event
4) Extracting the Precondition of each event by recursively integrating those of its subsidiary events.
5) Identifying all the events whose successive execution can satisfy the main goal.
6) Arranging those identified events into a plan according to their functional precedence.

An action, the basic element of an event, is defined to be what an agent can intentionally do with its body. The action is a primitive event, that is, the atomic element of an event in general. An action is schematically specified on its associated agent or agent class. A schematic action is repeated or continued to be instantiated into a plan. A schematic action, a $\triangleq$ $(S_P, \varDelta S; \overline{S_I})$ and $\overline{S_I} + \varDelta S \rightarrow \overline{S_F}$, where S_P, $\varDelta S$, $\overline{S_I}$ and $\overline{S_F}$, denote the precondition, change in situation, typical initial situation and typical final situation, respectively. An overbar denotes an average or a typical value. All those elements are of situation type. Likewise, schematic event

$$A_i \triangleq (S_P^i,\ \varDelta S_i;\ \overline{S_I^i}) \text{ and } \overline{S_I^i} + \varDelta S_i \rightarrow \overline{S_F^i})$$

S_F = {(objects) entities, relationships, information; (change) creation & destruction, state change, move, conversion, plus preservation}

To elaborate the planning phases,

1) Finding an event with the goal in its effects

Unless the goal is satisfied with the given conditions a case-based search is needed to find events which each can produce the goal situation. Of those candidate events, if any, the best one is selected and its precondition is identified.

2) & 4) Identifying Preconditions and Effects of events according to their composition

To identify the precondition of an event, those of its subsidiary events need to be identified first. The composition of each event is described in its associated ontology [54][57] or planner's world knowledge. Since each subsidiary event itself is another event it is to be successively decomposed into its own subsidiary events until they all reduce to actions.

The precondition and effect of event $\boldsymbol{A} = \prod_{i=0}^{M}(A_i)$ can be computed respectively as:

$$S_P = \bigcup_{j=1}^{M} S_P^j - \bigcup_{k=1}^{M} \overline{S_F^k},$$

$$\overline{\mathrm{S_F}} = \bigcup_{j=1}^{M} \overline{S_F^j} - \bigcup_{k=1}^{M} S_P^k$$

where $A_j,\ A_k \in A,\ M$ = the number of subsidiary events

transient conditions: Some preconditions of the subsidiary events in an event may exist only among those subsidiary events, requiring no external conditions from outside the event. That is, such a precondition of a subsidiary event can be internally satisfied by its preceding subsidiary events. Those internal conditions for event $\boldsymbol{A} = \prod_{i=0}^{M}(A_i)$ can be computed as,

$\bigcup_{j=1}^{M} S_P^j \cap \bigcup_{k=1}^{M} \overline{S_F^k}$, where $A_i, A_k \in A,\ M$ = the number of subsidiary events

Those internal preconditions could be regarded to be only transient as for the overall event so they won't be part of its precondition.

3) Adding events as stipulated by association of deontic type, but customary type generally applied to decomposition for vertical planning performed in 2).

5) & 6) Searching for the events required to satisfy the goal, and arranging them into a plan

Once the overall event has been identified in terms of its precondition and effects, the initial overall plan is to be laid out via backward reasoning with respect to the precondition. Specifically, the causality or the premise relation is exploited to deduce the events for a goal in backward search as $\{\boldsymbol{A} \mid S_P \rightarrow | \boldsymbol{A} \cup S_P \Rightarrow A,\ S_F \cap S_G \neq \emptyset\}$. The foregoing search and selection is recursively applied after setting as an intermediate goal each element of the precondition in the plan until all the derived intermediate goals are satisfiable with the average background conditions. At every round of the backward search its respective set of candidate events is deduced. That is,

$\forall s_j \in S_P^{i-1}$, where i denotes the i-th round of search starting from Round 0 for the overall event A^0

(i) Find events $\{A_j\}$ such that $\overline{S_F^j} \cap S_P^{i-1} \neq \emptyset$.

(ii) Select the best one $\dot{A}_j$ from $\{A_j\}$.

(iii) Collect the events found in (1) for each $s_j \in S_P^i$, to form the candidate event set $\{\dot{A}_j\}$ such that $\overline{S_I^i} + \varDelta S_j \rightarrow \overline{S_F^j}$ and $\overline{S_F^j} \supseteq S_G^{j-1}$.

If $S_P^i - \overline{S_I^i} \neq \emptyset$, seek to satisfy each $s_k \in S_P^i - \overline{S_I^i}$, i.e., $\forall_{s_k}$ as a goal, identify S_P^j such that $S_P^j \rightarrow | s_i$.

(iv) Sequence $\{\dot{A}_j\}$ into $\prod_{j=0}^{N} A_j$, where $N = |\{\dot{A}_j\}|$

$\forall A_j^{i-1} \in \{A_j\}$, where i denotes the i-th round of search starting from Round 0 at each selected event in $\{A_j\}$

(v) Find all the events $\{A_k\}$ such that $S_F^{i-1} \cap \overline{S_P^k} \neq \emptyset$. This is a forward search applied to Causality type to identify all events to be potentially affected, i.e., $A_j^{i-1} \Rightarrow \{A_k^i\}$.

The above algorithm is executed by the following pseudo code.

```
Begin
  Repeat
      FOR All Sp
          If Sf is equal to Sp
                Then insert Sp to List
          End If
      End FOR
      Sb ← Best Sp selected among List
      Push Sb to Event Stack
      Sf ← Sb
  Until Current Situation = Sf
  Pop from Event Stack
End
```

The effects resulting from the identified events generally include side effects besides the effects required for the goal. The effects that are not part of the goal S_G are referred to as side effects, i.e.,$S_f = S_F - S_G$. Those side effects might be detrimental enough to scuttle the entire plan.

