

Braid: Weaving Symbolic and Neural Knowledge into Coherent Logical Explanations

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Abstract

Traditional symbolic reasoning engines, while attractive for their precision and explicability, have a few major drawbacks: the use of brittle inference procedures that rely on exact matching (unification) of logical terms, an inability to deal with uncertainty, and the need for a precompiled rule-base of knowledge (the “knowledge acquisition” problem). To address these issues, we devise a novel logical reasoner called Braid, that supports probabilistic rules, and uses the notion of custom unification functions and dynamic rule generation to overcome the brittle matching and knowledge-gap problem prevalent in traditional reasoners. In this paper, we describe the reasoning algorithms used in Braid, and their implementation in a distributed task-based framework that builds proof-explanation graphs for an input query. We use a simple QA example from a children’s story to motivate Braid’s design and explain how the various components work together to produce a coherent logical explanation. Finally, we evaluate Braid on the ROC Story Cloze test and achieve close to state-of-the-art results while providing frame-based explanations.

Introduction and Related Work

Symbolic reasoning systems work well for certain knowledge-rich domains that typically involve a (pre-defined) set of axioms or rules, use structured queries and datasets, and have a need for precise logical inference with explanations. However, they have several well-known limitations. The inference procedures are highly brittle in that they require precise matching/unification of logical terms to construct a complete explanation. Moreover, such systems suffer from the knowledge acquisition problem (i.e. how does one acquire the rules). Often, the rules are hand-coded, an approach which doesn’t scale in general.

To address these issues, there has been a growing interest in exploring neuro-symbolic approaches, such as NL-Prolog (Leon et al. 2019) in which the authors use a Prolog-like system to do back-chaining from a query to find proofs, where the entities/predicates have distributed representations (allowing for weak unification), and the inference rules are learned during training by specializing generic templates like $P1(?X1, ?X3) :- P2(?X1, ?X2), P3(?X2, ?X3)$. However, NL-Prolog is an end-to-end (E2E) differentiable system whose explanations are not fully transparent (e.g. the

learned rule predicates have distributed representations and are not directly interpretable). Also, the embeddings for entities/predicates once learned during training are fixed at test time. Other neuro-symbolic approaches are built on similar ideas to encode logical semantics in E2E differentiable networks such as Logic Tensor Networks (Serafini and d’Avila Garcez 2016) and IBM’s Logic NNs (Riegel et al. 2020).

We take a complementary approach: our novel logical reasoner, called Braid, is at its core a symbolic reasoning engine, and thus capable of producing explicit logical explanations, but at the same time, it uses statistical methods to *inject* explicit term alignment or missing rule knowledge, considering the Knowledge Base (KB) context at run-time.

It does this by supporting *custom-unifiers*, which are functions that propose and score mappings between the terms of two logical propositions, given the KB as context. In our work, we use neural matching functions as unifiers. Braid also supports *dynamic rule-generators* - DRGs - which given a target proposition (goal) and a KB as input, output a scored list of hypothesized rules that are used to prove the target (these rules are fully interpretable, unlike in NL-Prolog). We describe a DRG implementation using a neural rule generation model that was trained on a dataset of crowd-sourced causal rules (Mostafazadeh et al. 2020).

We discuss the reasoning algorithms used in Braid, their implementation in a distributed task-based framework for proof graph building, and an evaluation of Braid on ROC stories (Nasrin Mostafazadeh 2016).

Motivating Example

We describe an example to illustrate the challenges that a logical reasoning engine faces when answering story understanding questions. The text below is from a children’s story (Grade: K) on the ReadWorks website (<http://readworks.org>).

Consider the following short story:

“Fernando and Zoey go to a plant sale. They buy mint plants. They like the minty smell of leaves. Zoey puts her plant near a sunny window. The plant looks green and healthy!”

The question we would like to answer is:

“Why does Zoey place the plant near the window?”

Questions of this nature are part of the **Template of Understanding**, defined in (Dunietz et al. 2020), that is used

to test an AI system’s deep understanding of a narrative story. The paper demonstrates that existing SOTA question-answering systems perform very poorly at this task, which remains an unsolved research problem.

