

PIEO Trees for Fun and Profit

We assume familiarity with [MLF+23], adopt its notational conventions, and borrow many of its definitions!

1 Structure & Semantics

Definition 1.1. For sets S , D , and predicates F over D , let $\mathbf{PIEO}(S, D, F)$ denote the set of *PIEOs* that

- (1) hold entries in S , decorated with meta-data in D
- (2) are ordered by \mathbf{Rk}
- (3) support predicates in F
- (4) admit partial functions

$$\begin{aligned} \text{pop} &: \mathbf{PIEO}(S, D, F) \times F \rightarrow S \times \mathbf{PIEO}(S, D, F) \\ \text{push} &: \mathbf{PIEO}(S, D, F) \times S \times D \times \mathbf{Rk} \rightarrow \mathbf{PIEO}(S, D, F) \\ \text{proj} &: \mathbf{PIEO}(S, D, F) \times F \rightarrow \mathbf{PIFO}(S) \end{aligned}$$

Maps push and pop are as usual. The *projection* $\text{proj}(p, f)$ is the PIFO of entries in p with data satisfying f . These three maps play nicely together:

$$\begin{aligned} \text{pop}(p, f) \text{ is undefined} &\iff \text{pop}(\text{proj}(p, f)) \text{ is undefined} & (1) \\ \text{pop}(p, f) = (\text{pkt}, p') &\iff \text{pop}(\text{proj}(p, f)) = (\text{pkt}, \text{proj}(p', f)) & (2) \\ \text{proj}(\text{push}(p, s, d, r), f) &= \begin{cases} \text{push}(\text{proj}(p, f), s, r) & f(d) \text{ holds true} \\ \text{proj}(p, f) & \text{otherwise} \end{cases} & (3) \end{aligned}$$

We consider PIEOs p, p' equal if, for all $f \in F$, $\text{proj}(p, f) = \text{proj}(p', f)$, i.e. their projections are always equal. For PIEO p , entry $s \in S$, and predicate $f \in F$, we write

- (1) $|p|$ for the number of entries in p
- (2) $|p|_f$ for the number of entries in p satisfying f
- (3) $|p|_{s,f}$ for the number of times s occurs in p with associated $d \in D$ such that $f(d)$ holds

We fix an opaque set **Data** and a collection \mathcal{F} of predicates defined on it. These predicates come with a total order \leq and the property that, $\forall d \in \mathbf{Data}$ and $f, f' \in \mathcal{F}$, $f \leq f' \wedge f(d) \implies f'(d)$.

Definition 1.2. The set of *PIEO trees* over $t \in \mathbf{Topo}$, denoted $\mathbf{PIEOTree}(t)$, is defined inductively by

$$\frac{p \in \mathbf{PIEO}(\mathbf{Pkt}, \mathbf{Data}, \mathcal{F})}{\text{Leaf}(p) \in \mathbf{PIEOTree}(*)} \quad \frac{n \in \mathbb{N} \quad ts \in \mathbf{Topo}^n \quad p \in \mathbf{PIEO}(\{1, \dots, n\}, \mathbf{Data}, \mathcal{F}) \quad \forall i \in [1, n]. \text{qs}[i] \in \mathbf{PIEOTree}(ts[i])}{\text{Internal}(\text{qs}, p) \in \mathbf{PIEOTree}(ts)}$$

Definition 1.3. Define $\text{pop} : \mathbf{PIEOTree}(t) \times \mathcal{F} \rightarrow \mathbf{Pkt} \times \mathbf{PIEOTree}(t)$ by

$$\frac{\text{pop}(p, f) = (\text{pkt}, p')}{\text{pop}(\text{Leaf}(p), f) = (\text{pkt}, \text{Leaf}(p'))} \quad \frac{\text{pop}(p, f) = (i, p') \quad \text{pop}(\text{qs}[i], f) = (\text{pkt}, q')}{\text{pop}(\text{Internal}(\text{qs}, p), f) = (\text{pkt}, \text{Internal}(\text{qs}[q'/i], p'))}$$

