Exercise 1 (Comparison). Let us compare the reduction technique based on ample sets with Petri net unfoldings. We shall see that both have advantages and disadvantages over each other.

For a Petri net $N$, let $U(N)$ be its unfolding and $M(N)$ be the associated transition system in which, for simplicity, we assume all actions to be invisible, and that the independence relation used for reduction is maximal.

1. First, construct a Petri net $N$ with two transitions $a, b$ such that: (i) the input places of $a$ and $b$ overlap; (ii) $a$ and $b$ are independent in $M(N)$.

In the following, let $(N_k)_{k \geq 1}$ be a family of 1-safe Petri nets such that for all $k$, the size of $N_k$ is $O(k)$.

2. Construct a family of nets such that for all $k$, any complete prefix of $U(N_k)$ is at least of size $2^k$, but $red(M(N_k))$ is of size $O(k)$.

3. Construct a family of nets such that for all $k$, $red(M(N_k))$ is at least of size $2^k$, but there is a complete prefix of $U(N_k)$ of size $O(k)$.

Hint: It suffices to regard nets whose rechability graph is acyclic. For (3), try to construct $N_k$ from $k$ separate components such that $U(N_k)$ is simply the juxtaposition of the unfoldings of the components.

Exercise 2 (Adequate Partial Orders). A partial order $\prec$ between events is adequate if the three following conditions are verified:

(a) $\prec$ is well-founded,

(b) $|t| \preceq |t'|$ implies $t \prec t'$, and

(c) $\prec$ is preserved by finite extensions: as in the lecture notes, if $t \prec t'$ and $B(t) = B(t')$, and $E$ and $E'$ are two isomorphic extensions of $|t|$ and $|t'|$ with $|u| = |t| \oplus E$ and $|u'| = |t'| \oplus E'$, then $u \prec u'$.

As you can guess, adequate partial orders result in complete unfoldings. (An event $e$ is a cutoff if there exists $f \prec e$ such that the markings associated with $e$ and $f$ are the same.)

1. Show that $\prec_s$ defined by $t \prec_s t'$ iff $|t| < |t'|$ is adequate.

2. Construct the finite unfolding of the following Petri net using $\prec_s$; how does the size of this unfolding relate to the number of reachable markings?
3. Suppose we define an arbitrary total order $\ll$ on the transitions $T$ of the Petri net, i.e. they are $t_1 \ll \cdots \ll t_n$. Given a set $S$ of events and conditions of $Q$, $\varphi(S)$ is the sequence $t_1^{i_1} \cdots t_n^{i_n}$ in $T^*$ where $i_j$ is the number of events labeled by $t_j$ in $S$. We also note $\ll$ for the lexicographic order on $T^*$.

Show that $\prec_e$ defined by $t \prec_e t' \text{ iff } ||t|| < ||t'||$ or $||t|| = ||t'||$ and $\varphi(|t|) \ll \varphi(|t'|)$ is adequate. Construct the finite unfolding for the previous Petri net using $\prec_e$.

4. There might still be examples where $\prec_e$ performs poorly. One solution would be to use a total adequate order; why? Give a 1-safe Petri net that shows that $\prec_e$ is not total.

**Exercise 3** (Computing $\text{pre}^*(C)$). Consider the pushdown system represented below, with stack alphabet $\Gamma = \{a, b\}$.

![Diagram of a pushdown system]

Apply the algorithm described in the lecture notes to compute a $P$-automaton accepting $\text{pre}^*(p_6b^*)$.

**Exercise 4** (Labelled Pushdown Systems). Let $P = (P, \Gamma, \Delta, \Sigma)$ be a labelled pushdown system, i.e. the rules in $\Delta$ are of the form $pA \xrightarrow{a} qw$, where $p, q \in P$ are control locations,
A ∈ Γ and w ∈ Γ* are stack symbols, and additionally a ∈ Σ is an *action*. The set of configurations Con(𝑃) consists of the tuples qw with q ∈ P and w ∈ Γ*. For two configurations c, c′ we write c ⇝ w c′, where w ∈ Σ*, if c can be transformed into c′ by a sequence of rules whose labels yield w.

Given a regular set of configurations C, it is known how to compute \( \text{pre}^*(C) = \{ c ∈ \text{Con}(𝑃) | ∃ c′ ∈ C, w ∈ Σ^*: c ⇝ w c′ \} \). If C is accepted by an automaton with n states, this takes \( O(n^2 \cdot |D|) \) time.

1. Let \( L ⊆ Σ^* \) be a regular language and C be a regular set of configurations. We define
   \[
   \text{pre}^*[L](C) := \{ c ∈ \text{Con}(𝑃) | ∃ c′ ∈ C, w ∈ L : c ⇝ w c′ \}.
   \]
   One can prove that \( \text{pre}^*[L](C) \) is regular. Describe how to compute a finite automaton accepting \( \text{pre}^*[L](C) \).

2. Give a bound on the amount of time it takes to compute \( \text{pre}^*[L](C) \).

**Exercise 5** (Data-flow Analysis). We consider a problem from interprocedural data-flow analysis. A program consists of a set Proc of procedures that can execute and recursively call one another. The behaviour of each procedure \( p \) is described by a flow graph, an example with two procedures is shown below.

Formally, a flow graph for procedure \( p ∈ \text{Proc} \) is a tuple \( G_p = (N_p, A, E_p, e_p, x_p) \), where

- \( N_p \) are the nodes, corresponding to program locations; we denote \( N := \bigcup_{p ∈ \text{Proc}} N_p \).
- \( A = A_I ∪ \{ \text{call}(p) | p ∈ \text{Proc} \} \) are the actions, where \( A_I \) are *internal actions* (such as assignments etc); additionally an action can call some procedure. \( A \) is identical for all procedures.
• $E_p \subseteq N_p \times A \times N_p$ are the edges, labelled with actions from $A$. We denote $E := \bigcup_{p \in \text{Proc}} E_p$.

• $e_p$ is the entry point of procedure $p$, i.e. when $p$ is called, execution will start at $e_p$.

• $x_p$ is the exit point of $p$ (without any outgoing edges); when $x_p$ is reached, $p$ terminates and execution resumes at last call site of $p$.

1. Construct a labelled pushdown system with one single control location that expresses the behaviour of the procedures in $\text{Proc}$.

Suppose that the internal actions in $A_I$ describe assignments to global variables, i.e. they are of the form $v := \text{expr}$, where $v$ is a variable and $\text{expr}$ the right-hand-side expression. If $v$ is a variable, then $D_v \subseteq A_I$ is the set of actions that assign a value to $v$ and $R_v \subseteq A_I$ the set of actions where $v$ occurs on the right-hand side.

Let $\text{Init} \in \text{Proc}$ be an initial procedure and $n \in N$ a node in the flow graph. We say that variable $v$ is live at $n$ if there exists a node $n'$ and an execution that (i) starts at $e_{\text{Init}}$, (ii) passes $n$, (iii) finally reaches $n'$ with an action from $R_v$, and (iv) there is no assignment to $v$ between $n$ and $n'$ in this execution. (Intuitively, this means that the value that $v$ has at $n$ matters for some execution; this is used in compiler construction to determine whether an optimizing compiler may “forget” the value of $v$ at $n$.) For instance, in the shown example, the variable $x$ is live at $n_1$ and $e_p$, but not in the other nodes.

2. Describe a regular language $L \subseteq A^*$ that describes the sequences of actions that can happen along such executions between $n$ and $n'$.

3. Describe how, given a variable $v$, one can compute the set of nodes $n$ such that $v$ is live at $n$. 