Figure 1 shows the logical interpretation of a sentence in the story. For each sentence, we generate multiple probabilistic interpretations (each associated with a confidence) by running a state-of-the-art semantic parser (Kalyanpur et al. 2020) and a co-reference resolution component (Stanford). We omit details about the NLP stack, as they are not relevant for this paper.

Zoey puts her plant near a sunny window
1. put(e2)
2. agent (e2, Zoey)
3. theme(e2, plant)
4. destination(e2, window, near)
5. hasProperty(window, sunny)

Figure 1: Logical interpretation of a story sentence

In the figure, *e2* is a constant which denotes an event/action, while *Zoey*, *plant* etc. are constants derived from story terms. On the other hand, predicates such as *put*, *agent*, *theme* etc. come from our lexical ontology called Hector. The Hector ontology is a collection of frames (concepts and relations) derived from FrameNet (Ruppenhofer et al. 2006) and NOAD (Stevenson and Lindberg 2010) that aims to capture the core meaning behind text.

The question interpretation is shown in Figure 2. We assume that we have run a co-reference algorithm on the question and story text, and so the same constants are used (when co-referential) in the question and story interpretations. The specific question representation (line 5) uses the *motivates* relation and is querying for Zoey’s goal which explains her performing the place action.

Question: Why does Zoey place the plant near the window?
1. place(e3)
2. agent(e3, Zoey)
3. theme(e3, plant)
4. destination(e3, window, near)
5. ?motivates(Zoey, e3, ?goal)

Figure 2: Logical interpretation of question

Answering this seemingly straightforward question requires a lot of implicit background knowledge, such as that a plant near a sunny window gets exposed to light, that plants need light to be healthy, and that Zoey wants the plant to stay alive (which motivated her action). Also, in this particular example, the *put* action (in the story) and the *place* action (in the question) are similar/synonymous in this context.

In the subsequent sections, we shall see how Braid resolves these issues via dynamic rule generation (to bring in background knowledge) and fuzzy unification (to overcome the verb action mismatch).

Braid

In this section, we describe the overall Braid framework – a parallelized infrastructure for constructing deductive proof/explanation graphs for a given query and KB. We start with two key Braid functions: Unifiers and Provers.

Unifiers

One of the core functions in any FOL-based reasoner is unification. The standard unification function (*syntactic unification*) takes a pair of predicate logic formulae P_1, P_2 , and checks if there exists a mapping of variables from one to the other which makes the two formulae equal. For example, the formulae $\text{hasPossession}(\text{Zoey}, ?y)$ and $\text{hasPossession}(?x, \text{plant})$ unify with the mapping $\{?x=\text{Zoey}, ?y=\text{plant}\}$.

We generalize the notion of unification to be any FOL formulae matching function, defined as follows:

$$\text{unify}(P_1, P_2, K) \rightarrow \{\text{UR}_1 \dots \text{UR}_n\}$$

where P_1, P_2 are predicate logic formulae, K is the knowledge base (which acts as context for the matching) and $\{\text{UR}_1 \dots \text{UR}_n\}$ are a set of **Unification Results**, where each UR contains the following information: a substitution that maps variables, entities or even the predicate in one formula to the other; score (0-1) which reflects the confidence of the mapping; and additional metadata used by the unifier function when making its decision (which can be exposed by Braid in the final explanation).

Consider the example described in the previous section, where the story interpretation contains the proposition $\text{put}(e1)$ while the question interpretation has the proposition $\text{place}(e3)$. Under standard unification, both these propositions would not unify, as they use different predicates and arguments. However, we have designed a custom unification function that considers word/phrase similarity (note: *place* and *put* are constants derived from story text) to align the two formulae, using the additional context that they share the same agent (*Zoey*), theme (*plant*) and destination (i.e. *near the window*) to boost the match score. Such a function may return $\text{unify}(\text{put}(e1), \text{place}(e2)) \rightarrow \{\text{put}=\text{place}, e1=e2\}, 0.9$.

Our default algorithm for fuzzy unification between (P_1, P_2) uses BERT to generate distributed representations for the predicates and arguments in the two formulae respectively, by running on the text the symbols were parsed from, then gets the pair-wise cosine-sim across the terms, and outputs a weighted sum of the similarity scores. If P_1 and P_2 are reified events, the algorithm computes a product of the scores for all the event-participant relations.