4. EXECUTION OF SCHEMATIC PLAN AGAINST CONCRETE SITUATION

A schematic event in the plan becomes instantiated into an occurrence by filling its associated roles (and props) with available instances from their respective domains. The historical position of the occurrence is determined in reference to the entity instances and spaces that play its associated roles and provide their locations, respectively. Its occurrence location depends directly or at least indirectly on those of its associated roles. An initiated occurrence will be completed or stopped halfway, and in case it is completed its goal may be accomplished successfully or not.

Given an initial situation at t= t_0 $S_I^i(t_0)$ such that $S_P^i(t_0) \subseteq S_I^i \subseteq \Omega$ the entire set of situations in the background world, the effect from the execution $A_i = (S_P^i,\ \Delta S_i;\ \overline{S_I^i})$ would be $\overline{S_I^i}(t_0^i) + \Delta S_i \rightarrow S_F^i$ such that $S_F^i(t_0) \subseteq S_Q^i \subseteq \Omega$. The overall result from the entire plan $\prod_i A_i$ against the initial conditions $\{S_I^i(0)\}$ is expected to be $\prod_i S_I^i(t_0^i) + \Delta S_i \supseteq S_G$, where $S_I^i(t_0^i)$ denotes an initial situation for A_i with $\cup_i S_I^i(t_0^i)$ constituting the initial background situations for $\prod_i A_i$.

Every element of a plan is eventually to be formulated in terms of its associated factor variables. We specify those variables in terms of their average values plus deviation ranges, i.e., $\overline{x} \pm \delta x$. Those values and ranges are statistically computed over a class of instances on top of over the temporal span of each such instance. In the execution of a plan, those statistical ranges are narrowed down for a particular agent selected for each role in the plan. Further, their actual values keep being updated to reflect their associated situation changing over time. However, it is always possible that their values aberrate from their planned values or ranges. Such an aberration could exceed a limit to result in what we call an accident.

4.1 Casting

To execute a plan for an event to achieve a goal, the roles in the plan need to be cast from their associated pools of qualified agents in the background world. Those candidate agents may well have their respective plans independent of that plan. The moment an agent is cast in a role, that particular agent from the background world becomes coupled with the schematic plan. That is, this casting of agents entails augmentation and elaboration of the original plan according to their individual conditions [11], [25], [28], [34], [35], [43] and respective scopes of involvement in the plan. Often the resulting modification of the plan might be substantial enough to lead to its overall replanning or withdrawal.

A large complicated event typical of our planning target usually demands cooperation from other agents. Agents in our virtual world are modeled as autonomous entities with *their respective models of world and independent planning capabilities*. Their autonomous capabilities can be exploited by the lead agent subcontracting subsidiary events to those agents, who each are given carte blanche for planning the corresponding plan fragments. This *indiscriminate autonomy level* of any (lead or another) agent is manifested when those agents are cast into roles [17] or lead agent's intention toward global goal is withdrawn, which both function as major sources of intricacy of event occurrences.

As the first step of coupling the schematic plan with the cast agents it is augmented to include the exogenous events that are expected to involve those cast agents. That is,

If $E\left(A_i \in \prod_{i=0}^{N} A_i\right) \cap E\left(A_j \notin \prod_{i=0}^{N} A_i\right) \neq \emptyset,\ A_j + \prod_{i=0}^{N} A_i \longrightarrow \prod_{i=0}^{N+1} A_i$ Where $E(A)$ denotes the agents (or entities) cast for $\boldsymbol{A}$.

The exogenous events (denoted by plain ovals illustrated in Fig. 2) are derived via *multiplicity of roles or props of cast entities* besides the four association types, and coupled to the original events E1 and E2 (by bold ovals) with independent lead agents H2 and H3, respectively. A detailed description of the diagram is given in Implementation and Discussion Section. Notice that solid nodes (i.e., circles, ovals and diamonds) collectively constitute the background world with different colors encoding different categories of its elements, while timing among event occurrences and entity states are not exactly represented.

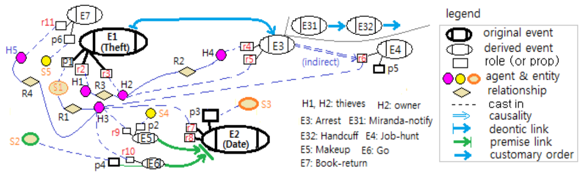

Fig. 2. Augmented plan due to cast roles with respect to their exogenous plans

The way such a cast agent could be involved in an exogenous event includes not just by being passively affected by the event but by being its agent or another active role. Specifically the plan is to be augmented by adding each cast agent's own and external factors of relevance that were not specified in the original plan but might indirectly affect the original event via the cast agent. These additional factors are linked to the original event in the plan via their associated agents' relationships with the cast agent, e.g., (the original event of) burglary detected by the *victim*'s friend H5 as visiting (the crime site of) his home in order to return his book she had borrowed (the linking relationship.) These relationships may be physical, social or mental with implication of potential events, and one of those associated agents could be the cast agent itself. In general, such linkage could successively propagate out to indirectly related factors. The range of those indirect linkages the resulting augmented plan should embrace is determined according to the probability of its occurrence, and the significance of its consequences, i.e., $f(Prob(E^i),\ Val(S_Q^i))$. Those exogenous events encompass ones that are self-induced, and propelled within each (autonomous) agent, e.g., taking a nap.

Formalizing roles of events: The set of entities involved in event A is composed of three groups such as ones in its Precondition, Effects (including Procedure) and transient ones.