Definition 1.4. Define $\text{push} : \mathbf{PIEOTree}(t) \times \mathbf{Pkt} \times \mathbf{Data} \times \mathbf{Path}(t) \rightarrow \mathbf{PIEOTree}(t)$ by

$$\frac{\text{push}(p, \text{pkt}, d, r) = p'}{\text{push}(\text{Leaf}(p), \text{pkt}, d, r) = \text{Leaf}(p')} \quad \frac{\text{push}(p, i, d, r) = p' \quad \text{push}(\text{qs}[i], \text{pkt}, d, pt) = q'}{\text{push}(\text{Internal}(\text{qs}, p), \text{pkt}, d, (i, r) :: pt) = \text{Internal}(\text{qs}[q'/i], p')}$$

Definition 1.5. Let $t \in \mathbf{Topo}$. A *control* over t is a triple (s, q, z) , where $s \in \mathbf{St}$ is the *current state*, q is a PIEO tree of topology t , and

$$z : \mathbf{St} \times \mathbf{Pkt} \rightarrow \mathbf{Data} \times \mathbf{Path}(t) \times \mathbf{St}$$

is a function called the *scheduling transaction*.

2 Well-Formedness

Definition 2.1. Fix $f \in \mathcal{F}$. Define $|\cdot|_f : \mathbf{PIEOTree}(t) \rightarrow \mathbb{N}$ by

$$|\text{Leaf}(p)| = |p|_f \qquad |\text{Internal}(qs, p)| = \sum_{i=1}^{|qs|} |qs[i]|_f$$

We say that $q \in \mathbf{PIEOTree}(t)$ is *well-formed* w.r.t f , denoted $\vdash_f q$, if it adheres to the following rules.

$$\frac{}{\vdash_f \text{Leaf}(p)} \qquad \frac{\forall i \in [1, |qs|], \vdash_f qs[i] \wedge |p|_{i,f} = |qs[i]|_f}{\vdash_f \text{Internal}(qs, p)}$$

We say q is well-formed, denoted $\vdash q$, if there exists $f \in \mathcal{F}$ such that, for all $f' \geq f$, $\vdash_{f'} q$.

Theorem 2.2. Let $t \in \mathbf{Topo}$, $\text{pkt} \in \mathbf{Pkt}$, $d \in \mathbf{Data}$, $f \in \mathcal{F}$, and $q \in \mathbf{PIEOTree}(t)$ such that $\vdash q$.

- (1) If $pt \in \mathbf{Path}(t)$, then $\text{push}(q, \text{pkt}, d, pt)$ is well-defined and $\vdash \text{push}(q, \text{pkt}, d, pt)$.
- (2) If $|q|_f > 0$, then $\text{pop}(q, f)$ is well-defined and $\vdash q'$, where $\text{pop}(q, f) = (\text{pkt}, q')$.

Proof. TBD

□

3 Projection

Definition 3.1. For $f \in \mathcal{F}$, define $\text{proj}_f : \mathbf{PIEOTree}(t) \rightarrow \mathbf{PIFOTree}(t)$ by

$$\frac{p' = \text{proj}(p, f)}{\text{proj}_f(\text{Leaf}(p)) = \text{Leaf}(p')} \quad \frac{p' = \text{proj}(p, f) \quad \forall i \in [1, |qs|], \quad qs'[i] = \text{proj}_f(qs[i])}{\text{proj}_f(\text{Internal}(qs, p)) = \text{Internal}(qs', p')}$$

Lemma 3.2. For $q, q' \in \mathbf{PIEOTree}(t)$,

$$\forall f \in \mathcal{F}, \text{proj}_f(q) = \text{proj}_f(q') \implies q = q'$$

Proof. Suppose $\text{proj}_f(q) = \text{proj}_f(q')$ for all $f \in \mathcal{F}$. We'll proceed by induction on t to show $q = q'$.

(Leaf) For $t = *$, let $q = \text{Leaf}(p)$ and $q' = \text{Leaf}(p')$. Since

$$\text{proj}_f(q) = \text{Leaf}(\text{proj}(p, f)) = \text{Leaf}(\text{proj}(p', f)) = \text{proj}_f(q')$$

we know $\text{proj}(p, f) = \text{proj}(p', f)$ for all $f \in \mathcal{F}$. By Definition 1.1, $p = p'$ and hence $q = q'$.