Provers

Similar to how SLD resolution (Prolog) works by building out a search tree for a given query/goal, Braid works by constructing a proof graph by using unification methods to backchain on clauses (rules/facts) in the KB.

To support various reasoning algorithms, we define the notion of a Prover, a function which given a (sub) goal and the KB, performs a “single step” expansion of the graph along a particular reasoning path.

$$\text{prover}(G, K) \rightarrow PD$$

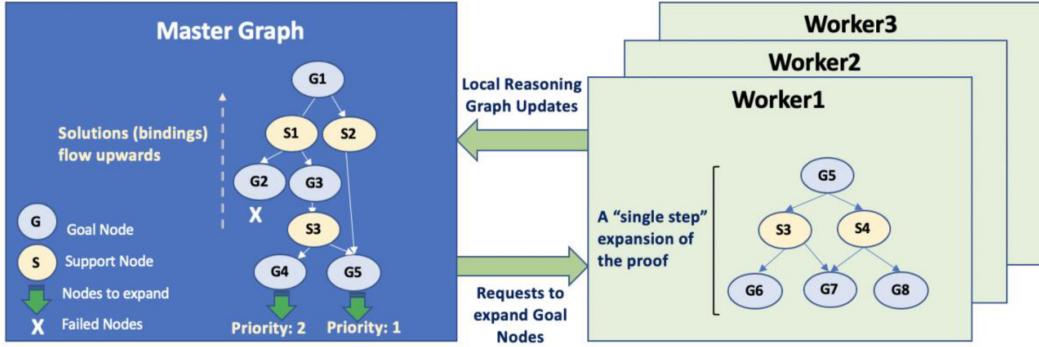


Figure 3: Distributed Proof Graph Builder

where G is the input goal, K the knowledge base, and PD is a partial proof-derivation graph with the following properties:

- PD has two types of nodes: goal nodes and support nodes.
- Support nodes provide justification for some goal node and play a key role in the flow of information (e.g. solution bindings) in the overall proof graph.
- Goal and support nodes in the graph are interleaved, i.e. a goal node can only have support nodes as its children (and vice versa).
- G (input goal node) has to be the root of the graph PD

For example, a *Rule-Based Prover* finds rules in the input KB whose respective consequents unify with the goal (using any implementation of the Unification interface defined earlier), and then output a partial proof-tree which has the goal as its root, a Rule-Support child node for each such rule whose consequents unify, and an additional edge from each support node to the corresponding antecedent of the rule. Note that the prover need not prove the antecedent immediately.

The main advantage of this design is its scalability for deployment in a distributed setting – each prover performs a local computation, without requiring knowledge about the overall proof-graph, which enables parallelization across cores and machines. Also, the communication between the master Braid algorithm (which constructs the entire proof graph) and each individual prover is kept to a minimum.

Distributed Proof Graph Builder

Braid uses a task-based framework where a central “Master” task builds the entire proof graph for the input goal by communicating with a set of “Worker” tasks, each of which use Provers to perform local graph-based reasoning (see Figure 3 for the architecture diagram).

The master algorithm is a generic, parallelized, graph building approach that continuously modifies a central Braid graph based on asynchronous updates coming in from (remote) workers.

Nodes in the Braid graph are either Goal nodes or Support nodes. Each node is associated with a collection of Unification-Results that represent bindings flowing into the node via its child edges. Crucially, atomic goal nodes are reused across the graph (i.e. there is only one node per

atomic goal proposition in the entire graph) which allows us to reuse solutions found earlier for the same goal proposition (caching).

Goal nodes have a State, which is one of three values: Success, Failure and Unknown. A special kind of support node is a Fact-Support node, which are graph leafs, and correspond to facts that unify with atomic goals.

