
Learning Graph Models for Retrosynthesis Prediction

Vignesh Ram Somnath¹

Charlotte Bunne¹

Connor W. Coley²

Andreas Krause¹ Regina Barzilay³

¹Department of Computer Science, ETH

²Department of Chemical Engineering, MIT

³Computer Science and Artificial Intelligence Lab, MIT

¹{vsomnath, bunnec, krausea}@ethz.ch, ²ccoley@mit.edu, ³regina@csail.mit.edu

Abstract

Retrosynthesis prediction is a fundamental problem in organic synthesis, where the task is to identify precursor molecules that can be used to synthesize a target molecule. A key consideration in building neural models for this task is aligning model design with strategies adopted by chemists. Building on this viewpoint, this paper introduces a graph-based approach that capitalizes on the idea that the graph topology of precursor molecules is largely unaltered during a chemical reaction. The model first predicts the set of graph edits transforming the target into incomplete molecules called *synthons*. Next, the model learns to expand synthons into complete molecules by attaching relevant *leaving groups*. This decomposition simplifies the architecture, making its predictions more interpretable, and also amenable to manual correction. Our model achieves a top-1 accuracy of 53.7%, outperforming previous template-free and semi-template-based methods.

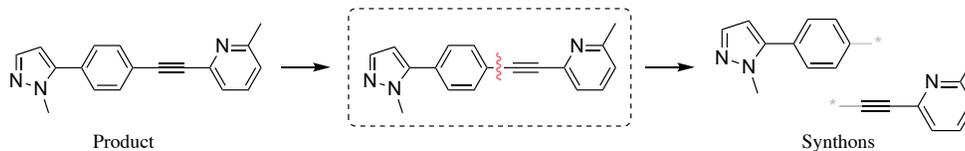
1 Introduction

Retrosynthesis prediction, first formalized by E. J. Corey [7] is a fundamental problem in organic synthesis that attempts to identify a series of chemical transformations for synthesizing a target molecule. In the single-step formulation, the task is to identify a set of reactant molecules given a target. Beyond simple reactions, many practical tasks involving complex organic molecules are difficult even for expert chemists. As a result, substantial experimental exploration is needed to cover for deficiencies of analytical approaches. This has motivated interest in computer-assisted retrosynthesis [6], with a recent surge in machine learning methods [2, 4, 8, 30, 9].

Computationally, the main challenge is how to explore the combinatorial space of reactions that can yield the target molecule. Largely, previous methods for retrosynthesis prediction can be divided into template-based [4, 8, 21] and template-free [2, 30] approaches. Template-based methods match a target molecule against a large set of templates, which are molecular subgraph patterns that highlight changes during a chemical reaction. Despite their interpretability, these methods fail to generalize to new reactions. Template-free methods bypass templates by learning a direct mapping from the SMILES [26] representations of the product to reactants. Despite their greater generalization potential, these methods generate reactant SMILES character by character, increasing generation complexity.

Another important consideration in building retrosynthesis models is aligning model design with strategies adopted by expert chemists. These strategies are influenced by fundamental properties of chemical reactions, independent of complexity level: (i.) the product atoms are always a subset of the

a Edit Prediction



b Synthon Completion

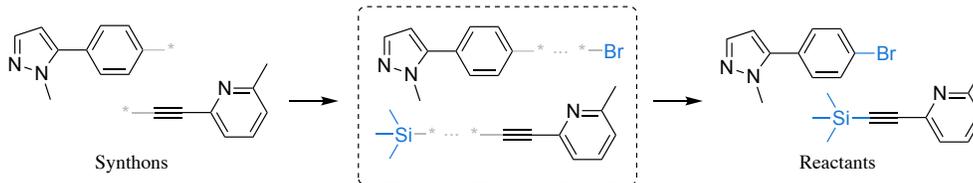


Figure 1: **Overview of Our Approach.** **a. Edit Prediction.** We train a model to learn a distribution over possible graph edits. In this case, the correct edit corresponds to breaking the bond marked in red. Applying this edit produces two synthons. **b. Synthon Completion.** Another model is trained to pick candidate leaving groups (blue) for each synthon from a discrete vocabulary, which are then attached to produce the final reactants.

reactant atoms¹, and (ii.) the molecular graph topology is largely unaltered from products to reactants. For example, in the standard retrosynthesis dataset, only 6.3% of the atoms in the product undergo any change in connectivity.

This consideration has received more attention in recent semi-template-based methods [22, 28], that generate reactants from a product in two stages: (i.) first identify intermediate molecules called synthons, (ii.) and then complete synthons into reactants by sequential generation of atoms or SMILES characters.. Our model GRAPHRETRO also uses a similar workflow. However, we avoid sequential generation for completing synthons by instead selecting subgraphs called *leaving groups* from a precomputed vocabulary. This vocabulary is constructed during preprocessing by extracting subgraphs that differ between a synthon and the corresponding reactant. The vocabulary has a small size (170 for USPTO-50k) indicating remarkable redundancy, while covering 99.7% of the test set. Operating at the level of these subgraphs greatly reduces the complexity of reactant generation, with improved empirical performance. This formulation also simplifies our architecture, and makes our predictions more transparent, interpretable and amenable to manual correction.

The benchmark dataset for evaluating retrosynthesis models is USPTO-50k [20], which consists of 50000 reactions across 10 reaction classes. The dataset contains an unexpected shortcut towards predicting the edit, in that the product atom with atom-mapping 1 is part of the edit in 75% of the cases, allowing predictions that depend on the position of the atom to overestimate performance. We canonicalize the product SMILES and remap the existing dataset, thereby removing the shortcut. On this remapped dataset, GRAPHRETRO achieves a top-1 accuracy of 53.7% when the reaction class is not known, outperforming both template-free and semi-template-based methods.

2 Related Work

Retrosynthesis Prediction Existing machine learning methods for retrosynthesis prediction can be divided into template-based, template-free and recent semi-template-based approaches.

Template-Based: Templates are either hand-crafted by experts [11, 24], or extracted algorithmically from large databases [3, 16]. Exhaustively applying large template sets is expensive due to the involved subgraph matching procedure. Template-based methods therefore utilize different ways of prioritizing templates, by either learning a conditional distribution over the template set [21], ranking templates based on molecular similarities to precedent reactions [4] or directly

¹ignoring impurities

modelling the joint distribution of templates and reactants using logic variables [8]. Despite their interpretability, these methods fail to generalize outside their rule set.

Template-Free: Template-free methods [17, 30, 2] learn a direct transformation from products to reactants using architectures from neural machine translation and a string based representation of molecules called SMILES [26]. Linearizing molecules as strings does not utilize the inherently rich chemical structure. In addition, the reactant SMILES are generated from scratch, character by character. Attempts have been made to improve validity by adding a syntax correcter [30] and a mixture model to improve diversity of suggestions [2], but the performance remains worse than [8] on the standard retrosynthesis dataset. [23] formulate retrosynthesis using energy-based models, with additional parameterizations and loss terms to enforce the duality between forward (reaction prediction) and backward (retrosynthesis) prediction.