(Node) For $t = \text{Node}(ts)$ and $n = |ts|$, let $q = \text{Internal}(qs, p)$ and $q' = \text{Internal}(qs', p')$. Notice

$$\begin{aligned} \text{proj}(p, f) &= \text{proj}(p', f) \\ \text{proj}_f(qs[i]) &= \text{proj}_f(qs'[i]) \end{aligned} \quad (i = 1, \dots, n)$$

for all $f \in \mathcal{F}$. Hence, $p = p'$ via Definition 1.1 and $qs = qs'$ by the inductive hypothesis, i.e. $q = q'$. \square

Lemma 3.3. For $q \in \mathbf{PIEOTree}(t)$ and $f \in \mathcal{F}$, $\text{pop}(q, f)$ is undefined if and only if $\text{pop}(\text{proj}_f(q))$ is undefined.

Proof. We'll do induction on t .

(Leaf) For $t = *$, let $q = \text{Leaf}(p)$ and $\text{proj}_f(q) = \text{Leaf}(p')$. By Equation (1) in Definition 1.1,

$$\begin{aligned} \text{pop}(q, f) \text{ is undefined} &\iff \text{pop}(p, f) \text{ is undefined} \\ &\iff \text{pop}(p') \text{ is undefined} \\ &\iff \text{pop}(\text{proj}_f(q)) \text{ is undefined} \end{aligned}$$

(Node) For $t = \text{Node}(ts)$, let $q = \text{Internal}(qs, p)$ and $\text{proj}_f(q) = \text{Internal}(qs', p')$. As before,

$$\text{pop}(p, f) \text{ is undefined} \iff \text{pop}(p') \text{ is undefined}$$

by Equation (1) in Definition 1.1 and

$$\text{pop}(qs[i], f) \text{ is undefined} \iff \text{pop}(qs'[i]) \text{ is undefined} \quad \forall i \in [1, |ts|]$$

by the inductive hypothesis. Hence, using Equation (2) in Definition 1.1,

$$\begin{aligned} \text{pop}(q, f) \text{ is undefined} &\iff \text{pop}(p, f) \text{ is undefined} \vee (\text{pop}(p, f) = (i, _) \wedge \text{pop}(qs[i], f) \text{ is undefined}) \\ &\iff \text{pop}(p') \text{ is undefined} \vee (\text{pop}(p') = (i, _) \wedge \text{pop}(qs'[i]) \text{ is undefined}) \\ &\iff \text{pop}(\text{proj}_f(q)) \text{ is undefined} \end{aligned}$$

\square

Lemma 3.4. For $q \in \mathbf{PIEOTree}(t)$ and $f \in \mathcal{F}$,

$$\text{pop}(q, f) = (\text{pkt}, q') \implies \text{pop}(\text{proj}_f(q)) = (\text{pkt}, \text{proj}_f(q'))$$

Proof. More induction on t !

(Leaf) For $t = *$, let

$$\begin{aligned} q &= \text{Leaf}(p_1) & \text{proj}_f(q) &= \text{Leaf}(p_2) \\ q' &= \text{Leaf}(p'_1) & \text{proj}_f(q') &= \text{Leaf}(p'_2) \end{aligned}$$

By Equation (2) in Definition 1.1,

$$\begin{aligned} \text{pop}(q, f) = (\text{pkt}, q') &\implies \text{pop}(p_1, f) = (\text{pkt}, p'_1) \\ &\implies \text{pop}(p_2) = \text{pop}(\text{proj}(p_1, f)) = (\text{pkt}, \text{proj}(p'_1, f)) = (\text{pkt}, p'_2) \\ &\implies \text{pop}(\text{proj}_f(q)) = (\text{pkt}, \text{proj}_f(q')) \end{aligned}$$

(Node) For $t = \text{Node}(ts)$, Let

$$\begin{aligned} q &= \text{Internal}(qs_1, p_1) & \text{proj}_f(q) &= \text{Internal}(qs_2, p_2) \\ q' &= \text{Internal}(qs'_1, p'_1) & \text{proj}_f(q') &= \text{Internal}(qs'_2, p'_2) \end{aligned}$$