The key functions of the master algorithm are:

- *Merging Local Graph changes into the central Master Graph*: which takes the next graph update coming from the worker and merges its contents into the main graph. If we are merging a new edge from the local graph sent by the worker, and there is an equivalent (under variable substitution) destination goal node in the master graph, we connect the new local goal node to a new Variable-Mapping Support node (which stores the underlying variable substitution) and connect the latter to the corresponding master goal node.
- *Determining Next Sub Goal*: uses a Goal Selection Strategy to determine which goal node(s) in the graph to expand next. The default ordering strategy uses the following features: an aggregation of the product of confidences of the supports in the path from the node to a query, the minimum path distance from the node to a query, a measure of goal complexity (computed using syntactic heuristics such as the number of nested formula in the goal), and a measure of goal “plausibility” (estimated by using a statistical language model to score text plausibility on the textual version of the goal proposition).

Detailed pseudo-code of the proof-graph builder algorithms are in the supplementary material (Appendix).

Reasoning Algorithms in Braid

We now describe two reasoning algorithms that have been implemented as Provers in Braid: a default reasoner that extends SLD and can be used to explain any query, and a specialized reasoner for explaining why agents carry out certain actions in a given story.

Default Backchaining Prover: SLD+

The default back-chainer in Braid is based on SLD resolution with a few key extensions (hence the name SLD+). The

algorithm is shown in Figure 4.

```

SLD+ Prover
(Configured with an aggregate collection of Unifier Functions AU, and a Rule-Generator RG)

// Given goal G and KB K, returns a partial derivation graph PD
prove(G, K)
1. PD = {G}
   // unify goal with facts in the KB
2. for (f in facts(K))
3.   for (UR in AU.unify(G, f)) // use configured unifier functions
4.     FS = new fact-support(F, UR)
5.     PD.expand(G -> FS)
   // process rules in KB, including dynamically generated rules
6. for (R in union(rules(K), RG.dynamicRules(G, K)))
7.   if (AU.unify(G, consequentOf(R))
8.     RS = new rule-support(R)
9.     ant = antecedentOf(RS)
10.    PD.expand(G -> RS -> ant)
11.    for (c in existentiallyQuantifiedPropsConsequentOf(r))
12.      PD.expand(c -> RS)
   // split the conjuncts of a conjunction; add a JOIN support node in between
13. if (G is a1 ^ a2..^ an) // conjunction
14.   JS = join-support(G)
15.   PD.expand(G -> JS -> a1...
                           \--> an)
16. return PD

// Method called when new bindings propagate in Master
propagateToProver(n, parent, s, U)
17. if (isRule(parent))
18.   update(parent, s, U) // update parent node's state and unification results
19. elif (isJoin(parent))
   // perform standard DB join operation on bindings, but use unification as fallback
20. state, unifs = doJoin(children(parent))
21. update(parent, state, unifs)

// can handle any query/goal
canProve(G)
  return true

```

Figure 4: Default Prover based on SLD resolution with extensions

Like SLD resolution, it tries to resolve the goal by unifying it with clauses (facts/rules) in the KB. Unlike standard SLD, however, it uses custom unifier functions when performing the unification (/matching) in three separate places: when matching the goal against facts in the KB (line 3), when unifying against the consequents of rules (line 7), and in the join operation when bindings are propagated (line 18) as a fallback if the standard DB join operation fails. As noted earlier, the unifiers return Unification-Results with a matching score which is used by Braid to score and rank the solutions and proofs for the input query.

Additional differences from standard implementations of SLD resolution include: the algorithm splits conjunctive goals into individual conjuncts which can be evaluated in parallel (lines 13-15); it uses a Rule-generator to dynamically generate rules for the given goal (line 6); and it creates additional nodes for rule consequents containing existentially quantified variables (lines 11-12), in order to forward propagate skolemized inferences.

“Agentful” Action Prover

For the motivating example, we need to explain the action of Zoey placing her plant near the sunny window. In general,

we refer to such actions as Agentful actions (the agent being Zoey in this case).

One reasoning strategy for explaining Agentful actions is the following: first find the motivations of the agent, and then check if the action carried out by the agent leads to one of the agent’s objective.

This reasoning strategy can be described by the following logical rule:

```

motivates (?agent, ?action,
?goal) :- hasGoal(?agent, ?goal),
leadsTo (?action, ?goal)

```

The rule uses the predicate `leadsTo` which has the following operational semantics: find a proof for the goal and check if the proof contains the specified action.