Semi-Template-Based: Our work is closely related to recently proposed semi-template-based methods [22, 28], which first identify synthons and then expand synthons into reactants through sequential generation using either a graph generative model [22] or a Transformer [28]. To reduce the complexity of reactant generation, we instead complete synthons using subgraphs called *leaving groups* selected from a precomputed vocabulary. This allows us to view synthon completion as a classification problem instead of a generative one. We also utilize the dependency graph between possible edits, and update edit predictions using a *message passing network* (MPN) [10] on this graph. Both innovations together yield a 4.8% and 3.3% performance improvement respectively over previous semi-template-based methods.

Reaction Center Identification The reaction center covers a small number of participating atoms involved in the reaction. Our work is also related to models that predict reaction outcomes by learning to rank atom pairs based on their likelihood to be in the reaction center [5, 12]. The task of identifying the reaction center is related to the step of deriving the synthons in our formulation. Our work departs from [5, 12] as we utilize the property that new bond formations occur rarely ($\sim 0.1\%$) from products to synthons, allowing us to predict a score only for existing bonds and atoms and reduce prediction complexity from $O(N^2)$ to $O(N)$. We also utilize the dependency graph between possible edits, and update edit predictions using a MPN on this graph.

Utilizing Substructures Substructures have been utilized in various tasks from sentence generation by fusing phrases to molecule generation and optimization [13, 14]. Our work is closely related to [14] which uses precomputed substructures as building blocks for property-conditioned molecule generation. However, instead of precomputing, synthons —analogous building blocks for reactants— are indirectly learnt during training.

3 Model Design

Our approach leverages the property that graph topology is largely unaltered from products to reactants. To achieve this, we first derive suitable building blocks from the product called *synthons*, and then complete them into valid reactants by adding specific functionalities called *leaving groups*. These derivations, called *edits*, are characterized by modifications to bonds or hydrogen counts on atoms. We first train a neural network to predict a score for possible edits (Section 3.1). The edit with the highest score is then applied to the product to obtain synthons. Since the number of unique leaving groups are small, we model leaving group selection as a classification problem over a precomputed vocabulary (Section 3.2). To produce candidate reactants, we attach the predicted leaving group to the corresponding synthon through chemically constrained rules. The overall process is outlined in Figure 1. Before describing the two modules, we introduce relevant preliminaries that set the background for the remainder of the paper.

Retrosynthesis Prediction A retrosynthesis pair R is described by a pair of molecular graphs $(\mathcal{G}_p, \mathcal{G}_r)$, where \mathcal{G}_p are the products and \mathcal{G}_r the reactants. A molecular graph is described as $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with atoms \mathcal{V} as nodes and bonds \mathcal{E} as edges. Prior work has focused on the single product case, while reactants can have multiple connected components, i.e. $\mathcal{G}_r = \{\mathcal{G}_{r_c}\}_{c=1}^C$. Retrosynthesis pairs are *atom-mapped* so that each product atom has a unique corresponding reactant atom. The retrosynthesis task then, is to infer $\{\mathcal{G}_{r_c}\}_{c=1}^C$ given \mathcal{G}_p .

Edits Edits consist of (i.) atom pairs $\{(a_i, a_j)\}$ where the bond type changes from products to reactants, and (ii.) atoms $\{a_i\}$ where the number of hydrogens attached to the atom change from products to reactants. We denote the set of edits by E . Since retrosynthesis pairs in the training set are atom-mapped, edits can be automatically identified by comparing the atoms and atom pairs in the product to their corresponding reactant counterparts.

Synthons and Leaving Groups Applying edits E to the product \mathcal{G}_p results in incomplete molecules called *synthons*. Synthons are analogous to rationales or building blocks, which are expanded into valid reactants by adding specific functionalities called *leaving groups* that are responsible for its reactivity. We denote synthons by \mathcal{G}_s and leaving groups by \mathcal{G}_l . We further assume that synthons and leaving groups have the same number of connected components as the reactants, i.e. $\mathcal{G}_s = \{\mathcal{G}_{s_c}\}_{c=1}^C$ and $\mathcal{G}_l = \{\mathcal{G}_{l_c}\}_{c=1}^C$. This assumption holds for 99.97% reactions in the training set.

Formally, our model generates reactants by first predicting the set of edits E that transform \mathcal{G}_p into \mathcal{G}_s , followed by predicting a leaving group \mathcal{G}_l to attach to each synthon \mathcal{G}_{s_c} . The model is defined as

$$P(\mathcal{G}_r|\mathcal{G}_p) = \sum_{E, \mathcal{G}_l} P(E|\mathcal{G}_p)P(\mathcal{G}_l|\mathcal{G}_p, \mathcal{G}_s), \quad (1)$$

where $\mathcal{G}_s, \mathcal{G}_r$ are deterministic given E, \mathcal{G}_l , and \mathcal{G}_p .

3.1 Edit Prediction

For a given retrosynthesis pair $R = (\mathcal{G}_p, \mathcal{G}_r)$, we predict an edit score only for existing bonds and atoms, instead of every atom pair as in [5, 12]. This choice is motivated by the low frequency ($\sim 0.1\%$) of new bond formations in the training set examples. Coupled with the sparsity of molecular graphs, this reduces the prediction complexity from $O(N^2)$ to $O(N)$ for a product with N atoms. Our edit prediction model has variants tailored to single and multiple edit prediction. Since 95% of the training set consists of single edit examples, the remainder of this section describes the setup for single edit prediction. A detailed description of our multiple edit prediction model can be found in Appendix D.

Each bond (u, v) in \mathcal{G}_p is associated with a label $y_{uvk} \in \{0, 1\}$ indicating whether its bond type k has changed from the products to reactants. Each atom u is associated with a label $y_u \in \{0, 1\}$ indicating a change in hydrogen count. We predict edit scores using representations that are learnt using a graph encoder.