Specifically, $E(A) = E(S_P) \cup E(S_F) \cup \{\hat{e}\}$, where $E(S)$ denotes the agents (or entities) involved in *S*. An Intermediate Entity $\hat{e}$ is an entity e such that $e \notin E(S_P)$ & $e \notin E(S_F)$. The set of intermediate entities, $\{\hat{e}\} = \{e \mid e \in E(S_P^{l-1})\ such\ that\ e \in \cup_{A_i^l} E(S_F^l), S_F^0 \supseteq goal\}$ where A_i^l denotes an event on the l-th round.

An event in general is executed by its associated roles. These roles include agent, target, beneficiary, instrument, etc.[58]. We could characterize the roles of events in terms of entities involved in their preconditions and effects [59]. Of the major roles, several are exemplified below,

target $\{e \mid e \in E(S_P)\ \&\ e \in E(S_F)\}$
theme $\{e \mid e \in E(S_P) \& e \in E(S_F), \tilde{e}(t) = \tilde{e}(t + \Delta t)$, where $\tilde{e}(t)$= state of e.$\}$
patient $\{e \mid e \in E(S_P) \& e \in E(S_F),\ \tilde{e}(t) \neq \tilde{e}(t + \Delta t)\}$
material $\{e \mid e \in E(S_P)\ \&\ e \notin E(S_F)\}$
instrument $\{e \mid e \in E(S_P)\ \&\ e \in E(S_F)\}$
catalyst $\{e \mid e \in E(S_P) \& e \in E(S_F),\ |T(A)| - |\overline{T(A)}| < 0\}$

Some of the roles of an event are considered essential while the others are optional according to the goal the event is to achieve. The essential roles are to be filled as the least premise for obtaining the intended effect by executing the planned event. They are assumed by agents recruited by its associated planner agent. If any of those agents playing its essential roles is missing or disabled it stops progressing, consequently with no chance to produce the targeted effect. Unlike a phenomenon, however, an intentional occurrence starts when its agent 'triggers' it regardless of whether its Precondition is satisfied or not.

4.2 Availability of candidate agents and historical context

Before filling the roles of an event their candidate agents' availability needs to be checked in a historical context. The plan against which the availability is judged includes all the (potential) events involving those candidate agents from the background world. Their availability would also vary according to their own (background) conditions of all sorts *underlying* the roles they undertake in events, independently of their associated subsidiary events involved in the schematic plan. For an agent with a set of events already assigned, $\{A_i, \mathrm{i} = 1,2,3,\ldots.\}$, its available time can be computed by, $\overline{d_i \vee d_{i+1} \vee d_{i+2} \ldots}$. i.e., $\overline{d_i} \wedge \overline{d_{i+1}} \wedge \overline{d_{i+2}} \ldots$ where d_i denotes the time duration of event A_i. In general, $d_i \wedge d_j \neq \emptyset$, $i \neq$ j. If concurrent execution of multiple events is possible a micro-planning is additionally needed [32].

A plan is executed in a historical context established on the dualistic coordinates of time and space. That is, it is reified into an occurrence with respect not only to the time but to the space in order to reflect its associated spatial relations including the locational change of its candidate agents. To keep our planning focused on the temporal aspects, the spatial dimension is collapsed into the temporal dimension in light of its dependency on time, that is, $s = f(t) \longrightarrow t = f^{-1}(s)$. Given an itinerary $L = ((\mathrm{s_i}, \mathrm{s_{i+1}}), (\mathrm{s_{i+1}}, \mathrm{s_{i+2}}), \ldots (\mathrm{s_{j-1}}, \mathrm{s_j}))$ where $(\mathrm{s_k}, \mathrm{s_{k+1}})$ denotes a leg in L, and $\Delta L = s_i - s_j$, $\Delta \mathrm{t_k} = \mathrm{f^{-1}(s_k)} - \mathrm{f^{-1}(s_{k-1})}$, for the k-th leg of L and $\Delta T = \sum_{k=i}^{j} \Delta t_k$. A leg is defined to be a linear segment of a spatial path, and can be as long a stretch as a runway and as short as a walking pace. For any leg $(\mathrm{s_k}, \mathrm{s_{k+1}})$, $\Delta s_k = s_{k+1} - s_k$ and $\Delta \mathrm{t_k} \geq 0$. In general a personal schedule varies over time, as a consequence the free time of agent H, $H.u$, becomes *H.u(t)*. The scheduling is especially complicated when the personal schedules of two agents are both variable like in transferring from a bus to another in a busy city [40].

4.3 Augmentation of schematic plan with respect to the cast agents

What could affect agents cast in the roles of an event or involved in subcontracted subsidiary events becomes of additional concern to the overall planner. If an agent is selected into a role its associated schematic plan is augmented to take the agent into account with respect to its personal schedule. That is, if human agent ***H*** is cast for occurrence A_i, A_i becomes an *arranged* part of the main plan with ***H*** as its agent. Specifically, if $T(A_i) \cap T(\prod_{k=1}^{K} A_k^H) = \emptyset$ then $\prod_{n=1}^{N} A_n^T + A_i \rightarrow \prod_{n=1}^{N+1} A_n^T$, where ***T***() denotes the time span of, and A_n^T denotes an arranged event in the main plan. Accordingly the personal plan of ***H*** is augmented as $\prod_{k=1}^{K} A_k^H + A_i \rightarrow \prod_{k=1}^{K+1} A_k^H$. After all its associated roles are cast, the final form of the main plan $\prod_{n=1}^{N_T} A_n^T \subseteq \sum_{i=1}^{P} (\prod_{k=1}^{K_i} A_k^{H_i})$, where N_T denotes the number of events involved in the original plan; *P* denotes the number of roles, K_i denotes the number of events undertaken by H_i the agents cast for the plan, and $A_k^{H_i}$ denotes the events undertaken by H_i. The special case that $\prod_{n=1}^{N_T} A_n^T = \sum_{i=1}^{P} (\prod_{k=1}^{K_i} A_k^{H_i})$ corresponds to a situation where all the cast agents are assigned exclusively to the main plan. Meanwhile $\sum_{i=1}^{P} (\prod_{k=1}^{K_i} A_k^{H_i}) - \prod_{n=1}^{N_T} A_n^T$ corresponds to the events that could affect the main plan but are not under the supervision of its lead agent.