The default SLD+ prover does not have support for handling specialized predicates like `leadsTo`. Moreover, for efficiency sake, the antecedents of the rule should be evaluated in the order specified above – i.e. first, find the goals of the agent, and then for each goal, look for a proof for that goal and check if the action is part of the proof-tree. We implement this single-rule logic using a specialized prover called the Agentful Action Prover. In this prover implementation, when bound agent-goal solutions (for the first antecedent) are propagated back to the prover support node, it searches for proofs for the second (now fully bound) antecedent, and finally checks if the action is part of any proof.

Dynamic Rule Generator (DRG)

As noted in the introduction, the idea behind dynamic rule-generation is to provide missing rule knowledge on the fly to the reasoning engine, where the rules can come from an external function (the rule generator). The generic DRG interface has one core method, which given a target goal and KB, returns rules relevant to proving the goal. We now describe a neural DRG implementation.

POSSIBLE CAUSES »	EVENT / STATE	» POSSIBLE EFFECTS
Olivia feel(s) competitive	» Olivia plays in a soccer game	» Olivia runs toward the goal
Olivia want(s) competition		Olivia want(s) success
Olivia want(s) fun		Olivia feel(s) competitive
Olivia feel(s) competition		Olivia want(s) to win
Olivia want(s) to play soccer		Olivia has the ball
Olivia goes to a soccer game		Olivia feel(s) happy
Olivia wants to play soccer		Olivia feel(s) excited
Olivia plays soccer		Olivia gets the ball
Olivia likes soccer		She has the ball
Olivia likes to play soccer		Olivia scores a goal

Figure 5: GLUCOSE suggestion for a story about soccer.

GLUCOSE is a crowd-sourced dataset of around 500K common-sense explanatory rules. The dataset consists of both general and specific semi-structured inference rules that apply to short children’s stories. The rules are collected along ten dimensions of causal explanations, focusing on events, states, motivations, emotions, and naive psychology.

(Mostafazadeh et al. 2020) had shown that by fine-tuning pre-trained transformer models on the GLUCOSE data, the resultant neural generative model was able to produce contextual common sense inference rules on unseen stories with surprisingly high accuracy. Example inferences

by the Glucose DRG on a children’s story are shown in Figure 5.

We use the GLUCOSE trained model as our DRG implementation for the deep story understanding problem, since the GLUCOSE rules were acquired along the same dimensions defined in the Template of Understanding. In other applications (such as in the next section), we create alternate DRG implementations more suited to the given task.

The input to the GLUCOSE DRG is a goal proposition and the KB propositions as context, and we run our Natural Language Generation (NLG) component (a straightforward template-based approach) to produce textual versions of all the logical formulae. We then feed the textual goal and context to the neural GLUCOSE model which returns textual rules with confidences. Finally, we convert these unstructured rules back into a structured logical form using the semantic parser.

Proof Finding and Ranking using ILP

Once the Braid Master has built the master proof-graph for an input query, which encapsulates a collection of proof trees, the final step is to extract a ranked list of valid proofs for the query answers, provided the status of the original goal (query) node is Success.

The default proof-finding procedure in Braid is cast as an Integer Linear Programming (ILP) problem: we create binary variables that represent the inclusion/exclusion of each node in the graph.

The ILP program has the following constraints

- The query/solution goal node must be included
- If a goal node is included, exactly one of its support nodes must be included
- If a support node is included, all its antecedent (children) goal nodes must be included; unless it is a Fact-Support node, in which case it is a leaf node

Along with the following objective function: maximize the product of confidences of all included nodes.

Each solution to the ILP problem constitutes a single proof-tree to the input query, and the top solution has the highest overall confidence.

Putting it all together

Braid solves the motivating example by generating the proof tree shown in Figure 6.

It starts by using the Agentful Action Prover (AAP) to backchain on the rule R1, which first looks for Zoey’s goals and then checks if the “place” action (e3) performed by Zoey can lead to one of her goals (line 1). The sub-proofs use rules to infer that Zoey wants her plant to be healthy (R2), and that the plant being in contact with light causes it to become healthy (R4). Note that R2, R4 and R5 are dynamically generated by the GLUCOSE-based DRG, while R3, R6 and R7 come from the semantics of “buy”, “put” and “sunny” respectively, as manually defined in the Hector ontology. Finally, a fuzzy unification function is used to realize that put and place are similar actions in this context.