Using Equation (2) in Definition 1.1 again and the inductive hypothesis,

$$\begin{aligned} \text{pop}(q, f) = (\text{pkt}, q') &\implies \text{pop}(p_1, f) = (i, p'_1) \wedge \text{pop}(qs_1[i], f) = (\text{pkt}, qs'_1[i]) \\ &\implies \text{pop}(\text{proj}(p_1, f)) = (i, \text{proj}(p'_1, f)) \wedge \text{pop}(\text{proj}_f(qs_1[i])) = (\text{pkt}, \text{proj}_f(qs'_1[i])) \\ &\implies \text{pop}(p_2) = (i, p'_2) \wedge \text{pop}(qs_2[i]) = (\text{pkt}, qs'_2[i]) \\ &\implies \text{pop}(\text{proj}_f(q)) = (\text{pkt}, \text{proj}_f(q')) \end{aligned}$$

□

Lemma 3.5. For $q \in \text{PIEOTree}(t)$, $\text{pkt} \in \mathbf{Pkt}$, $d \in \mathbf{Data}$, $pt \in \mathbf{Path}(t)$, and $f \in \mathcal{F}$,

$$\text{proj}_f(\text{push}(q, \text{pkt}, d, pt)) = \begin{cases} \text{push}(\text{proj}_f(q), \text{pkt}, pt) & f(d) \text{ holds true} \\ \text{proj}_f(q) & \text{otherwise} \end{cases}$$

Proof. Even more induction on t !

(Leaf) For $t = *$, let $q = \text{Leaf}(p)$ and $pt = r$. By Equation (3) in Definition 1.1.

$$\begin{aligned} \text{proj}_f(\text{push}(q, \text{pkt}, d, pt)) &= \text{Leaf}(\text{proj}(\text{push}(p, \text{pkt}, d, r), f)) \\ &= \begin{cases} \text{Leaf}(\text{push}(\text{proj}(p, f), \text{pkt}, r)) & f(d) \text{ holds true} \\ \text{Leaf}(\text{proj}(p, f)) & \text{otherwise} \end{cases} \\ &= \begin{cases} \text{push}(\text{proj}_f(q), \text{pkt}, pt) & f(d) \text{ holds true} \\ \text{proj}_f(q) & \text{otherwise} \end{cases} \end{aligned}$$

(Node) For $t = \text{Node}(ts)$, let $pt = (i, r) :: pt'$ and

$$\begin{aligned} q &= \text{Internal}(qs, p) \\ \text{proj}_f(q) &= \text{Internal}(qs', p') \\ \text{push}(\text{proj}_f(q), \text{pkt}, pt) &= \text{Internal}(qs'', p'') \\ \text{proj}_f(\text{push}(q, \text{pkt}, d, pt)) &= \text{Internal}(qs''', p''') \end{aligned}$$

By Equation (3) in Definition 1.1 and the inductive hypothesis,

$$\begin{aligned} p''' &= \begin{cases} \text{push}(\text{proj}(p, f), i, r) & f(d) \text{ holds true} \\ \text{proj}(p, f) & \text{otherwise} \end{cases} \\ &= \begin{cases} \text{push}(p', i, r) & f(d) \text{ holds true} \\ p' & \text{otherwise} \end{cases} = \begin{cases} p'' & f(d) \text{ holds true} \\ p' & \text{otherwise} \end{cases} \\ qs'''[i] &= \begin{cases} \text{push}(\text{proj}_f(qs[i]), \text{pkt}, pt') & f(d) \text{ holds true} \\ \text{proj}_f(qs[i]) & \text{otherwise} \end{cases} \\ &= \begin{cases} \text{push}(qs'[i], \text{pkt}, pt') & f(d) \text{ holds true} \\ qs'[i] & \text{otherwise} \end{cases} = \begin{cases} qs''[i] & f(d) \text{ holds true} \\ qs'[i] & \text{otherwise} \end{cases} \end{aligned}$$

By inspection of Definition 1.4 and Definition 3.1,

$$qs'[j] = qs''[j] = qs'''[j] = \text{proj}_f(qs[j])$$

for all $j \in [1, |ts|]$ such that $j \neq i$. Hence,

$$qs''' = \begin{cases} qs'' & f(d) \text{ holds true} \\ qs' & \text{otherwise} \end{cases}$$

