Least and Greatest Fixpoints

Metodi Formali per il Software e i Servizi

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Fixpoints

We briefly recall few notions on fixpoints.

- Consider the equation:
$$X = f(X)$$
where f is an operator from $2^{\mathcal{S}}$ to $2^{\mathcal{S}}$ ($2^{\mathcal{S}}$ denotes the set of all subsets of a set $\mathcal{S}$).
- Every solution $\mathcal{E}$ of this equation is called a **fixpoint** of the operator f
- every set $\mathcal{E}$ such that $f(\mathcal{E}) \subseteq \mathcal{E}$ is called **pre-fixpoint**, and
- every set $\mathcal{E}$ such that $\mathcal{E} \subseteq f(\mathcal{E})$ is called **post-fixpoint**.
- In general, an equation as the one above may have either no solution, a finite number of solutions, or an infinite number of them. Among the various solutions, the smallest and the greatest solutions (with respect to set-inclusion) have a prominent position, if they exist.
- The the smallest and the greatest solutions are called **least fixpoint** and **greatest fixpoint**, respectively.

Tarski-Knaster fixpoint theorem

We say that f is **monotonic** wrt $\subseteq$ (set-inclusion) whenever $\mathcal{E}_1 \subseteq \mathcal{E}_2$ implies $f(\mathcal{E}_1) \subseteq f(\mathcal{E}_2)$.

Theorem (Tarski'55)

Let $\mathcal{S}$ be a set, and f an operator from $2^{\mathcal{S}}$ to $2^{\mathcal{S}}$ that is monotonic wrt $\subseteq$. Then:

- *There exists a unique least fixpoint of f, which is given by $\bigcap\{\mathcal{E} \subseteq \mathcal{S} \mid f(\mathcal{E}) \subseteq \mathcal{E}\}$.*
- *There exists a unique greatest fixpoint of f, which is given by $\bigcup\{\mathcal{E} \subseteq \mathcal{S} \mid \mathcal{E} \subseteq f(\mathcal{E})\}$.*

Proof of Tarski-Knaster theorem: least fixpoint

We start by showing the proof for the **least fixpoint** part. (The proof for the greatest fixpoint is analogous, see later).

Let us define $\mathcal{L} = \bigcap\{\mathcal{E} \subseteq \mathcal{S} \mid f(\mathcal{E}) \subseteq \mathcal{E}\}$.

Lemma

$f(\mathcal{L}) \subseteq \mathcal{L}$

Proof.

- For every $\mathcal{E}$ such that $f(\mathcal{E}) \subseteq \mathcal{E}$, we have $\mathcal{L} \subseteq \mathcal{E}$, by definition of $\mathcal{L}$.
- By monotonicity of f, we have $f(\mathcal{L}) \subseteq f(\mathcal{E})$.
- Hence $f(\mathcal{L}) \subseteq \mathcal{E}$ (for every $\mathcal{E}$ such that $f(\mathcal{E}) \subseteq \mathcal{E}$).
- But then $f(\mathcal{L})$ is contained in the intersection of all such $\mathcal{E}$, so we have $f(\mathcal{L}) \subseteq \mathcal{L}$.

$\square$

Proof of Tarski-Knaster theorem: least fixpoint

Lemma

$\mathcal{L} \subseteq f(\mathcal{L})$

Proof.

- By the previous lemma, we have $f(\mathcal{L}) \subseteq \mathcal{L}$.
- But then $f(f(\mathcal{L})) \subseteq f(\mathcal{L})$, by monotonicity.
- Hence, $\bar{\mathcal{E}} = f(\mathcal{L})$ is such that $f(\bar{\mathcal{E}}) \subseteq \bar{\mathcal{E}}$.
- Thus, $\mathcal{L} \subseteq f(\mathcal{L})$, by definition of $\mathcal{L}$.

□

Proof of Tarski-Knaster theorem: least fixpoint

The previous two lemmas together show that $\mathcal{L}$ is indeed a fixpoint: $\mathcal{L} = f(\mathcal{L})$.
We still need to show that is the **least** fixpoint.

Lemma

*$\mathcal{L}$ is the **least** fixpoint: for every $f(\mathcal{E}) = \mathcal{E}$ we have $\mathcal{L} \subseteq \mathcal{E}$.*

Proof.

By contradiction.

- Suppose not. Then there exists an $\hat{\mathcal{E}}$ such that $f(\hat{\mathcal{E}}) = \hat{\mathcal{E}}$ and $\hat{\mathcal{E}} \subset \mathcal{L}$.
- Being $\hat{\mathcal{E}}$ a fixpoint (i.e., $f(\hat{\mathcal{E}}) = \hat{\mathcal{E}}$), we have in particular $f(\hat{\mathcal{E}}) \subseteq \hat{\mathcal{E}}$.
- Hence by definition of $\mathcal{L}$, we get $\mathcal{L} \subseteq \hat{\mathcal{E}}$. Contradiction.

□

Proof of Tarski-Knaster theorem: greatest fixpoint

Now we prove the **greatest fixpoint** part.