While this example shows how Braid’s components come together to produce a deep logical explanation in keeping with the Template of Understanding for narratives, more work is needed to demonstrate high accuracy across a large story set. However, preliminary results are promising - on a small sample of 10 children’s stories from ReadWorks, Braid gets an accuracy of 60% over 50 questions in the “zero-shot” setting (i.e. without any training; since we have no ground truth data for explanations) which is substantially better than SOTA systems (38%) at this task. Also note that with Braid the user can give feedback on each element of the proof (e.g. a faulty fuzzy unification or an invalid rule), and this knowledge is directly used as training to improve the underlying neural function. Getting this fine-grained training signal is not possible with other neuro-symbolic systems.

Evaluation: ROC Story Cloze Test

To demonstrate the effectiveness of using explicit semantic representations and dynamic rule generation for a more constrained NLP reasoning task (as compared to general deep story understanding), we used Braid to tackle the ROC Story Cloze Test. The Story Cloze task is as follows: given a 4 sentence story, and two possible endings, pick the more plausible story ending (one that fits better in the context of the story). Examples are shown in Table 1. For our experiments, we focus on the Spring 2016 ROC dataset, which has a validation set and a test set of 1871 examples each.

This task relies on commonsense knowledge, which is typically hard to acquire and represent explicitly. Nevertheless, recent advances in transformer-based language models, such as GPT2 and BERT, have made it possible to build E2E neural solutions that do very well (accuracy in the high 80s) on this task. A common downside with these approaches is the lack of explicability. Instead of a pure neural approach, we developed a hybrid neuro-symbolic solution to this problem using Braid, one that is capable of giving an explanation for choosing a particular story ending.

Our approach is based on the notion of Schank’s scripts (Schank and Abelson 1975), and assumes that each of the stories involves one or more frames or situations, and that information in the story is consistent with the frames. For example, the first row in Table 1 might correspond to the frame *lesson-learned* since Rick realizes the folly of his ways; the second to the frame *made-plan-executed* as Ignacio has a goal in mind and works hard to achieve it; while the third row might correspond to the frame *change-belief-happy* where Nya was initially nervous about a trip that she eventually enjoyed.

Our hypothesis is that if we can correctly detect the applicable frame from the first 4 sentences of the story, we should be able to predict the right ending that is consistent with the detected frame. Furthermore, the frame provides an explanation for the chosen ending.

Frame Inference

We decompose the Story Cloze problem into two steps:

1. Detect a frame given the first four sentences of the story, i.e. estimate $Pr(Frame|Story)$

Logical Proof

1. motivates(Zoey, e3, hasState(plant, Healthy)) :- hasGoal(Zoey, hasState(plant, Healthy)) ^ leadsTo(e3, hasState(plant, Healthy)) [R1]
2. | _hasGoal(Zoey, hasState(plant, Healthy)) :- hasPossession(Zoey, plant) [0.8] [R2]
3. | _hasPossession(Zoey, plant) :- buy(e1) ^ buyer(e1, Zoey) ^ theme(e1, plant) [1.0] [R3]
4. | _buy(e1) ^ buyer(e1, Zoey) ^ theme(e1, plant) [FACTS]
5. | _hasState(plant, Healthy) :- contact(plant, light, ambient, high) [0.65] [R4]
6. | _contact(plant, light, ambient, high) :- contact(window, light, ambient, high) ^ near(plant, window) [0.7][R5]
7. | _ contact(window, light, ambient, high) [FACT]
8. | _near(plant, window) :- put(e2) ^ theme(e2, plant) ^ destination(e2, window, near)[1.0] [R6]
9. | _put(e2) ^ theme(e2, plant) ^ destination(e2, window, near) [FACTS]
10. | _contact(window, light, ambient, high) :- hasProperty(window, sunny) [1.0] [R7]
11. | _put(e2) ~ place(e3) [0.9] [FUZZY UNIFICATION]

NLG for explanation

Zoey possesses a plant as a result of buying it. Because Zoey possesses a plant, she wants the plant to be healthy. This motivates her to move the plant to the window.

Moving the plant to the window leads to it being healthy for the following reason(s): After she moves the plant, it is near to the window. The window is in contact with sunlight, which is ambient. As a result, the plant is in contact with sunlight, so it becomes healthy.