Putting everything together,

$$\begin{aligned} \text{proj}_f(\text{push}(q, \text{pkt}, d, pt)) &= \text{Internal}(qs''', p''') \\ &= \begin{cases} \text{Internal}(qs'', p'') & f(d) \text{ holds true} \\ \text{Internal}(qs', p') & \text{otherwise} \end{cases} \\ &= \begin{cases} \text{push}(\text{proj}_f(q), \text{pkt}, pt) & f(d) \text{ holds true} \\ \text{proj}_f(q) & \text{otherwise} \end{cases} \end{aligned}$$

□

4 Embedding & Simulation

Definition 4.1. Let $t_1, t_2 \in \mathbf{Topo}$. We call a relation $R \subseteq \mathbf{PIEOTree}(t_1) \times \mathbf{PIEOTree}(t_2)$ a *simulation* if, for all $\text{pkt} \in \mathbf{Pkt}$, $f \in \mathcal{F}$, and $q_1 R q_2$,

- (1) If $\text{pop}(q_1, f)$ is undefined, then so is $\text{pop}(q_2, f)$
- (2) If $\text{pop}(q_1, f) = (\text{pkt}, q'_1)$, then $\text{pop}(q_2, f) = (\text{pkt}, q'_2)$ such that $q'_1 R q'_2$.
- (3) For all $pt_1 \in \mathbf{Path}(t_1)$ and $d \in \mathbf{Data}$, there exists $pt_2 \in \mathbf{Path}(t_2)$ such that

$$\text{push}(q_1, \text{pkt}, d, pt_1) R \text{push}(q_2, \text{pkt}, d, pt_2)$$

If such a simulation exists, we say that q_1 is *simulated* by q_2 , and we write $q_1 \preccurlyeq q_2$.

Remark 4.2. For all further discussion, we assume our embeddings are injective.

Definition 4.3. For $t_1, t_2 \in \mathbf{Topo}$, let f be an embedding from t_1 to t_2 . We lift f to a map \bar{f} from $\mathbf{PIEOTree}(t_1)$ to $\mathbf{PIEOTree}(t_2)$ inductively.

- For $t_1 = *$, define $\bar{f}(q) = q$. This is well-defined by [MLF⁺23, Lemma 5.2].
 - For $t_1 = \text{Node}(ts_1)$, $n = |ts_1|$, $q = \text{Internal}(qs, p)$, construct $\bar{f}_\alpha(q) \in \mathbf{PIEOTree}(t_2/\alpha)$ for each prefix α of $f(i)$ for some $i \in [1, n]$. Inductively, we'll build up from $f(i)$'s to ϵ and set $\bar{f}(q) = \bar{f}_\epsilon(q)$.
 - Let $\alpha = f(i)$ for some $i \in [1, n]$. We'll set $\bar{f}_\alpha(q) = \bar{f}_i(qs[i])$, where f_i embeds t_1/i into $t_2/f(i)$ as per [MLF⁺23, Lemma 5.2]. This well-defined by the injectivity of f .
 - Let α point to a transient node, say with m children. For $1 \leq j \leq m$ such that $\alpha \cdot j$ is not a prefix of some $f(i)$, define $\bar{f}(q)_{\alpha \cdot j}$ to be the PIEO tree with empty PIEOs on all leaves and internal nodes. With this and recursion, we know $\bar{f}(q)_{\alpha \cdot j} \in \mathbf{PIEOTree}(t_2/(\alpha \cdot j))$ for all $j \in [1, m]$.
- We create a new PIEO p_α as follows:
- (1) Start with p_α empty
 - (2) For each i in p such that $\alpha \cdot j$ is a prefix of $f(i)$, push j into p_α with i 's data and rank
- Finally, for all $j \in [1, m]$, set $qs_\alpha[j] = \bar{f}(q)_{\alpha \cdot j}$ and $\bar{f}(q)_\alpha = \text{Internal}(qs_\alpha, p_\alpha)$.