Graph Encoder To obtain atom representations, we use a variant of the *message passing network* (MPN) described in [10]. Each atom u has a feature vector \mathbf{x}_u indicating its atom type, degree and other properties. Each bond (u, v) has a feature vector \mathbf{x}_{uv} indicating its aromaticity, bond type and ring membership. For simplicity, we denote the encoding process by $\text{MPN}(\cdot)$ and describe architectural details in Appendix A. The MPN computes atom representations $\{\mathbf{c}_u | u \in \mathcal{G}\}$ via

$$\{\mathbf{c}_u\} = \text{MPN}(\mathcal{G}, \{\mathbf{x}_u\}, \{\mathbf{x}_{uv}\}_{v \in \mathcal{N}(u)}), \quad (2)$$

where $\mathcal{N}(u)$ denotes the neighbors of atom u . The graph representation $\mathbf{c}_\mathcal{G}$ is an aggregation of atom representations, i.e. $\mathbf{c}_\mathcal{G} = \sum_{u \in \mathcal{V}} \mathbf{c}_u$. When \mathcal{G} has connected components $\{\mathcal{G}_i\}$, we get a set of graph representations $\{\mathbf{c}_{\mathcal{G}_i}\}$. For a bond (u, v) , we define its representation $\mathbf{c}_{uv} = (\text{ABS}(\mathbf{c}_u, \mathbf{c}_v) || \mathbf{c}_u + \mathbf{c}_v)$, where ABS denotes absolute difference and $||$ refers to concatenation. This ensures our representations are permutation invariant. These representations are then used to predict atom and bond edit scores using corresponding neural networks,

$$s_u = \mathbf{u}_a^T \tau(\mathbf{W}_a \mathbf{c}_u + b) \quad (3)$$

$$s_{uvk} = \mathbf{u}_k^T \tau(\mathbf{W}_k \mathbf{c}_{uv} + b_k), \quad (4)$$

where $\tau(\cdot)$ is the ReLU activation function.

Updating Bond Edit Scores Unlike a typical classification problem where the labels are independent, edits can have possible dependencies between each other. For example, bonds part of a stable system such as an aromatic ring have a greater tendency to remain unchanged (label 0). We attempt

to leverage such dependencies to update initial edit scores. To this end, we build a graph with bonds (u, v) as nodes, and introduce an edge between bonds sharing an atom. We use another MPN(\cdot) on this graph to learn aggregated neighborhood messages \mathbf{m}_{uv} , and update the edit scores s_{uvk} in a manner similar to how LSTMs update representations,

$$f_{uvk} = \sigma(\mathbf{W}_{\mathbf{kx}}^f \mathbf{x}_{uv} + \mathbf{W}_{\mathbf{km}}^f \mathbf{m}_{uv}) \quad (5)$$

$$i_{uvk} = \sigma(\mathbf{W}_{\mathbf{kx}}^i \mathbf{x}_{uv} + \mathbf{W}_{\mathbf{km}}^i \mathbf{m}_{uv}) \quad (6)$$

$$\tilde{m}_{uvk} = \mathbf{u}_m \tau(\mathbf{W}_{\mathbf{kx}}^m \mathbf{x}_{uv} + \mathbf{W}_{\mathbf{km}}^m \mathbf{m}_{uv}) \quad (7)$$

$$\tilde{s}_{uvk} = f_{uvk} \cdot s_{uvk} + i_{uvk} \cdot \tilde{m}_{uvk}. \quad (8)$$

Training We train by minimizing the cross-entropy loss over possible bond and atom edits

$$\mathcal{L}_e = - \sum_{(\mathcal{G}_p, E)} \left(\sum_{((u,v),k) \in E} y_{uvk} \log(\tilde{s}_{uvk}) + \sum_{u \in E} y_u \log(s_u) \right). \quad (9)$$

The cross-entropy loss enforces the model to learn a distribution over possible edits instead of reasoning about each edit independently, as with the binary cross entropy loss used in [12, 5].

3.2 Synthons Completion

Synthons are completed into valid reactants by adding specific functionalities called *leaving groups*. This involves two complementary tasks: (i.) selecting the appropriate leaving group, and (ii.) attaching the leaving group to the synthon. As ground truth leaving groups are not directly provided, we extract the leaving groups and construct a vocabulary \mathcal{X} of unique leaving groups during preprocessing.

The vocabulary has a limited size ($|\mathcal{X}| = 170$ for a standard dataset with 50,000 examples, and 72000 synthons) indicating the redundancy of leaving groups used in accomplishing retrosynthetic transformations. This redundancy also allows us to formulate leaving group selection as a classification problem over \mathcal{X} , while retaining the ability to generate diverse reactants using different combinations of leaving groups.

Vocabulary Construction Before constructing the vocabulary, we align connected components of synthon and reactant graphs by comparing atom mapping overlaps. Using aligned pairs $\mathcal{G}_{s_c} = (\mathcal{V}_{s_c}, \mathcal{E}_{s_c})$ and $\mathcal{G}_{r_c} = (\mathcal{V}_{r_c}, \mathcal{E}_{r_c})$ as input, the leaving group vocabulary \mathcal{X} is constructed by extracting subgraphs $\mathcal{G}_{l_c} = (\mathcal{V}_{l_c}, \mathcal{E}_{l_c})$ such that $\mathcal{V}_{l_c} = \mathcal{V}_{r_c} \setminus \mathcal{V}_{s_c}$. Atoms $\{a_i\}$ in the leaving groups that attach to synthons are marked with a special symbol. We also add three tokens to \mathcal{X} namely START, which indicates the start of synthon completion, END, which indicates that there is no leaving group to add and PAD, which is used to handle variable numbers of synthon components in a minibatch.

Leaving Group Selection For synthon component $c \leq C$, where C is the number of connected components in the synthon graph, we use three inputs for leaving group selection – the product representation $\mathbf{c}_{\mathcal{G}_p}$, the synthon component representation $\mathbf{c}_{\mathcal{G}_{s_c}}$, and the leaving group representation for the previous synthon component, $\mathbf{e}_{l_{c-1}}$. The product and synthon representations are learnt using the MPN(\cdot). For each $x_i \in \mathcal{X}$, representations can be learnt by either training independent embedding vectors (*ind*) or by treating each x_i as a subgraph and using the MPN(\cdot) (*shared*). In the *shared* setting, we use the same MPN(\cdot) as the product and synthons.

The leaving group probabilities are then computed by combining $\mathbf{c}_{\mathcal{G}_p}$, $\mathbf{c}_{\mathcal{G}_{s_c}}$ and $\mathbf{e}_{l_{c-1}}$ via a single layer neural network and softmax function

$$\hat{q}_{l_c} = \text{softmax}(\mathbf{U}\tau(\mathbf{W}_1 \mathbf{c}_{\mathcal{G}_p} + \mathbf{W}_2 \mathbf{c}_{\mathcal{G}_{s_c}} + \mathbf{W}_3 \mathbf{e}_{l_{c-1}})), \quad (10)$$

where \hat{q}_{l_c} is distribution learnt over \mathcal{X} . Using the representation of the previous leaving group $\mathbf{e}_{l_{c-1}}$ allows the model to understand *combinations* of leaving groups that generate the desired product from the reactants. We also include the product representation $\mathbf{c}_{\mathcal{G}_p}$ as the synthon graphs are derived from the product graph.