Let us define $\mathcal{G} = \bigcup\{\mathcal{E} \subseteq \mathcal{S} \mid \mathcal{E} \subseteq f(\mathcal{E})\}$.

Lemma

$\mathcal{G} \subseteq f(\mathcal{G})$

Proof.

- For every $\mathcal{E}$ such that $\mathcal{E} \subseteq f(\mathcal{E})$, we have $\mathcal{E} \subseteq \mathcal{G}$, by definition of $\mathcal{G}$.
- Consider now $e \in \mathcal{G}$. Then there exists an $\hat{\mathcal{E}}$ such that $\hat{\mathcal{E}} \subseteq f(\hat{\mathcal{E}})$, $e \in \hat{\mathcal{E}}$, by definition of $\mathcal{G}$.
- But $\hat{\mathcal{E}} \subseteq \mathcal{G}$, and by monotonicity $f(\hat{\mathcal{E}}) \subseteq f(\mathcal{G})$, hence $e \in f(\mathcal{G})$.

□

Proof of Tarski-Knaster theorem: greatest fixpoint

Lemma

$f(\mathcal{G}) \subseteq \mathcal{G}$

Proof.

- By the previous lemma we have $\mathcal{G} \subseteq f(G)$
- But then, we have that $f(\mathcal{G}) \subseteq f(f(\mathcal{G}))$, by monotonicity.
- Hence, $\bar{\mathcal{E}} = f(\mathcal{G})$ is such that $\bar{\mathcal{E}} \subseteq f(\bar{\mathcal{E}})$.
- Thus, $f(\mathcal{G}) \subseteq \mathcal{G}$, by definition of $\mathcal{G}$.

□

Proof of Tarski-Knaster theorem: greatest fixpoint

The previous two lemmas together show that $\mathcal{L}$ is indeed a fixpoint: $\mathcal{G} = f(\mathcal{G})$. We still need to show that is the **greatest** fixpoint.

Lemma

*$\mathcal{G}$ is the **greatest** fixpoint: for every $\mathcal{E} = f(\mathcal{E})$ we have $\mathcal{E} \subseteq \mathcal{G}$.*

Proof.

By contradiction.

- Suppose not. Then there exists an $\hat{\mathcal{E}}$ such that $\hat{\mathcal{E}} = f(\hat{\mathcal{E}})$ and $\mathcal{G} \subset \hat{\mathcal{E}}$.
- Being $\hat{\mathcal{E}}$ a fixpoint, we have $\hat{\mathcal{E}} \subseteq f(\hat{\mathcal{E}})$.
- Hence by definition of $\mathcal{G}$, we get $\hat{\mathcal{E}} \subseteq \mathcal{G}$. Contradiction.

□

Approximates of least fixpoints

The approximates for a least fixpoint $\mathcal{L} = \bigcap\{\mathcal{E} \subseteq \mathcal{S} \mid f(\mathcal{E}) \subseteq \mathcal{E}\}$ are as follows:

$$\begin{aligned} Z_0 &\doteq \emptyset \\ Z_1 &\doteq f(Z_0) \\ Z_2 &\doteq f(Z_1) \\ \ldots \end{aligned}$$

Lemma

For all i, $Z_i \subseteq Z_{i+1}$.

Proof.

By induction on i.

- Base case: $i = 0$. By definition $Z_0 = \emptyset$, and trivially $\emptyset \subseteq Z_1$.
- Inductive case: $i = k + 1$. By inductive hypothesis we assume $Z_{k-1} \subseteq Z_k$, and we show that $Z_k \subseteq Z_{k+1}$.
  - $f(Z_{k-1}) \subseteq f(Z_k)$, by monotonicity.
  - But $f(Z_{k-1}) = Z_k$ and $f(Z_k) = Z_{k+1}$, hence we have $Z_k \subseteq Z_{k+1}$.

□

Approximates of least fixpoints

Lemma

For all i, $Z_i \subseteq \mathcal{L}$.

Proof.

By induction on i.

- Base case: $i = 0$. By definition $Z_0 = \emptyset$, and trivially $\emptyset \subseteq \mathcal{L}$.
- Inductive case: $i = k + 1$. By inductive hypothesis we assume $Z_k \subseteq \mathcal{L}$, and we show that $Z_{k+1} \subseteq \mathcal{L}$.
  - $f(Z_k) \subseteq f(\mathcal{L})$, by monotonicity.
  - But then $f(Z_k) \subseteq \mathcal{L}$, since $\mathcal{L} = f(\mathcal{L})$.
  - Hence, considering that $f(Z_k) = Z_{k+1}$, we have $Z_{k+1} \subseteq \mathcal{L}$.

□

Approximates of least fixpoints

Theorem (Tarski-Knaster on approximates of least fixpoints)

If for some n, $Z_{n+1} = Z_n$, then $Z_n = \mathcal{L}$.

Proof.

- $Z_n \subseteq \mathcal{L}$ by the above lemma.
- On the other hand, since $Z_{n+1} = f(Z_n) = Z_n$, we trivially get $f(Z_n) \subseteq Z_n$, and hence $\mathcal{L} \subseteq Z_n$ by definition of $\mathcal{L}$.