Theorem 4.4. The following diagram commutes

$$\begin{array}{ccc} \mathbf{PIEOTree}(t_1) & \xrightarrow{\bar{f}} & \mathbf{PIEOTree}(t_2) \\ \downarrow \text{proj}_g & & \downarrow \text{proj}_g \\ \mathbf{PIFOTree}(t_1) & \xrightarrow{\hat{f}} & \mathbf{PIFOTree}(t_2) \end{array}$$

In other words, for $q \in \mathbf{PIEOTree}(t_1)$ and $g \in \mathcal{F}$, $\text{proj}_g(\bar{f}(q)) = \hat{f}(\text{proj}_g(q))$.

Proof. We'll proceed by induction on t_1 . Suppose $t_1 = *$ and $q = \text{Leaf}(p)$. By [MLF+23, Lemma 5.3], $t_2 = *$ as well. By Definition 4.3 and [MLF+23, Definition 5.4], both \bar{f} and \hat{f} are the identity. Hence,

$$\text{proj}_g(\bar{f}(q)) = \text{proj}_g(q) = \hat{f}(\text{proj}_g(q))$$

Suppose $t_1 = \text{Node}(ts)$ and $q = \text{Internal}(qs, p)$. For any prefix α of $f(i)$ for $i \in [1, |ts|]$, we'll show

$$\text{proj}_g(\bar{f}(q)_\alpha) = \hat{f}(\text{proj}_g(q))_\alpha \quad (*)$$

by inverse induction on α . Instantiating Equation $(*)$ with $\alpha = \epsilon$ yields the desired result.

- For $\alpha = f(i)$, Equation $(*)$ holds by the outer inductive hypothesis because

$$\text{proj}_g(\bar{f}(q)_\alpha) = \text{proj}_g(\bar{f}_i(q)) = \hat{f}_i(\text{proj}_g(q)) = \hat{f}(\text{proj}_g(q))_\alpha$$

- Suppose α is some strict prefix of $f(i)$, pointing to a node with m children. Let

$$\text{proj}_g(\bar{f}(q)) = \text{Internal}(qs', p') \quad \text{and} \quad \hat{f}(\text{proj}_g(q)) = \text{Internal}(qs'', p'')$$

There's two parts to showing Equation $(*)$, namely $qs' = qs''$ and $p' = p''$.

- For all $j \in [1, m]$,

$$\text{proj}_g(\bar{f}(q)_{\alpha \cdot j}) = \hat{f}(\text{proj}_g(q))_{\alpha \cdot j}$$

For j such that $\alpha \cdot j$ is a prefix of some $f(i)$, this follows from the inner inductive hypothesis. For all other j , notice the LHS and RHS are both PIFO trees of topology t_2 , with empty PIFOs on all leaves and internal nodes. Hence, $qs'[j] = qs''[j]$ for all $j \in [1, m]$, i.e. $qs' = qs''$.

- By inspection, it's clear following the construction for p_α from Definition 4.3 and then computing the projection $\text{proj}(p_\alpha, g)$ yields the same result as following the recipe for p_α from [MLF+23, Definition 5.4] on the projection $\text{proj}_g(q)$: that is, exactly when we filter out elements not satisfying g does not matter. Hence, $p' = p''$.

□

Lemma 4.5. Let $t_1, t_2 \in \mathbf{Topo}$ and f be an embedding of t_1 inside t_2 . For $g \in \mathcal{F}$,

$$\text{pop}(q, g) \text{ is undefined} \implies \text{pop}(\bar{f}(q), g) \text{ is undefined}$$

Proof. Suppose $\text{pop}(q, g)$ is undefined. Applying both Lemma 3.3 and [MLF+23, Lemma 5.6], notice $\text{pop}(\hat{f}(\text{proj}_g(q)))$ is undefined. By Theorem 4.4, $\hat{f}(\text{proj}_g(q)) = \text{proj}_g(\bar{f}(q))$. Hence, $\text{pop}(\text{proj}_g(\bar{f}(q)))$ is undefined. Applying Lemma 3.3 once more, $\text{pop}(\bar{f}(q), g)$ is undefined. □

Lemma 4.6. Let $t_1, t_2 \in \mathbf{Topo}$ and f be an embedding of t_1 inside t_2 . For $g \in \mathcal{F}$,

$$\text{pop}(q, g) = (\text{pkt}, q') \implies \text{pop}(\bar{f}(q), g) = (\text{pkt}, \bar{f}(q'))$$

Almost a clone of the proof [MLF+23, Lemma 5.7].