Training For step c , given the one hot encoding of the true leaving group q_{l_c} , we minimize the cross-entropy loss

$$\mathcal{L}_s = \sum_{c=1}^C \mathcal{L}(\hat{q}_{l_c}, q_{l_c}). \quad (11)$$

Training utilizes teacher-forcing [27] so that the model makes predictions given correct histories. During inference, at every step, we use the representation of leaving group from the previous step with the highest predicted probability.

Leaving Group Attachment Attaching leaving groups to synthons is a deterministic process and not learnt during training. The task involves identification of the type of bonds to add between attaching atoms in the leaving group (marked during vocabulary construction), and the atom(s) participating in the edit. These bonds can be inferred by applying the *valency* constraint, which determines the maximum number of neighbors for each atom. The attachment process does not modify any stereochemistry. Given synthons and leaving groups, the attachment process has a 100% accuracy. The detailed procedure is described in Appendix B.

3.3 Inference

Inference is performed using beam search with a log-likelihood scoring function. For a beam width n , we select n edits with highest scores and apply them to the product to obtain n synthons, where each synthon can consist of multiple connected components. The synthons form the nodes for beam search. Each node maintains a cumulative score by aggregating the log-likelihoods of the edit and predicted leaving groups. Leaving group inference starts with a connected component for each synthon, and selects n leaving groups with highest log-likelihoods. From the n^2 possibilities, we select n nodes with the highest cumulative scores. This process is repeated until all nodes have a leaving group predicted for each synthon component.

4 Evaluation

Evaluating retrosynthesis models is challenging as multiple sets of reactants can be generated from the same product. To deal with this, previous works [4, 8] evaluate the ability of the model to recover retrosynthetic strategies recorded in the dataset.

Data We use the benchmark dataset USPTO-50k [20] for all our experiments. The dataset contains 50,000 atom-mapped reactions across 10 reaction classes. We use the same dataset version and splits as provided by [8]. The USPTO-50k dataset contains a shortcut in that the product atom with atom-mapping 1 is part of the edit in $\sim 75\%$ of the cases. If the product SMILES is not canonicalized, predictions utilizing operations that depend on the position of the atom or bond will be able to use the shortcut, and overestimate performance. We canonicalize the product SMILES, and reassign atom-mappings to the reactant atoms based on the canonical ordering, which removes the shortcut. Details on the remapping procedure can be found in Appendix C.2.

Evaluation We use the top- n accuracy ($n = 1, 3, 5, 10$) as our evaluation metric, defined as the fraction of examples where the recorded reactants are suggested by the model with rank $\leq n$. Following prior work [4, 30, 8], we compute the accuracy by comparing the canonical SMILES of predicted reactants to the ground truth. Atom-mapping is excluded from this comparison, but stereochemistry, which describes the relative orientation of atoms in the molecule, is retained. The evaluation is carried out for two settings, with the reaction class being known or unknown.

Baselines For evaluating overall performance, we compare GRAPHRETRO to nine baselines — four template-based, three template-free, and two semi-template-based methods. These include:

Template-Based: RETROSIM [4] ranks templates for a given target molecule by computing molecular similarities to precedent reactions. NEURALSVM [21] trains a model to rank templates given a target molecule. GLN [8] models the joint distribution of templates and reactants in a

Table 1: **Top- n exact match accuracy.** Best values within each section are highlighted in bold.

Model	Top- n Accuracy (%)								
	$n =$	Reaction class known				Reaction class unknown			
		1	3	5	10	1	3	5	10
Template-Based									
RETROSIM [4]	52.9	73.8	81.2	88.1	37.3	54.7	63.3	74.1	
NEURALSVM [21]	55.3	76.0	81.4	85.1	44.4	65.3	72.4	78.9	
GLN [8]	64.2	79.1	85.2	90.0	52.5	69.0	75.6	83.7	
DUALTB [23]	67.7	84.8	88.9	92.0	55.2	74.6	80.5	86.9	
Template-Free									
SCROP [30]	59.0	74.8	78.1	81.1	43.7	60.0	65.2	68.7	
LV-TRANSFORMER [2]	-	-	-	-	40.5	65.1	72.8	79.4	
DUALTF [23]	65.7	81.9	84.7	85.9	53.6	70.7	74.6	77.0	
Semi-Template-Based									
G2Gs [22]	61.0	81.3	86.0	88.7	48.9	67.6	72.5	75.5	
RETROXPRT [28]	62.1	75.8	78.5	80.9	50.4	61.1	62.3	63.4	
GRAPHRETRO (ours)	63.9	81.5	85.2	88.1	53.7	68.3	72.2	75.5	

hierarchical fashion using logic variables. DUALTB [23] uses an energy-based model formulation for retrosynthesis, with additional parameterizations and loss terms to enforce the duality between forward (reaction prediction) and backward (retrosynthesis prediction). Inference is carried out using reactant candidates obtained by applying an extracted template set to the products.

Template-Free: SCROP [30], LV-TRANSFORMER [2] and DUALTF [23] use the Transformer architecture [25] to output reactant SMILES given a product SMILES. To improve the validity of their suggestions, SCROP include a second Transformer that functions as a syntax corrector. LV-TRANSFORMER uses a latent variable mixture model to improve diversity of suggestions. DUALTF utilizes additional parameterizations and loss terms to enforce the duality between forward (reaction prediction) and backward (retrosynthesis prediction).

Semi-Template-Based: G2Gs [22] and RETROXPRT [28] first identify synthons, and then expand the synthons into reactants by either sequential generation of atoms and bonds (G2Gs), or using the Transformer architecture (RETROXPRT). The training dataset for the Transformer in [28] is augmented with incorrectly predicted synthons with the goal of learning a correction mechanism.

Results for NEURALSVM are taken from [8]. The authors in [28] report their performance being affected by the dataset leakage². Thus, we use the most recent results from their website on the canonicalized dataset. For remaining baselines, we directly use the values reported in their paper. For the synthon completion module, we use the *ind* configuration given its better empirical performance.

4.1 Overall Performance

Reaction class unknown As shown in Table 1, when the reaction class is unknown, GRAPHRETRO outperforms G2Gs by 4.8% and RETROXPRT by 3.3% in top-1 accuracy. Performance improvements are also seen for larger n , except for $n = 5$. Barring DUALTB, the top-1 accuracy is also better than other template-free and template-based methods. For larger n , one reason for lower top- n accuracies than most template-based methods is that templates already contain combinations of leaving group patterns. In contrast, our model learns to discover these during training. A second hypothesis to this end is that simply adding log-likelihood scores from edit prediction and synthon completion models may be suboptimal and bias the beam search in the direction of the more dominating term. We leave it to future work to investigate scoring functions that rank the attachment.