The events that could affect the planned event via its cast agents from outside the plan are to be coupled to the schematic event. Of those exogenous events, ones that could immediately affect those agents are $\{A_k^0 \mid E(A_i) \cap E(A_k^0) \neq \emptyset\}$. In general, such impacts could come from distant events through successive propagation, specifically the propagation between adjacent events is computed by $\{A_k^l \mid E(\{A_k^{l-1}\}) \cap E(A_k^l) \neq \emptyset\}$. The entire set of relevant events is in theory, $\cup_{\mathrm{l}=1}^{\infty} \{\mathrm{A_k^l}\}$. Those exogenous events encompass both the background and environmental events. The direct effect of a background event is confined within a particular entity whereas that of an environmental event reaches all the entities within the environment. (Either type of event could be little affected by those entities.)

The effects of an event generally go beyond what its associated agent wishes to obtain. However, those consequential effects should become a part of the plan for the event. The consequence of the main event A_0, $S_Q^0 = \{S_F^k \mid S_F^0 \cap S_P^k \neq \emptyset\}$. In general, the consequence of A_i could propagate to the next level, $S_Q^{i+1} = \{S_F^k \mid S_Q^i \cap S_P^k \neq \emptyset\}$. The entire consequence S_Q resulting from the successive propagation sums up to $\bigcup_{i=1}^{\infty} S_Q^i$.

4.4 Subcontracting and phenomenon as subsidiary event

To execute a composite event composed of many subsidiary events, its lead agent takes charge of some of them on its own, and subcontracts the others. The subcontracted events from an event are regarded as external components, i.e., components supplied as a whole from the outside [40], though they are still to be properly sequenced into the event with respect to their Effects (and possibly Procedures.) Suppose, for example, an orchestra is hired to perform as a subsidiary event of a party (event.) The host (i.e., lead agent) of the party would regard it as the hired human agent's exclusive responsibility to fulfill that subsidiary event, that is, the hired agent is given carte blanche as for planning of that particular subsidiary event of performing music. Thus, the host needs not be concerned with that subsidiary event (and associated entities) for the overall event, but has only to use it as a whole. In general a subsidiary event could be broken recursively down to an ordered set of actions and their associated entities at the finest level. Those elementary components of the actions (or their agents) are represented as the leaf nodes in a tree-structured schedule for the event.

A phenomenon, once triggered, spontaneously develops unlike an agent's intentional event, which needs to be kept driven by her intention. While this spontaneity is shared with a subcontracted event as for lead agent, still a phenomenon (a subsidiary event) is to be tightly supervised by some agent playing a part in the overall event. For example, a furnace begins to burn if only ignited, whereas it is to be continuously watched by its agent (or operator) for proper fuel supply, possible overheat, etc.

4.5 Instantiation of an action into occurrences

A planned event is actually performed when its associated actions are executed by their respective host agents. In executing a plan, the actions specified therein are instantiated into occurrences against given conditions. That is, its primitive dynamic elements are executed in continuation or repetition of actions, which in their schematic forms are modeled as the basic functions of their host agents. According to its associated conditions, action a_i in its schematic form is iterated a number of times or continued for a while, to become an occurrence A_k. The effect of A_k is an accumulation of unit effects from a_i in A_k as $\Delta S_k = \sum_i \Delta S_i^k$, where the unit effect of a_i^k, $\Delta s_i^k = s_i^k(t_0^k + i\Delta t^k) - s_i^k(t_0^k + (i-1)\Delta t^k)$ with Δt^k denoting the cycle time or unit time of a_i^k.

In general a primitive action occurrence is in itself another event occurrence, which may be subject to planning. A micro-planning at this level is characterized by the fact its entire procedure is performed exclusively by its host agent. From the perspective of the overall planner, an action occurrence is effectively equivalent to any subcontracted occurrence in that a single agent is in full charge of an entire occurrence of either type. That is, the agent is to decide on, among others, the actual duration or the exact number of iterations of the action and the detailed motions on its associated actual conditions, e.g., terrain for walking.

4.6 Concurrent execution of events

The events in a plan are partially ordered so some of them are comparable and the others are not [60]. In general a planned event can start to be executed only when all its preceding events have successfully finished, resulting in $\bigwedge_i s_i, \forall s_i \in S_P$. That is, event A can be executed if $\forall_i \widehat{A_i}$, $A \nsucc \widehat{A_i}$ where $\widehat{A_i} \in$ the set of unfinished events. As a result, incomparable events may always be executed in parallel without regard to the others among themselves. $\{\widehat{A_i}\}$ shrinks as the occurrence progresses.

4.7 Failure of event occurrence

A plan is inevitably sketchy due mainly to the unpredictability of its relevant conditions from the ever-changing reality, letting alone its planner's limited knowledge. As a consequence, it is to be continuously adjusted according to the its associated conditions changing over time. Still, failure is unavoidable, which provides good chances of learning experiences and sources of narrative interests [23].

If any of the essential preconditions turns out to be unsatisfiable, $\overline{\bigwedge_i s_i, \forall s_i \in S_P}$, in its execution, the plan may need to be rescheduled or can be judged as infeasible. Time Tree with branching time future and a single past [23] lays down to handle failure (entailing consideration of alternatives or repair, or forgoing in case of optional event.)