Proof. We'll proceed by induction on t_1 . Suppose $t_1 = *$. By [MLF+23, Lemma 5.3], $t_2 = *$ as well. By Definition 4.3, \bar{f} is the identity. Hence,

$$\text{pop}(q, g) = (\text{pkt}, q') \implies \text{pop}(\bar{f}(q), g) = \text{pop}(q, g) = (\text{pkt}, q') = (\text{pkt}, \bar{f}(q'))$$

Suppose $t_1 = \text{Node}(ts)$. Let

$$q = \text{Internal}(qs, p) \quad q' = \text{Internal}(qs', p') \quad \text{pop}(p, g) = (j, p')$$

For any prefix α of some $f(i)$ (where $i \in [1, |ts|]$), we'll show

$$\begin{aligned} \text{pop}(\bar{f}(q)_\alpha, g) &= (\text{pkt}, \bar{f}(q')_\alpha) & \text{if } \alpha \text{ is a prefix of } f(j) \\ \bar{f}(q)_\alpha &= \bar{f}(q')_\alpha & \text{otherwise} \end{aligned} \quad (\dagger)$$

by inverse induction on α . Instantiating Equation (\dagger) with $\alpha = \epsilon$ yields the desired result.

- Suppose $\alpha = f(i)$. If α is a prefix of $f(j)$, $i = j$ by injectivity and [MLF+23, Definition 5.2, Equation (3)]. Recall $\text{pop}(qs[j], g) = (\text{pkt}, qs'[j])$. Hence, by the outer inductive hypothesis,

$$\text{pop}(\bar{f}(q)_\alpha, g) = \text{pop}(\bar{f}_i(qs[j]), g) = (\text{pkt}, \bar{f}_i(qs'[j])) = (\text{pkt}, \bar{f}(q')_\alpha)$$

- Once more, suppose $\alpha = f(i)$. If α is not a prefix of $f(j)$, then $i \neq j$. Since $qs[i] = qs'[i]$,

$$\bar{f}(q)_\alpha = \bar{f}_i(qs[i]) = \bar{f}_i(qs'[i]) = \bar{f}(q')_\alpha$$

- Suppose α is some strict prefix of $f(j)$, pointing to a node with m children. Let

$$\bar{f}(q)_\alpha = \text{Internal}(qs_\alpha, p_\alpha) \quad \bar{f}(q')_\alpha = \text{Internal}(qs'_\alpha, p'_\alpha)$$

There exists $k \in [1, m]$ such that $\alpha \cdot k$ is a prefix of $f(j)$. By the inner inductive hypothesis,

$$qs_\alpha[i] = \bar{f}(q)_{\alpha \cdot i} = \bar{f}(q')_{\alpha \cdot i} = qs'_\alpha[i] \text{ for } i \in [1, m] \text{ with } i \neq k \quad (!)$$

$$\text{pop}(qs_\alpha[k], g) = \text{pop}(\bar{f}(q)_{\alpha \cdot k}, g) = (\text{pkt}, \bar{f}(q')_{\alpha \cdot k}) = (\text{pkt}, qs'_\alpha[k])$$

Via the construction in Definition 4.3 and since $\text{pop}(p, g) = p'$, $\text{pop}(p_\alpha, g) = (k, p'_\alpha)$. Putting everything together, $\text{pop}(\bar{f}(q)_\alpha, g) = (\text{pkt}, \bar{f}(q')_\alpha)$, as desired.