Figure 6: **Explanation for: Why does Zoey place her plant near the window?** Note that FACTS in the proof, which are generated by the NL interpretation components, are also associated with confidences (not shown above) that are factored into the final explanation score. Also, we have an Natural Language Generation (NLG) module, beyond the scope of this paper, which generates a more consumable explanation for end-users from the logical proof tree.

Story	Right Ending	Wrong Ending
Rick grew up in a troubled household. He never found good support in family, and turned to gangs. It wasn't long before Rick got shot in a robbery. The incident caused him to turn a new leaf.	He is happy now	He joined a gang
Ignacio wants to play a sport while he is in college. Since he was a good swimmer, he decides to try out for swim team. Ignacio makes it onto the team easily. At the first swim meet, Ignacio wins second place!	Ignacio gave up swimming.	Ignacio won a silver medal.
Nya had been asked on a paintball trip with friends. She was nervous about going. But she went anyways, hoping to have fun. She shot paintballs at her friends and laughed the whole time.	She loved it so much she planned a trip for the next week.	She was shot and vowed to never go there again.

Table 1: ROC Story Cloze Test Examples

2. For each possible ending, compute the probability of it being the ending of the story considering the detected frame, i.e. $Pr(\text{Ending}|\text{Story}, \text{Frame})$

Our first challenge was to define a collection of relevant frames for the ROC stories. We analyzed a random sample of 350 story examples from the validation set (approximately 1/5th of the entire set) and manually labeled each story with a frame. Each frame is a generic description of the situa-

tion unfolding in the story. The process of frame creation was iterative but admittedly subjective - we generalized concepts that seemed too specific, or specialized highly generic concepts to capture sentiment/emotion. In all, we created a set of 19 frames. Examples include: *met expectations* (*happy/sad*), *surprise* (*pleasant/unpleasant*), *resolving problem*, *persistence* (*worked/failed*), *ran into accident* etc.

We used this annotated set to train a classifier using a pre-trained encoder-decoder model (T5-base), which given the first four sentences of the story as input, predicts the corresponding frame. We used a 90/10 split for train/dev and found that the classifier accuracy to be 87.5% on the dev set. The high accuracy with relatively little training data is not surprising given the power of pre-trained transformers and the nature of this task. We then applied the trained frame detection classifier to the entire validation set in order to label the frames for all the 1871 stories in it. This gave us a “bronze” dataset of frame labels for each story.

The bronze frame labels were used to create larger training sets (from the entire validation set) for the two steps described above, i.e., classifying a frame given a story, and classifying whether a given ending to a story is consistent with the frame. Moreover, we created two different train sets - one using raw text, and the other using semantic parses, obtained by running the semantic parser on each of the story and ending sentences. The training data format for the second step was *input*: story SEP ending SEP frame, *output*: 1 / 0 for right/wrong story ending (SEP stands for a separator token). Finally, we built neural generative models using the above training data.