An occurrence progresses on its planned course only when its condition values stay within their expected margins. In practice, however, it is always possible that those values deviate from their normal ranges specified in the plan, causing the occurrence to veer off its planned course or even to disrupt with results being invalid for the goal. These deviations could happen in various aspects of the occurrence, such as deviation in terms of individual parameter variable $\boldsymbol{x}$, $(x(t) > \overline{x} + \delta x) \vee (x(t) < \bar{x} - \delta x)$; deviation with respect to current situation versus typical background situation $|\overline{S_I^0} - S_I^0(t)| \gg \Delta$; numerous variations possible during the procedure $\Delta S_i(t)$, $t_1^i < t < t_2^i$; discrepancy between the expected and actual effects at each event level $\delta S_i = S_F^i - \overline{S_F^i}$, and eventually the final effects may not satisfy the original goal $\prod_i (S_I^i + \Delta S_i) \nsupseteq S_G$.

In general, the effect from executing $A_i = (S_P^i, \Delta S_i, \overline{S_I^i})$ against an initial situation S_I^i would deviate by $\delta S_i = S_F^i - \overline{S_F^i}$ from the typical one. Those deviations resulting from executing the entire schedule $\prod_i A_i$ would sum up to an overall deviation,

$$\Delta S = \prod_i (S_I^i + \Delta S_i) - \prod_i (\overline{S_I^i} + \Delta S_i).$$

The conditions that could cause a disruption include a cast agent getting disabled and a key instrument getting kaput, etc. Such a disruption amounts to the occurrence idling on itself until its associated failure is resolved as for the overall schedule. It could delay the overall schedule if it is on a critical path in the plan. The occurrence resumes only when the failed entity is remedied if reversible or an alternative entity is substituted if replaceable. If a failure is incorrigible because there is no alternative, or it is too costly to fix, or for another fatal reason, its effect would propagate *upward* the composition hierarchy of the overall event. At the same time, it is impossible for event *A* to horizontally progress until none of its preceding occurrences, i.e., $\{B_i | S_F^i \cap S_P \neq \emptyset\}$, is incomplete.

Minimum execution time and Critical path: The minimum time required to complete an event depends on its preceding events as well as the event itself. That is, the minimum completion time for an event could be computed as the maximum of the completion times of its immediately preceding events plus its own completion time or duration [56]. Let *A, B* be events with its duration denoted by δ(). The minimum completion time of *A*, $\boldsymbol{T}(A) = Max(\{T(B_i | S_F^B \cap S_P^A \neq \emptyset\}) + \delta(A)$.

A sequence of events that yields the minimum completion time for a composite event is called the critical path for the event [56]. A delay in performing any occurrence on a critical path causes a delay in the total completion time required for the entire occurrence containing the delayed occurrence. If the completion time for any event B that is not on the critical path is prolonged beyond its conjunctive peers B_i, i.e., let $A,\ B,\ B_i$ be events, $\forall B_i,\ B_i \neq B,\ \boldsymbol{T}(B) > \boldsymbol{T}(B_i)$ for $B \in \{B_i | S_F^B \cap S_P^A \neq \emptyset$, for some $A\}$, the critical path is changed to one that goes through the prolonged event.

4.8 Disruption of occurrence due to lack of intention

Apart from the dissatisfaction of its essential conditions, an intentional event could also be disrupted due to its agent's withdrawal of the intention. [23], [29]. In the execution of a schedule, an event becomes an occurrence when its associated parameters are instantiated with specific values corresponding to its surrounding situation. Unless an occurrence consists of a single action occurrence, i.e., $A = \ll a_i \gg$, its subsidiary occurrences are to be coupled as scheduled via their matching conditions produced during its execution. The couplings between those occurrences are driven by the intention of the lead agent. Hence if the intention to perform an occurrence is withdrawn for some reason after its outset, the occurrences it entails would become disoriented as their common final goal becomes void. Consequently the original schedule would be fragmented into as many isolated subsidiary schedules as the number of occurrences directly subcontracted by their lead agent. That is, the couplings between A and B_i's such that $E(S_F^{B_i}) \cap E(S_P^A) \neq \emptyset$ are severed so B_i's become independent occurrences isolated from *A*. If a disrupted occurrence, *B*, happens to be an intermediate occurrence, the occurrences it entails $\{A_i | E(S_P^{A_i}) \cap E(S_F^B) \neq \emptyset\}$ would all be interrupted until *B* resumes. Even though the original (global) schedule is no longer pursued by its agent, however, those subsidiary schedules could proceed unaffected until their associated agents become aware of the withdrawal from the global schedule.

In parallel with the horizontal dissolution above, a disrupted schedule would undergo a vertical disintegration of its subsidiary events. This disintegration would propagate recursively, i.e., from each subsidiary schedule to its own subsidiary schedules, all the way down to ones of actions corresponding to the leaf nodes of the original schedule tree. That is,

$$A_i^l = \prod_j A_j^{l-1} \rightarrow \{A_j\},\ A_i^{l-1} = \prod_k A_k^{l-2} \rightarrow \ \dots\ \rightarrow \{a_i\}.$$

These isolated subsidiary schedules would finally multiply to as many as there are agents, though many of these subsidiary schedules might be undertaken by the same agent. As far as the global goal is concerned the intermediate results from those isolated subsidiary occurrences as of their respective disruption times are rendered useless unless their agents attempt to salvage them.

In addition to this downward disruption, an occurrence might be interrupted upwardly due to failure of an essential subsidiary occurrence. If such a failure is not irreparable the interrupted occurrence could be resumed afterward. Both disruptions affect only forward along the development of an occurrence, from a disrupted subsidiary occurrence toward the last occurrence to the global goal.