- Suppose α is some strict prefix of some $f(i)$ but not $f(j)$, pointing to a node with m children. Let

$$\bar{f}(q)_\alpha = \text{Internal}(qs_\alpha, p_\alpha) \quad \bar{f}(q')_\alpha = \text{Internal}(qs'_\alpha, p'_\alpha)$$

Since p and p' agree on all indices i such that $f(i)$ is a child of α , $p_\alpha = p'_\alpha$. For $i \in [1, m]$, since $\alpha \cdot i$ is not a prefix of $f(j)$, the inner inductive hypothesis yields

$$qs_\alpha[i] = \bar{f}(q)_{\alpha \cdot i} = \bar{f}(q')_{\alpha \cdot i} = qs'_\alpha[i] \quad (!!)$$

Putting everything together, $\bar{f}(q)_\alpha = \bar{f}(q')_\alpha$, as desired.

NOTE: even when $\alpha \cdot i$ is not a prefix of any $f(i)$, Equation (!) and Equation (!!) hold! Both $\bar{f}(q)_{\alpha \cdot i}$ and $\bar{f}(q')_{\alpha \cdot i}$ would be PIEO trees with empty PIEOs on all leaf and internal nodes. \square

Lemma 4.7. Let $t_1, t_2 \in \mathbf{Topo}$ and f be an embedding of t_1 inside t_2 . For $\text{pkt} \in \mathbf{Pkt}$, $d \in \mathbf{Data}$, and $pt \in \mathbf{Path}(t_1)$,

$$\bar{f}(\text{push}(q, \text{pkt}, d, pt)) = \text{push}(\bar{f}(q), \text{pkt}, d, \tilde{f}(pt))$$

Proof. Let $q_2 = \bar{f}(q_1)$. For $g \in \mathcal{F}$ such that $g(d)$ holds true,

$$\begin{aligned} \text{(by Theorem 4.4)} \quad \text{proj}_g(\bar{f}(\text{push}(q_1, \text{pkt}, d, pt))) &= \hat{f}(\text{proj}_g(\text{push}(q_1, \text{pkt}, d, pt))) \\ \text{(by Lemma 3.5)} &= \hat{f}(\text{push}(\text{proj}_g(q_1), \text{pkt}, pt)) \\ \text{(by [MLF⁺23, Lemma 5.9])} &= \text{push}(\hat{f}(\text{proj}_g(q_1)), \text{pkt}, \tilde{f}(pt)) \\ \text{(by Theorem 4.4)} &= \text{push}(\text{proj}_g(q_2), \text{pkt}, \tilde{f}(pt)) \\ \text{(by Lemma 3.5)} &= \text{proj}_g(\text{push}(q_2, \text{pkt}, d, \tilde{f}(pt))) \end{aligned}$$

For $g \in \mathcal{F}$ such that $g(d)$ does not hold true,

$$\begin{aligned} \text{(by Theorem 4.4)} \quad \text{proj}_g(\bar{f}(\text{push}(q_1, \text{pkt}, d, pt))) &= \hat{f}(\text{proj}_g(\text{push}(q_1, \text{pkt}, d, pt))) \\ \text{(by Lemma 3.5)} &= \hat{f}(\text{proj}_g(q_1)) \\ \text{(by Theorem 4.4)} &= \text{proj}_g(q_2) \\ \text{(by Lemma 3.5)} &= \text{proj}_g(\text{push}(q_2, \text{pkt}, d, \tilde{f}(pt))) \end{aligned}$$

Overall, $\text{proj}_g(\bar{f}(\text{push}(q_1, \text{pkt}, d, pt))) = \text{proj}_g(\text{push}(q_2, \text{pkt}, d, \tilde{f}(pt)))$ for all $g \in \mathcal{F}$. Hence,

$$\bar{f}(\text{push}(q_1, \text{pkt}, d, pt)) = \text{push}(q_2, \text{pkt}, d, \tilde{f}(pt))$$

by Lemma 3.2, as desired. \square

Theorem 4.8. Let $t_1, t_2 \in \mathbf{Topo}$. If f embeds t_1 into t_2 , then

$$R = \{(q, \bar{f}(q)) \mid q \in \mathbf{PIEOTree}(t_1)\}$$

is a simulation.

Proof. By Lemma 4.5, Lemma 4.6, and Lemma 4.7, the conditions from Definition 4.1 hold. \square

References

- [MLF⁺23] Anshuman Mohan, Yunhe Liu, Nate Foster, Tobias Kappé, and Dexter Kozen. Formal abstractions for packet scheduling, 2023.