The models from the two steps are used in neural dy-

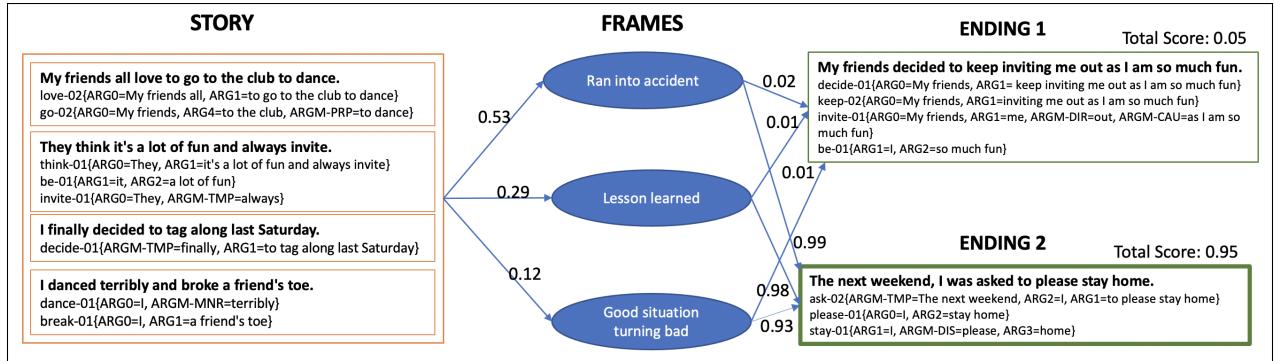


Figure 7: Example of Frame-Based Explanation for a ROC Story Ending. The figure shows the inference paths found by Braid using the neural classifiers (for detecting frames given story, and ending given frame+story), along with the corresponding rule scores. The semantic interpretations are shown below each sentence. Only the top-3 frames predicted for the story are shown in the figure (Note: Final scores consider the entire frame distribution).

namic rule generators (DRGs): the first which produces rules of the form: `frame :- story`, while the second generates `ending :- story, frame` rules. The rules have confidences coming from the corresponding classifier.

Experiments

- Baseline:** Our baseline system is an E2E neural model. We train a binary classifier (fine-tuning T5-base) on the validation set to predict whether a given ending to a story is correct. At test time, we apply the classifier to both endings and pick the one with the higher score.
- Frame-Inference-via-Text:** Use the textual versions of the two neural DRGs described in the previous subsection. The DRGs are fine-tuned on the T5-base model.
- Frame-Inference-via-Semantic-Parsing:** Use the semantic-parse versions of the two neural DRGs described in the previous section (fine-tuned on T5-base).
- Frame-Inference-via-Semantic-Parsing-fine-tuned-Glucose:** Same as experiment 3 except the DRGs are fine-tuned on the Glucose rule generation model, instead of starting with T5-base.

Experiments 2-4 use Braid to solve the problem. We initialize a knowledge-base consisting of the 4 sentence story, represented either as textual propositions (Expt. 2), or semantic parse propositions (Expt. 3 / 4).

Note that in experiments 3 and 4, using semantic parsing to map textual phrases to predicates (as shown in Figure 7) and using those predicate embeddings for unification is exactly our weak-unification approach, while the textual approach in experiment 2 maps phrases to syntactic parse predicates and uses exact (strict) unification for matching.

All DRG models were trained on a single GPU with an effective batch size of 64, a learning rate of $1e-3$ and $\text{warmup}=100$ steps. Models for frame-detection (step 1) were trained for 100 epochs, while models for ending-prediction (step 2) were trained for 10 epochs.

We use a two stage prover to solve the story cloze task: the prover first issues an open variable frame query (`frame (?X)`) to the frame-detection-DRG (which uses the

Model	Acc.
E2E Neural Baseline	86.15%
Braid: Frame Inf (Text)	87.17%
Braid: Frame Inf (Sem Parse)	87.76%
Braid: Frame Inf (Sem Parse + Glucose-tuned)	89.88%
HintNet (Zhou, Huang, and Zhu 2019)	79.2%
GPT2 (Alec et al. 2019)	86.5%
ISCK (Chen, Chen, and Yu 2019)	87.6%
BERT-base + MNLI (Li, Ding, and Liu 2019)	90.6%

Table 2: ROC Story Cloze (Spring 2016) Test Results

story KB as context) to infer potential frames. These frame inferences are added to the KB via the generated rules. Then, the prover issues a query for each ending choice to the second DRG, which uses the story and frames as context to produce rules deriving the ending. Lastly, Braid searches for all proofs for each of the endings (in this case, each proof is a linear chain back from the ending to the frame and then to the story). The final proof scoring function marginalizes across all the intermediate frame propositions.

Results of the experiments are shown in Table 2. The table also includes the performance scores from other SOTA systems on this task, as a point of comparison. We can see that Braid is highly competitive with the SOTA systems while providing frame-based explanations (e.g. Figure 7).

Conclusion

We describe Braid, a novel reasoner that combines symbolic reasoning with statistical functions for fuzzy unification and dynamic rule generation. To manage the larger proof search space (due to the relaxed unification and the probabilistic rules generated on the fly), our implementation uses a best-first search algorithm in a distributed task-based framework to construct proof graphs iteratively. Finally, we show how Braid is adapted for a commonsense reasoning task (ROC Story Cloze), and achieves close to SOTA results while generating logical explanations.

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