Supplementary Material
FSE 2022 submission

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In the following, to have a self contained document we provide the proof of the Lemma 1 together with our grounding algorithm.

Lemma 1 (Over-approximation Query). *For an FOL formula ϕ_f, and a domain $D_{AU\downarrow}$, if $\phi_g = G(\phi_f, D_{AU\downarrow})$ is UNSAT, then so is ϕ_f.*

Proof. Suppose ϕ_g is UNSAT but there exists a solution v_f for ϕ_f in some domain D_{AU} (D_{AU} may be different from $D_{AU\downarrow}$). We show that we can always construct a solution v_g that satisfies ϕ_g, which causes a contradiction. First, we construct a solution v'_g for $\phi'_g = G(\phi_f, D_{AU})$ from the solution v_f (for ϕ_f). Then, we construct a solution v_g for ϕ_g from the solution v'_g for ϕ'_g.

We can construct a solution v'_g for ϕ'_g in $D_{AU} \cup NewRs$ where $NewRs$ are the new relational objects added by G. The encoding of G uses the standard way for expanding universally quantified expression by enumerating every relation object in D_{AU} (L:10). For every existentially quantified expression, there exists some relation object $r \in D_{AU}$ enabled by v_f that satisfies the expression in ϕ_f, whereas ϕ'_g contains a new relational object $r' \in NewRs$ for satisfying the same expression (L:6). Let $v_f(r) = v'_g(r')$ for r and r', and then v'_g is a solution to ϕ'_g.

To construct the solution v_g for $\phi_g = G(\phi_f, D_{AU\downarrow})$ from the solution v'_g for $\phi'_g = G(\phi_f, D_{AU})$, we consider the expansion of universally quantified expression in ϕ_f (L:8). For every relational objects in $r^+ \in D_{AU} - D_{AU\downarrow}$, G creates constraints (L:10) in ϕ'_g, but not in ϕ_g. On the other hand, for every relational objects in $r^- \in D_{AU\downarrow} - D_{AU}$, we disable r^- in the solution v_g, (i.e., $v_g(r^-) = \perp$). Therefore, the constraints instantiated by r^- (at L:10) in ϕ_g are vacuously satisfied.

For every relational object $r \in D_{AU\downarrow} \cap D_{AU}$, we let $v_g(r) = v'_g(r)$, and all shared constraints in ϕ_g and ϕ'_g are satisfied by v_g and v'_g, respectively. Therefore, v_g is a solution to ϕ_g. Contradiction. □

Algorithm 1 G grounds an FOL formula with quantifiers over relational objects

Input an FOL formula ϕ_f.
Input a domain of relational objects $D_{AU\downarrow}$.
Output a grounded quantifier-free formula ϕ_g over relational objects.

if IS_ATOM(ϕ_f) **then return** ϕ_f **end if**
if $\phi_f.op = \exists$ **then** *//process the existential operator*
    $Cls \leftarrow \phi_f.class$
    //creates a new relational object of class Cls
    $newR \leftarrow$ NEWACT(Cls)
    return G (ϕ_f.body[$\phi_f.headAct \leftarrow newR$], $D_{AU\downarrow}$)
end if
if $\phi_f.op = \forall$ **then** *//process the universal operator*
    $Cls \leftarrow \phi_f.class$
    return $\bigwedge_{[r:Cls] \in D_{AU\downarrow}} r \Rightarrow G$ (ϕ_f.body[$\phi_f.head \leftarrow r$], $D_{AU\downarrow}$)
end if
return $\phi_f.op(G$ (ϕ_{child}, $D_{AU\downarrow}$) for ϕ_{child} in ϕ_f.body)