□

Observe also that once for some n, $Z_{n+1} = Z_n$, then for all $m \geq n$ we have $Z_{m+1} = Z_m$, by definition of approximates.

In fact this theorem can be generalized by ranging n over ordinals instead of natural numbers.

Approximates of least fixpoints

The above theorem gives us a simple sound procedure to compute the least fixpoint:

Least fixpoint algorithm

$Z_{old} := \emptyset;$
$Z := f(Z_{old});$
while $(Z \neq Z_{old})\{$
  $Z_{old} := Z;$
  $Z := f(Z);$
$\}$

If in $\mathcal{L} = \bigcap\{\mathcal{E} \subseteq \mathcal{S} \mid f(\mathcal{E}) \subseteq \mathcal{E}\}$ the set $\mathcal{S}$ **is finite** then the above procedure **terminates** in $|\mathcal{S}|$ steps and becomes **sound and complete**.

Notice the above procedure is **polynomial** in the size of $\mathcal{S}$.

Approximates of greatest fixpoints

The approximates for the greatest fixpoint $\mathcal{G} = \bigcup\{\mathcal{E} \subseteq \mathcal{S} \mid \mathcal{E} \subseteq f(\mathcal{E})\}$ are as follows:

$$Z_0 \doteq \mathcal{S}$$
$$Z_1 \doteq f(Z_0)$$
$$Z_2 \doteq f(Z_1)$$
$$\ldots$$

Lemma

For all i, $Z_{i+1} \subseteq Z_i$.

Proof.

By induction on i.

- Base case: $i = 0$. By definition $Z_0 = \mathcal{S}$, and trivially $Z_1 \subseteq \mathcal{S}$.
- Inductive case: $i = k + 1$: by inductive hypothesis we assume $Z_k \subseteq Z_{k-1}$, and we show that $Z_{k+1} \subseteq Z_k$.
  - $f(Z_k) \subseteq f(Z_{k-1})$, by monotonicity.
  - But $f(Z_k = Z_{k+1}$ and $f(Z_{k-1}) = Z_k$ hence $Z_{k+1} \subseteq Z_k$.

□

Approximates of greatest fixpoints

Lemma

For all i, $\mathcal{G} \subseteq Z_i$.

Proof.

By induction on i.

- Base case: $i = 0$. By definition $Z_0 = \mathcal{S}$, and trivially $\mathcal{G} \subseteq \mathcal{S}$.
- Inductive case: $i = k + 1$: by inductive hypothesis we assume $\mathcal{G} \subseteq Z_k$, and we show that $G \subseteq Z_{k+1}$.
  - $f(\mathcal{G}) \subseteq f(Z_k)$, by monotonicity.
  - But then $\mathcal{G} \subseteq f(Z_k)$, since $\mathcal{G} = f(\mathcal{G})$.
  - Hence, considering that $f(Z_k) = Z_{k+1}$, we get $\mathcal{G} \subseteq Z_{k+1}$.

□

Approximates of greatest fixpoints

Theorem (Tarski-Knaster on approximates of greatest fixpoint)

If for some n, $Z_{n+1} = Z_n$, then $Z_n = \mathcal{G}$.

Proof.

- $\mathcal{G} \subseteq Z_n$ by the above lemma.
- On the other hand, since $Z_{n+1} = f(Z_n) = Z_n$, we trivially get $Z_n \subseteq f(Z_n)$, and hence $Z_n \subseteq \mathcal{G}$ by definition of $\mathcal{G}$.

□

Observe also that once for some n, $Z_{n+1} = Z_n$, then for all $m \geq n$ we have $Z_{m+1} = Z_m$, by definition of approximates.

In fact this theorem can be generalized by ranging n over ordinals instead of natural numbers.

Approximates of greatest fixpoints

The above theorem gives us a simple sound procedure to compute the greatest fixpoint:

Greatest fixpoint algorithm

$Z_{old} := \mathcal{S};$
$Z := f(Z_{old});$
while $(Z \neq Z_{old})\{$
$\quad Z_{old} := Z;$
$\quad Z := f(Z);$
$\}$

If in $\mathcal{G} = \bigcup\{\mathcal{E} \subseteq \mathcal{S} \mid \mathcal{E} \subseteq f(\mathcal{E})\}$ the set $\mathcal{S}$ **is finite** then the above procedure **terminates** in $|\mathcal{S}|$ steps and becomes **sound and complete**.

Notice the above procedure is **polynomial** in the size of $\mathcal{S}$.

Discussion

For simplicity we have considered fixpoint wrt set-inclusion. In fact, the only property of set inclusion that we have used is the **lattice** implicitly defined by it.

We recall that a lattice is a the partial order (defined by set inclusion in our case), with the minimal element ($\emptyset$ in our case) and maximal element ($\mathcal{S}$ in our case).

We can immediately extend all the results presented here to arbitrary lattices substituting to the relation $\subseteq$ the relation $\leq$ of the lattice.