²<https://github.com/uta-smile/RetroXpert>

Reaction class known When the reaction class is known, GRAPHRETRO outperforms G2Gs and RETROXPRT by a margin of 3% and 2% respectively in top-1 accuracy. GRAPHRETRO also outperforms all the template-free methods in top- n accuracy. for GRAPHRETRO are also better than most template-based and template-free methods. When the reaction class is known, RETROSIM and GLN restrict template sets corresponding to the reaction class, thus improving performance. The increased edit prediction performance (Section 4.2) for GRAPHRETRO helps outweigh this factor, achieving comparable or better performance till $n = 5$.

4.2 Individual Module Performance

To gain more insight into the working of GRAPHRETRO, we evaluate the top- n accuracy ($n = 1, 2, 3, 5$) of edit prediction and synthon completion modules, along with corresponding ablation studies, with results shown in Table 2.

Edit Prediction For the edit prediction module, we compare the true edit(s) to top- n edits predicted by the model. We also consider two ablation studies, one where we directly use the initial edit scores without updating them, and the other where we predict edits using atom-pairs instead of existing bonds and atoms. Both design choices lead to improvements in performance, as shown in Table 2. We hypothesize that the larger improvement compared to edit prediction using atom-pairs is due to the easier optimization procedure, with lesser imbalance between labels 1 and 0.

Synthon Completion For evaluating the synthon completion module, we first apply the true edits to obtain synthons, and compare the true leaving groups to top- n leaving groups predicted by the model. We test the performance of both the *ind* and *shared* configurations. Both configurations perform similarly, and are able to identify $\sim 97\%$ (close to its upper bound of 99.7%) of the true leaving groups in its top-5 choices, when the reaction class is known. The top-1, 3 and 5 accuracies of the synthon completion for unknown reaction classes for G2Gs are 61.1%, 81.5% and 86.7% respectively, while ours are 75.6%, 92.5% and 96.1%, indicating a 10-14% performance improvement using a classification formulation over the generative one adopted by G2Gs.

Table 2: **Performance Study** of edit prediction and synthon completion modules

Setting	Top- n Accuracy (%)								
	$n =$	Reaction class known				Reaction class unknown			
		1	2	3	5	1	2	3	5
Edit Prediction		84.6	92.2	93.7	94.5	70.8	85.1	89.5	92.7
- without edit score updates		84.3	92.1	93.7	94.5	70.1	84.8	89.4	92.6
- predicting on atom pairs		81.9	89.5	90.9	92.1	68.6	83.2	88.3	91.8
Synthon Completion (<i>ind</i>)		77.4	89.5	94.2	97.6	75.6	87.4	92.5	96.1
Synthon Completion (<i>shared</i>)		76.9	89.6	93.9	97.4	74.9	87.7	92.9	96.3

4.3 Example Predictions

In Figure 2, we visualize the model predictions and the ground truth for three cases. Figure 2a shows an example where the model identifies both the edits and leaving groups correctly. In Figure 2b, the correct edit is identified but the predicted leaving groups are incorrect. We hypothesize this is due to the fact that in the training set, leaving groups attaching to the carbonyl carbon (C=O) are small (e.g. -OH, -NH₂, halides). The true leaving group in this example, however, is large. The model is unable to reason about this and predicts the small leaving group -I. In Figure 2c, the model identifies the edit and consequently the leaving group incorrectly. This highlights a limitation of our model. If the edit is predicted incorrectly, the model cannot suggest the true precursors.

4.4 Limitations

The simplified and interpretable construction of GRAPHRETRO comes with certain limitations. First, the overall performance of the model is limited by the performance of the edit prediction step. If the

predicted edit is incorrect, the true reactants cannot be salvaged. This limitation is partly remedied by our model design, that allows for user intervention to correct the edit. Second, our method is reliant on atom-mapping for extracting edits and leaving groups. Extracting edits directly based on substructure matching currently suffer from false positives, and heuristics to correct for these result in correct edits in only ~90% of the cases. Third, our formulation assumes that we have as many synthons as reactants, which is violated in some reactions. We leave it to future work to extend the model to realize a single reactant from multiple synthons, and introduce more chemically meaningful edit correction mechanisms.

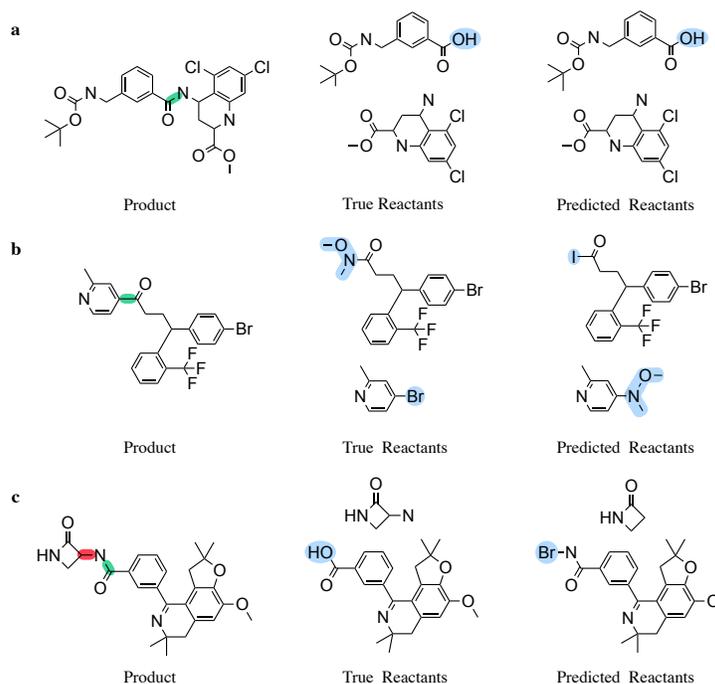


Figure 2: **Example Predictions.** The true edit and incorrect edit (if any) are highlighted in green and red respectively. The true and predicted leaving groups are highlighted in blue. **a.** Correctly predicted example by the model. **b.** Correctly predicted edit but incorrectly predicted leaving groups. **c.** Incorrectly predicted edit and leaving group.

5 Conclusion

Previous methods for single-step retrosynthesis either restrict prediction to a template set, are insensitive to molecular graph structure or generate molecules from scratch. We address these shortcomings by introducing a graph-based semi-template-based model inspired by a chemist’s workflow, enhancing the interpretability of retrosynthesis models. Given a target molecule, we first identify synthetic building blocks (*synthons*) which are then realized into valid reactants, thus avoiding molecule generation from scratch. Our model outperforms previous semi-template-methods by significant margins on the benchmark dataset. Future work aims to extend the model to realize a single reactant from multiple synthons, and introduce more chemically meaningful components to improve the synergy between such tools for retrosynthesis prediction and a practitioner’s expertise.