4.9 Replaceability of entities cast in event roles

Each role in an occurrence has a set of candidate instances forming its associated domain, from which its associated planner would select. Such a domain ranges in size from an empty set to an (practically) infinite set. Depending on the size being one, (i.e., one of a kind), two, or more, what to do differs significantly in planning, rescheduling or resuming after disruption of an event. In case an occurrence is a subsidiary occurrence of another occurrence, however, it may be just one of several alternative occurrences (or events in the first place), or its effects may be only optional. Further the agent of its overarching occurrence may have substitutes for its currently-cast agent.

A common reason for an occurrence going awry is the failure of a participating entity playing an essential role in it. Such a failing entity must be remedied or replaced to resume an occurrence thereby interrupted. The decisions about its redemption would be based on its associated agent's judgment on its expected costs. In general, the closer to the goal the occurrence has developed, the costlier it would become to replace the entities involved therein. Specifically the entities cast in patient or other roles [59] usually become less and less replaceable as the occurrence progresses since those entities likely have undergone changes toward the goal states, that is, $\lim_{t \to t_0 + \Delta t} \tilde{e}(t) \in S_G,\ \forall e = R_i(A)$. Of various thematic roles [60], a beneficiary, an agent or a target, for example, is not replaceable since such a role represents the entire value or meaning for the particular occurrence.

5. IMPLEMENTATION AND DISCUSSION

5.1 Overall structure and contents of our implementation

We implemented an event simulation system based on our planning method. A short scenario is performed by the implemented system to demonstrate its viability as a general event planning method for simulating diverse situations in a historical context. Considering our planning is aimed to provide immersed pedagogical experience through concurrent events progressing in their common background world, we focus on inter-event coherency beyond intra-event planning and on modeling the background world numerous interrelated events concur. Our simulation shows in situation many facets of event occurrences in an integrated but layered manner according to their abstraction levels, i.e., in a schematic, instance, occurrence, and visual levels [52]. The overall structure of the simulation system is diagrammed in Fig. 3. The implementation used Visual Studio and OpenGL along with a Microsoft Access database linked to MFC via ODBC.

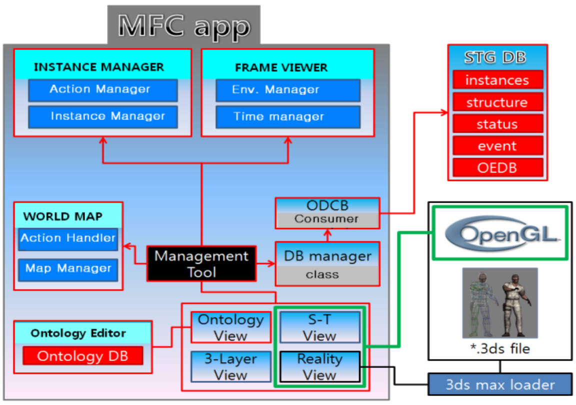

Fig. 3. Overall structure of the situation simulator

The main screen of the simulation system shows the temporal cross-section of a situation in our cyber-world [61] (and a video.) As shown in Fig. 3, the Ontology View, the (3-layer) Instance View, the Reality View and the Spatio-Temporal (ST) View are arranged in a counterclockwise order starting from the upper left view. These four views provide diverse visual and conceptual perspectives for the users on the background world in different abstraction levels, corresponding to different education levels. The most abstract Ontology View and Instance View show the schematic and instantial information about the entities, relations and events relevant to the current situation. The ST View enables the spatial location of each physical entity instance and the spatial configuration of related physical entity instances to be described in the 2.5 dimension. Each instance or occurrence is specified with its life span along the time axis. It also is equipped with a logical zooming function used to view complex structures in a hierarchical manner according to the user's learning level and disposition.

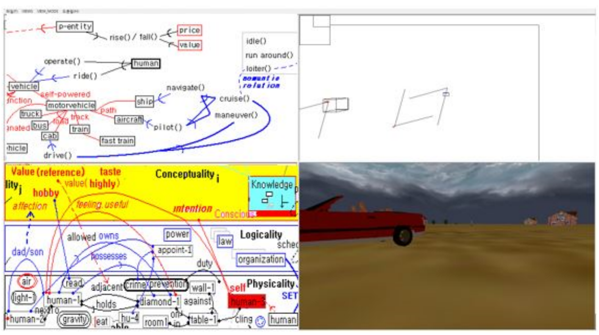

Fig. 4. Main screen of situation simulation

5.2 Application of a short scenario with theft and date to our simulation system

We apply a short scenario to a simulation system we implemented. This simulated world could be used for immersive types of intelligent tutoring systems, where students learn by experiencing in simulated situations. This situation involves not only the physical aspects related to breaking into the house, but also the social concepts like ownership and crime and the mental concepts like desire and intention (which are beyond our scope [43].) In the following description, the *italic* and **bold-face** indicate the roles in the current event and the concepts (i.e., entities, relationships, rules, etc.) of the background world, respectively, with the **bold** and *Italic* type denoting overlap of both. To explicitly model the separation between the background world and event roles (and casting of roles), we use *R*[**x**], if needed, to represent that an agent instance **x** is cast into a role *R* of an event. All the relations and relevant facts are described from MY (omniscient) perspective.

The overall situation in our focus unfolds as: As **my brother** [**Human-agent2**] prepares himself in ***his home*** [**House1**], *the thieves* [**Human-agent3 & agent4**] wait for **him** to leave. Then **he** leaves in ***his car*** [**Auto1**] to meet his date, and *the (accomplice) thief* burglarizes **his house** and runs away with **a valuable** [**Gem1 in Safe1**]. This situation as a whole would spread to involve several events starting from the initial two events, the date with my brother as its main agent and the theft with the (accomplice) thief as its main agent.