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References

- [1] J. Bradshaw, M. J. Kusner, B. Paige, M. H. S. Segler, and J. M. Hernández-Lobato. A Generative Model For Electron Paths. In *International Conference on Learning Representations (ICLR)*, 2019.
- [2] B. Chen, T. Shen, T. S. Jaakkola, and R. Barzilay. Learning to Make Generalizable and Diverse Predictions for Retrosynthesis. In Submission, 2019.
- [3] C. W. Coley, R. Barzilay, T. S. Jaakkola, W. H. Green, and K. F. Jensen. Prediction of Organic Reaction Outcomes Using Machine Learning. In *ACS Central Science*. ACS Publications, 2017.
- [4] C. W. Coley, L. Rogers, W. H. Green, and K. F. Jensen. Computer-Assisted Retrosynthesis Based on Molecular Similarity. *ACS Central Science*, 3, 2017.
- [5] C. W. Coley, W. Jin, L. Rogers, T. F. Jamison, T. S. Jaakkola, W. H. Green, R. Barzilay, and K. F. Jensen. A graph-convolutional neural network model for the prediction of chemical reactivity. *Chemical Science*, 10, 2019.
- [6] E. Corey and W. T. Wipke. Computer-assisted design of complex organic syntheses. *Science*, 166(3902):178–192, 1969.
- [7] E. J. Corey. The Logic of Chemical Synthesis: Multistep Synthesis of Complex Carbogenic Molecules (Nobel Lecture). *Angewandte Chemie International Edition*, 30, 1991.
- [8] H. Dai, C. Li, C. Coley, B. Dai, and L. Song. Retrosynthesis Prediction with Conditional Graph Logic Network. In *Advances in Neural Information Processing Systems (NeurIPS)*, volume 32, 2019.
- [9] S. Genheden, A. Thakkar, V. Chadimová, J.-L. Reymond, O. Engkvist, and E. Bjerrum. Aizynthfinder: a fast, robust and flexible open-source software for retrosynthetic planning. *Journal of cheminformatics*, 12(1):1–9, 2020.
- [10] J. Gilmer, S. S. Schoenholz, P. F. Riley, O. Vinyals, and G. E. Dahl. Neural Message Passing for Quantum Chemistry. In *International Conference on Machine Learning (ICML)*, volume 70, 2017.
- [11] M. Hartenfeller, M. Eberle, P. Meier, C. Nieto-Oberhuber, K.-H. Altmann, G. Schneider, E. Jacoby, and S. Renner. A Collection of Robust Organic Synthesis Reactions for In Silico Molecule Design. In *Journal of Chemical Information and Modeling*, volume 51. ACS Publications, 2011.
- [12] W. Jin, C. Coley, R. Barzilay, and T. Jaakkola. Predicting Organic Reaction Outcomes with Weisfeiler-Lehman Network. In *Advances in Neural Information Processing Systems (NeurIPS)*, volume 30, 2017.
- [13] W. Jin, R. Barzilay, and T. Jaakkola. Junction Tree Variational Autoencoder for Molecular Graph Generation. In *International Conference on Machine Learning (ICML)*, volume 32, 2018.
- [14] W. Jin, R. Barzilay, and T. Jaakkola. Composing Molecules with Multiple Property Constraints. In *International Conference on Machine Learning (ICML)*, 2020.
- [15] G. Landrum. RDKit: Open-Source Cheminformatics Software. 2016.
- [16] J. Law, Z. Zsoldos, A. Simon, D. Reid, Y. Liu, S. Y. Khew, A. P. Johnson, S. Major, R. A. Wade, and H. Y. Ando. Route Designer: A Retrosynthetic Analysis Tool Utilizing Automated Retrosynthetic Rule Generation. *Journal of Chemical Information and Modeling*, 49, 2009.
- [17] B. Liu, B. Ramsundar, P. Kawthekar, J. Shi, J. Gomes, Q. Luu Nguyen, S. Ho, J. Sloane, P. Wender, and V. Pande. Retrosynthetic Reaction Prediction Using Neural Sequence-to-Sequence Models. In *ACS Central Science*, volume 3. ACS Publications, 2017.

- [18] A. Paszke, S. Gross, F. Massa, A. Lerer, J. Bradbury, G. Chanan, T. Killeen, Z. Lin, N. Gimelshein, L. Antiga, A. Desmaison, A. Kopf, E. Yang, Z. DeVito, M. Raison, A. Tejani, S. Chilamkurthy, B. Steiner, L. Fang, J. Bai, and S. Chintala. Pytorch: An imperative style, high-performance deep learning library. In *Advances in Neural Information Processing Systems 32*, pages 8024–8035. Curran Associates, Inc., 2019. URL <http://papers.neurips.cc/paper/9015-pytorch-an-imperative-style-high-performance-deep-learning-library.pdf>.
- [19] L. Pattanaik, O.-E. Ganea, I. Coley, K. F. Jensen, W. H. Green, and C. W. Coley. Message passing networks for molecules with tetrahedral chirality. *arXiv preprint arXiv:2012.00094*, 2020.
- [20] N. Schneider, N. Stiefl, and G. A. Landrum. What’s What: The (Nearly) Definitive Guide to Reaction Role Assignment. In *Journal of Chemical Information and Modeling*, volume 56. ACS Publications, 2016.
- [21] M. H. Segler and M. P. Waller. Neural-Symbolic Machine Learning for Retrosynthesis and Reaction Prediction. *Chemistry—A European Journal*, 23, 2017.
- [22] C. Shi, M. Xu, H. Guo, M. Zhang, and J. Tang. A graph to graphs framework for retrosynthesis prediction, 2020.
- [23] R. Sun, H. Dai, L. Li, S. Kearnes, and B. Dai. Energy-based view of retrosynthesis, 2021. URL <https://openreview.net/forum?id=0Hj3tFCSjUd>.
- [24] S. Szymkuć, E. P. Gajewska, T. Klucznik, K. Molga, P. Dittwald, M. Startek, M. Bajczyk, and B. A. Grzybowski. Computer-assisted synthetic planning: The end of the beginning. *Angewandte Chemie International Edition*, 55(20):5904–5937, 2016.
- [25] A. Vaswani, N. Shazeer, N. Parmar, J. Uszkoreit, L. Jones, A. N. Gomez, Ł. Kaiser, and I. Polosukhin. Attention is All You Need. In *Advances in Neural Information Processing Systems (NeurIPS)*, volume 30, 2017.
- [26] D. Weininger. SMILES, a Chemical Language and Information System. *Journal of Chemical Information and Computer Sciences*, 28, 1988.
- [27] R. J. Williams and D. Zipser. A Learning Algorithm for Continually Running Fully Recurrent Neural Networks. In *Neural Computation*, volume 1. MIT Press, 1989.
- [28] C. Yan, Q. Ding, P. Zhao, S. Zheng, J. YANG, Y. Yu, and J. Huang. Retroxpert: Decompose retrosynthesis prediction like a chemist. In H. Larochelle, M. Ranzato, R. Hadsell, M. F. Balcan, and H. Lin, editors, *Advances in Neural Information Processing Systems*, volume 33, pages 11248–11258. Curran Associates, Inc., 2020. URL <https://proceedings.neurips.cc/paper/2020/file/819f46e52c25763a55cc642422644317-Paper.pdf>.
- [29] K. Yang, K. Swanson, W. Jin, C. Coley, P. Eiden, H. Gao, A. Guzman-Perez, T. Hopper, B. Kelley, M. Mathea, et al. Analyzing learned molecular representations for property prediction. *Journal of chemical information and modeling*, 59(8):3370–3388, 2019.
- [30] S. Zheng, J. Rao, Z. Zhang, J. Xu, and Y. Yang. Predicting Retrosynthetic Reactions using Self-Corrected Transformer Neural Networks. In *Journal of Chemical Information and Modeling*. ACS Publications, 2019.

A Message Passing Network

We use the message passing network as proposed in [13], which is an improved variant of the Directed-Message Passing Neural Network (D-MPNN) proposed in [29]. We use this network owing to its good performance across different molecular machine learning tasks.

At message passing step t , each bond $(u, v) \in \mathcal{E}$ is associated with two messages $\mathbf{m}_{uv}^{(t)}$ and $\mathbf{m}_{vu}^{(t)}$. Message $\mathbf{m}_{uv}^{(t)}$ is updated using

$$\mathbf{m}_{uv}^{(t+1)} = \text{GRU}\left(\mathbf{x}_u, \mathbf{x}_{uv}, \{\mathbf{m}_{wu}^{(t)}\}_{w \in N(u) \setminus v}\right), \quad (12)$$

where GRU denotes the Gated Recurrent Unit, adapted for message passing [13]

$$\mathbf{s}_{uv} = \sum_{k \in N(u) \setminus v} \mathbf{m}_{ku}^{(t)} \quad (13)$$

$$\mathbf{z}_{uv} = \sigma(\mathbf{W}_z[\mathbf{x}_u, \mathbf{x}_{uv}, \mathbf{s}_{uv}] + b_z) \quad (14)$$

$$\mathbf{r}_{ku} = \sigma(\mathbf{W}_r[\mathbf{x}_u, \mathbf{x}_{uv}, \mathbf{m}_{ku}^{(t)}] + b_r) \quad (15)$$

$$\tilde{\mathbf{r}}_{uv} = \sum_{k \in N(u) \setminus v} \mathbf{r}_{ku} \odot \mathbf{m}_{ku}^{(t)} \quad (16)$$

$$\tilde{\mathbf{m}}_{uv} = \tanh(\mathbf{W}[\mathbf{x}_u, \mathbf{x}_{uv}] + \mathbf{U}\tilde{\mathbf{r}}_{uv} + b) \quad (17)$$

$$\mathbf{m}_{uv}^{(t+1)} = (1 - \mathbf{z}_{uv}) \odot \mathbf{s}_{uv} + \mathbf{z}_{uv} \odot \tilde{\mathbf{m}}_{uv}. \quad (18)$$

After T steps of iteration, we aggregate the messages with a neural network $g(\cdot)$ to derive the representation for each atom

$$\mathbf{c}_u = g\left(\mathbf{x}_u, \sum_{k \in N(u)} \mathbf{m}_{vu}^{(T)}\right). \quad (19)$$

We do not include any stereochemical features, nor is the message passing network stereochemically aware. We leave it to future work to explore the effects of recent message passing networks [19] that utilize aggregation functions that are stereochemically aware.

B Leaving Group Attachment

Attaching atoms in the leaving groups were marked during vocabulary construction. The number of such atoms are used to divide leaving groups into single and multiple attachment categories. The single attachment leaving groups are further divided into single and double bond attachments depending on the *valency* of the attaching atom. By default, for leaving groups in the multiple attachments category, a single bond is added between attaching atom(s) on the synthon and leaving groups. For multiple attachment leaving groups with a combination of single and double bonds, the attachment is hardcoded. A single edit can result in a maximum of two attaching atoms for the synthon(s). For the case where the model predicts a leaving group with a single attachment, and the predicted edit results in a synthon with two attaching atoms, we attach to the first atom. For the opposite case where we have multiple attaching atoms on the leaving group and a single attaching atom for the synthon, atoms on the leaving group are attached through respective bonds. The former case represents incorrect model predictions, and is not observed as ground truth.

C Experimental Details

Our model is implemented in PyTorch [18]. We also use the open-source software RDKit [15] to canonicalize product molecules, extracting edits and leaving groups from molecules, for attaching leaving groups to synthons and generating reactant SMILES.

C.1 Input Features

C.1.1 Product & Synthon Graphs

In this graph, the nodes are atoms and bonds are edges. We use the following node and edge features,

Node Feature	Count	One-hot	Possible Values
Atom symbol	65	Yes	C, N, O etc.
Atom degree	10	Yes	0, 1, 2, 3, 4, 5, 6, 7, 8, 9
Formal charge of the atom	5	Yes	-1, -2, 1, 2, 0
Valency of the atom	7	Yes	0, 1, 2, 3, 4, 5, 6
Hybridization of the atom	5	Yes	SP, SP2, SP3, SP3D, SP3D2
Number of associated hydrogens	5	Yes	0, 1, 3, 4, 5
Part of an aromatic ring	1	No	0, 1

Edge Feature	Count	One-hot	Possible Values
Bond type	4	Yes	Single, Double, Triple, Aromatic
Whether bond is conjugated	1	No	0, 1
Whether bond is part of ring	1	No	0, 1

C.1.2 Bond Graph

In this graph, the bonds are nodes, and two bonds share an edge if they have a common atom. The features used for this graph include,

Node Feature	Count	One-hot	Possible Values
Bond type	4	Yes	Single, Double, Triple, Aromatic
Whether bond is conjugated	1	No	0, 1
Whether bond is part of ring	1	No	0, 1

The edge features include the atom features (Node Features table in Appendix C.1.1 for details) of the common atom, the bond type and conjugation of the participating bonds, and if the two bonds are part of the same ring.

C.2 Dataset Splits

We evaluate our model on the USPTO-50k [20] dataset. We use the same dataset and splits as provided by [8]. The USPTO-50k dataset contains a shortcut in that the product atom with atom-mapping 1 is part of the edit in ~75% of the cases. If the product SMILES is not canonicalized, predictions utilizing operations that depend on the position of the atom or bond will be able to use the shortcut, and overestimate performance. Before extracting edits and leaving groups, we remap the existing dataset to remove this shortcut,

Remapping USPTO-50k Dataset We first canonicalize the product molecule by clearing out atom numbers and converting the molecule to SMILES. The atoms in the canonicalized product have an atom mapping corresponding to their ordering. We then apply substructure matching between the original product and canonicalized product to identify the correspondence between the original and updated atom mappings, which we then use to update the atom mapping of the corresponding reactant atoms. To verify the correctness of the remapping procedure, we compare the number of extracted edits from the original and remapped products and reactants.