The development of the situation is captured in a series of snapshot scenes as shown in Fig. 5. Each scene is juxtaposed with its associated ST View showing a 2.5D view of spatial configuration. To narrate the scenes, in Scene 1 **my brother** is exiting **his house** through **its main gate** [**Steel-gate1**]. In Scene 2 **my brother** is getting in **his car** heading for *the appointed place* [**Restaurant1]**. In Scene 3 **police** is chasing *the (mastermind) thief***'s car**. In Scene 4 **my brother** is returning to **his house** to see what happened. In Scene 5 *the policeman* is handcuffing *the (mastermind) thief*. The last window shows a part of the diagrammatical modeling of the events in situation along the time line against their associated schedules. Specifically, Window⑥ visualizes the currently existing entity instances along the time axis, and temporal elapse using the scrollbar below. The center line indicates the present time constantly advancing, and it divides the past and the future to its left and right, respectively. The event occurrences denoted by broken lines refer to ones that are scheduled to happen in the future. The instances linked by the blue bold lines to the leading part of an occurrence play the roles therein as labeled on the lines (e.g., agent, target etc.). In general, a composite occurrence like a theft could be part of another composite occurrence, and conversely a composite occurrence could be broken all the way down in terms of a few predefined primitive actions.

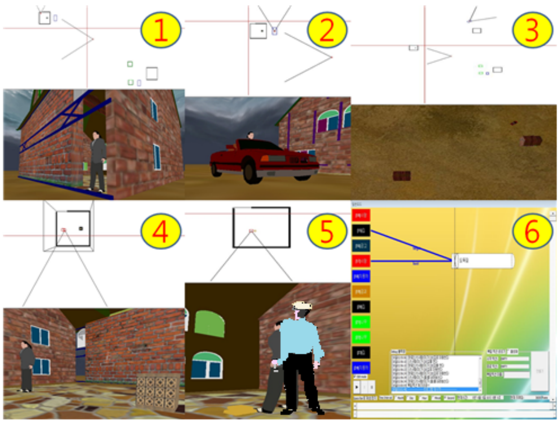

Fig. 5. A Sequence of scenes showing a situation in spatio-temporal context

Discussion along the scenario: A number of independent autonomous agents including those illustrated in Fig. 2 preexist in, and are parts of, this background world, and they share the world as their common environment. These agents along with the other entities occupy their respective (dynamically varying) positions in the historical domain, where the background world unfolds. They are interrelated in lesser or more closely, at least in historical context (e.g., collocated or contemporarily.) Each agent tends to be involved in different relationships at once. Event, the most comprehensive type of relationship encompassing usual entities and (static) relationships and up to temporal aspects, lasts only for a while, which renders agents' involvement in an event temporary in an omniscient perspective.

Our two initial events involve their respective sets of roles as presented below. A theft event and a date event are planned by independent agents but these originally-independent events come to be coupled via a common entity, i.e., valuables stored in a safe, as the target of the theft and as the object of an ownership at once, and a background linkage that the owner agent happens to be the agent participating in the date. (The parts enclosed by square parentheses indicate scenario development distinguished from the commentaries.)

[_According to the theft plan, the *accomplice* burgled the house while his *mastermind* acts as a *lookout* watching for the police. Our situation starts with a scene the *accomplice* waiting for **the owner** to leave home.]

The safe and the gem therein are modeled in the background world, to change (e.g., rust) in time on their own or due to interactions with other entities (including environmental ones,) whereby their states are variable in historical context.

[On spotting his departure, the accomplice breaks into the house by scaling its fence. After several tries to open the safe to no avail he decides to carry it whole out **instead of** its content.]

This change in the target of carrying requires a partial re-planning (corresponding to local re-planning [8]). As unsatisfied executability conditions in general are a main source of action failure and consequently story variations [36], our model elaborates on these conditions with respect to their essentiality, repairablility, replaceablility, etc. as another measure for generating further experiences. This elaboration is in line with our principle to trace causality chain across the background world beyond on-stage effects confined within a scene or an event [36].

[_While sneaking out he accidentally drops the safe with a thud; noticing something might be happening in his house **the owner** returns home off **his original schedule** (set in his background independently of the theft.) On sensing things might go awry inside the *mastermind* starts running away, which happened to be discovered by nearby *patrolling policemen* and chased. Before long *the suspect* gets caught flagrante delicto and interrogated. As the scenario focus moves to the police arrest from the theft, the theft could become part of the background. In the arrest, the *mastermind suspect* is first notified of his 'Miranda Rights.']

This notification is a customary step of the legal procedure of police arrest, as stipulated by a law.

[From a background check *he* is found to be **on probation** for the same crime.]

This **historical** fact may well affect his penalty later in a subsequent trial (another instance of normative procedure a criminal activity entails.)

[Also, *he* turns out to be a long-lost childhood **friend** of one of *those policemen* on the scene.]

This is a consequence of **a past socializing event (maybe many of such events) between them**, which fact provides a clue to favorably modulating subsequent interaction between them or diverting the scenario to a new main event (rather than digressing to a side story), e.g., making a nostalgic visit to their hometown. Notice **their friendship** is a preexisting part of the background world rather than a contrived set-up just for a particular side story as in conventional drama.

In general, desire (and its corresponding goal) to perform an event could arise according to agent's judgment on either precondition or postcondition of the event (among numerous origins of his relevant associations) as known to him [36]: desire to exploit a current condition to perform a long-awaited event whose precondition happens to be (almost) satisfied by the current condition, or desire induced from a given situation which might be fulfilled by the postcondition of some event he is knowledgeable of. This thinking process can be formalized based on a two-tier structuring of the world with the thought layer over the layer of objective facts, and origin of judgment can be further elaborated in terms of mood and personality [46].