C.3 Hyperparameter Tuning

Edit Prediction The table below indicates the hyperparameter sweep for edit prediction,

Parameter	Values
Hidden dimension of MPN	[256, 512, 768]
Hidden dimensions of MLP	[256, 512, [512, 256]]
MPN depth	[5, 10]
Learning rate decay	[0.6, 0.9]

Synthon Completion We ran a hyperparameter sweep only for the *ind* configuration given its better empirical performance. The sweep configuration is indicated in the following table,

Parameter	Values
Hidden dimensions of MLP	[300, 150, [300, 150]]

C.4 Network Architectures

All models are trained with the Adam optimizer and an initial learning rate of 0.001.

C.4.1 Edit Prediction

We run the MPN for $T = 10$ iterations, with a hidden layer dimension of 256. The initial edit scores are predicted with a MLP of hidden layer dimension 512. In the reaction class unknown setting, we update the initial edit scores using a smaller MPN which is run for $T = 3$ iterations, and has a hidden layer dimension of 64. We also use dropout on the node embeddings and the hidden layers of MLP with a probability of 0.15 and 0.3 respectively. We apply a learning rate decay of 0.9 based on validation accuracy, with patience 10 and an improvement threshold of 0.01. Gradients are clipped to a norm of 10.0. Both models are trained for 200 epochs. The model has 1.03M parameters in the reaction class known setting, and 1.06M parameters in the reaction class unknown setting.

C.4.2 Synthon Completion

The network architecture and training details are largely similar across the reaction class known and unknown settings. We run the MPN for $T = 10$ iterations, with a hidden layer dimension of 300. The embedding dimension of leaving groups is set to 200. In the reaction class known setting, the classifier over leaving groups is a two layer MLP, with hidden dimensions of 300 and 150, while in the reaction class unknown setting, the classifier is a single layer MLP with a hidden layer dimension of 300. We also use dropout on the node embeddings and the hidden layers of MLP with a probability of 0.15 and 0.3 respectively. We apply a learning rate decay of 0.9 based on the validation accuracy, with a patience of 5 epochs, and a threshold value for improvement set to 0.01. Gradients are clipped to a norm of 10.0. The model is trained for 100 epochs. When the reaction class is known, the model has 0.84M parameters, while in the reaction class unknown case, the model has 0.81M parameters.

C.5 Computing

The edit prediction models were trained in about 23-24 hours on a single NVIDIA 1080Ti GPU, while the synthon completion models were trained in about 12-13 hours on the same GPU configuration.

D Multiple Edit Prediction

We propose an autoregressive model for multiple edit prediction that allows us to represent arbitrary length edit sets. The model makes no assumption on the connectivity of the reaction centers or the electron flow topology, addressing the drawbacks mentioned in [1, 12].

Each edit step t uses the intermediate graph $\mathcal{G}_s^{(t)}$ as input, obtained by applying the edits until t to \mathcal{G}_p . Atom and bond labels are now indexed by the edit step, and a new termination symbol $y_d^{(t)}$ is introduced such that $\sum_{(u,v),k} y_{uvk}^{(t)} + \sum_u y_u^{(t)} + y_d^{(t)} = 1$. The number of atoms remain unchanged during edit prediction, allowing us to associate a hidden state $\mathbf{h}_u^{(t)}$ with every atom u . Given representations $\mathbf{c}_u^{(t)}$ returned by the $\text{MPN}(\cdot)$ for $\mathcal{G}_s^{(t)}$, we update the atom hidden states as

$$\mathbf{h}_u^{(t)} = \tau \left(\mathbf{W}_h \mathbf{h}_u^{(t-1)} + \mathbf{W}_c \mathbf{c}_u^{(t)} + b \right). \quad (20)$$

The bond hidden state $\mathbf{h}_{uv}^{(t)} = (\mathbf{h}_u^{(t)} \parallel \mathbf{h}_v^{(t)})$ is defined similar to the single edit case. We also compute the termination score using a molecule hidden state $\mathbf{h}_m^{(t)} = \sum_{u \in \mathcal{G}_s^{(t)}} \mathbf{h}_u^{(t)}$. The edit logits are predicted by passing these hidden states through corresponding neural networks

$$s_{uvk}^{(t)} = \mathbf{u}_k^T \tau \left(\mathbf{W}_k \mathbf{h}_{uv}^{(t)} + b_k \right) \quad (21)$$

$$s_u^{(t)} = \mathbf{u}_a^T \tau \left(\mathbf{W}_a \mathbf{h}_u^{(t)} + b_a \right) \quad (22)$$

$$s_d^{(t)} = \mathbf{u}_d^T \tau \left(\mathbf{W}_d \mathbf{h}_m^{(t)} + b_d \right). \quad (23)$$

Training Training minimizes the cross-entropy loss over possible edits, aggregated over edit steps

$$\mathcal{L}_e(\mathcal{T}_e) = - \sum_{(\mathcal{G}_p, E) \in \mathcal{T}_e} \sum_{t=1}^{|E|} \left(\sum_{(j,k) \in E[t]} y_{uvk}^{(t)} \log(s_{uvk}^{(t)}) + \sum_{u \in E[t]} y_u^{(t)} \log(s_u^{(t)}) + y_d^{(t)} \log(s_d^{(t)}) \right). \quad (24)$$

Training utilizes *teacher-forcing* so that the model makes predictions given correct histories.

E Reaction Class Performance

Table 3 describes the 10 reaction classes found in the USPTO-50k dataset. This description was taken from [4]. Table ?? shows the performance of GRAPHRETRO across the different reaction classes. Reaction class 4 characterizing heterocycle formations is composed only of multiple edit examples, which our model cannot currently predict.

Table 3: **Reaction Class Description** of the 10 reaction classes found in USPTO-50k dataset

Class	Description	Fraction of Dataset (%)
1	heteroatom alkylation and arylation	30.3
2	acylation and related processes	23.8
3	CC bond formation	11.3
4	heterocycle formation	1.8
5	protections	1.3
6	deprotections	16.5
7	reductions	9.2
8	oxidations	1.6
9	functional group interconversion (FGI)	3.7
10	functional group addition (FGA)	0.5

Table 4: **GRAPHRETRO Performance** across the USPTO-50k reaction classes

Model	1	2	3	4	5	6	7	8	9	10
GRAPHRETRO	0.57	0.63	0.38	0.0	0.53	0.54	0.56	0.55	0.32	0.83