Event coupling through an agent instead of ***the safe*** would have far greater implications. Suppose the theft *victim* happens to be a child. That association would implicate **me** into the theft event, resultantly the scope of potential consequence reflected on the corresponding event planning would expand as widely as to include all my background conditions as well. For example, I, on his call, may have to break off my schedule to assist him.

In general, an event occurrence could be adjusted or modified by its cast agents' individual states or ambient conditions in the background world. Suppose, for example, **my brother** found he had left ***his wallet*** behind soon after leaving home and decided to return home. As for the event of the theft, this exogenous condition on the *victim* agent could indirectly hinder its development as soon as its *thief* agent spots **my brother** returning. Otherwise, a *passer-by* might witness the scene and report it to *the police*, triggering a compounding event of police investigation.

Until the *mastermind*'s (tacit) determination of abandoning his plan of theft is transmitted to *his accomplice* the activity of *the accomplice* goes on progressing as originally conspired. That is, the plan failure is only on *the mastermind* but not on *the accomplice* for a while. The *mastermind*'s impromptu decision (a situated action [20]) is based on his judgment that a retry after repair or with an alternative [36] is infeasible under the current conditions. In parallel with this downward propagation of failure, a failure in some subsidiary event in general could scuttle its overarching event and propagate recursively upward to the topmost event, i.e., the entire event. In this scenario, for example, *the accomplice's* sprained foot could impair his walking and carrying out **the safe** and eventually thwart the theft in its entirety. (Notice incidentally that while failure is among less tricky concepts it is still not definitely definable in case of an event involving multiple independent agents like with two-phase transaction control as in distributed database [62].)

A list of event association instances derivable by the four association types in the schematic phase of planning with respect to the above scenario is given below, where ' ' delimit *event instances*; ∥ denotes parallel progression; < > enclose an overarching procedure (or event) specified in the sequential order of subsidiary events;

causality type '*accomplice dropping safe'* ⇒ *'mastermind's escape'* ∥ *'owner's return'*
premise type *'owner's return home'* →| *'check to see what happened'*; *'theft'* →| *'obtain gem or money'*
deontic type *'theft'* |→ *'penalize'*
customary type arrest = <*'notify Miranda rights'* → *'apprehend'* → … >

6. CONCLUSION AND FUTURE RESEARCH

We have developed an agent-centric event planning method for providing pedagogical experiences with an objective of learning declarative knowledge. This two-level event planning, inter- and intra-event level planning, identifies for a given goal a number of events and arranges them into a schematic plan according to their hierarchical composition and associated causalities and other associations. These additional types of association include normative procedure and deontic types between events besides types based on the conventional causality. The resulting schematic plan is augmented with exogenous events to reflect the individual conditions of those agents cast in its associated roles as well as its impacts on the background world. Eventually it is reified to a branched sequence of a number of occurrences uniformly of atomic actions arranged toward their overall goal. Throughout its execution phase, the plan is adjusted to the conditions of the particular agents (and entities) cast in its associated roles (and props) and other ambient conditions. Due to the strict separation of roles from candidate agents from the background world the resulting planning is compounded by a potentially complicated event of casting in terms of availability of agents, subcontracting and concurrent execution of its subsidiary events, critical path with respect to a required execution time, etc. Further compounding problems in execution phase include disruption of plan execution due to failure of its associated roles or other unforeseen changes in varying conditions.

By implementing a situation simulation system based on our event planning method we demonstrated its viability as a general platform to provide diverse situations (The situation in this simulated virtual world is characterized its relevant event occurrences and their results accumulated over time.) Through a typical scenario we illustrated how a schematic plan could be augmented and adjusted according to its functional associations with various exogenous factors and changing conditions. This implementation reflecting a multi-dimensional, multi-layered nature of our planning enables the user to view an occurrence from many specific aspects or perspectives as well as an overall context. In the time dimension, the complex occurrence could be visually planned in diverse abstraction levels according to its hierarchical composition and different time units as modeled.

Limitations: Constructing a full-blown background world in a practical level is a vast undertaking, which the affordance of our simulation largely depends on. Our approach shares the same problem of authoring burden with [10], especially for the case-based search [14], which is inevitable due to inherent nature of any large problem domain. Likewise, the quality of intricate interactions among agents is mostly left to author's responsibility. The world model without proper modality entails determinism in action effect and single cause of change among other simplifying assumptions, which is to be improved by developing a sophisticated multi-modal world within agents' conceptual worlds for a realistic simulation of the agents' behavior and events. While agent's knowledge determines the extent its plans could be expanded, we implicitly take an omniscient perspective for each agent about the world, which obviously does not reflect the reality.

While decisions on action executability condition in terms of cross product of numerous qualitative and quantitative parameter values instead of binary decision between success and failure [36] significantly enhances diversity of situations, they are bound to incur combinatorial explosion. To alleviate combinatorial explosion in planning, we are exploring into various modularization techniques like one in [49]. Those techniques include designing articulated course of event progression delimited by intermediate goals, and clustering entities by interrelationship beyond intra-relationships [22], [43] in addition to layering and segmentation of world knowledge as previously introduced.

Future research: Existing user or learner interaction models [13], [17], [26], [46] are to be tailored to fit our learners. The learner model is to statistically compile learning performance (indexed to background world) from the events each learner has experienced. Personality traits in agents' attitude model [25], [28] should be elaborated based on values, reason etc. beyond emotion [11], [43]. A computation model is needed to provide performance for the implementation of concurrent events involving many interrelated agents and entities [32]. An effective similarity measure [55] is to be devised for our event planning especially for case-based search [20]. Also, pedagogical control in a global perspective is needed over all the events throughout the timeline, which is implied in [45].

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