Farkas Lemma made easy
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Farkas Lemma made easy

Tool Demonstration

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Abstract

In this paper, we present fckcc, a scripting tool to prototype program analyses and transformations exploiting the affine form of Farkas lemma. Our language is general enough to prototype in a few lines sophisticated termination and scheduling algorithms. The tool is freely available and may be tried online via a web interface. We believe that fckcc is the missing chain to accelerate the development of program analyses and transformations exploiting the affine form of Farkas lemma.

ACM Reference Format:

1 Introduction

Many program analyses require to handle universally quantified constraints such as $\forall x \in D : \Phi(x)$, where $D$ is a convex polyhedron and $\Phi$ is a conjunction of affine constraints. For instance, this occurs in loop scheduling [5, 6], loop tiling [3], program termination [2] or generation of loop invariants [4]. Farkas lemma – affine form – provides a way to get rid of that universal quantification, at the price of introducing quadratic terms. It is even possible to use Farkas lemma to turn universally quantified quadratic constraints into existentially quantified affine constraints [5, 6]. However, this requires tricky algebraic manipulations, notoriously difficult to experiment by hand and to implement.

In this tool demonstration, we present a scripting tool, fckcc [1] which makes it possible to manipulate easily Farkas lemma to benefit from those nice properties. Specifically, we will discuss the following points:

• A general formulation for the resolution of equations $\forall x : S(\bar{x}) = 0$ where $S$ is a summation of affine forms including Farkas terms. So far, this resolution was applied for specific instances of Farkas summation. This result is the basic engine of the fckcc scripting language.

• A scripting language to apply and exploit Farkas lemma; among polyhedra, affine functions and affine forms.

2 Farkas lemma in polyhedral compilation

This section presents the theoretical background of this tool demonstration. We first introduce the affine form of Farkas lemma. Then, we present our theorem to solve equations $\forall \bar{x} : S(\bar{x}) = 0$ where $S$ is a summation of affine forms including Farkas terms. This formalization will then be exploited to design the fckcc language.

Lemma 2.1 (Farkas Lemma, affine form). Consider a non-empty convex polyhedron $P = (\bar{x}, A\bar{x} + \bar{b} \geq 0) \subseteq \mathbb{R}^n$ and an affine form $\phi : \mathbb{R}^n \rightarrow \mathbb{R}$ such that $\phi(\bar{x}) \geq 0 \forall \bar{x} \in P$.

Then: $\exists \lambda \geq 0, \lambda_0 \geq 0$ such that:

$$\phi(\bar{x}) = ^t\bar{\lambda}(A\bar{x} + \bar{b}) + \lambda_0 \forall \bar{x}$$

Hence, Farkas lemma makes it possible to remove the quantification $\forall \bar{x} \in P$ by encoding directly the positivity over $P$ into the definition of $\phi$, thanks to the Farkas multipliers $\bar{\lambda}$ and $\lambda_0$. In the remainder, Farkas terms will be denoted by: $\mathcal{F}(\lambda_0, \bar{\lambda}, A, \bar{b})(\bar{x}) = ^t\bar{\lambda}(A\bar{x} + \bar{b}) + \lambda_0$. We now recall our theorem [1] to solve equations $\forall \bar{x} : S(\bar{x}) = 0$ where $S$ involves Farkas terms. The result is expressed as a conjunction of affine constraints, which is suited for integer linear programming:

Theorem 2.2 (solve). Consider a summation $S(\bar{x}) = \bar{u} \cdot \bar{x} + v + \sum_i \delta(\lambda_i, \bar{\lambda}_i, A_i, \bar{b}_i)(\bar{x})$ of affine forms, including Farkas terms. Then:

$$\forall \bar{x} : S(\bar{x}) = 0 \iff \begin{cases} \bar{u} + \sum_i ^tA_i\bar{\lambda}_i = 0 \land v + \sum_i (\bar{\lambda}_i \cdot \bar{b}_i + \lambda_0) = 0 \end{cases}$$
Applying Farkas lemma, this translates to:

\[ \forall (i, j) \in D_N \]  

(1)

Applying Farkas lemma, this translates to:

\[ \forall \theta(i, j, N) \geq 0 \] s.t. \( \theta(i, j, N) = \gamma(\theta_0 A, \theta_0 A, \theta_0 A) \) \( (i', j') \) \( \Delta_N \)

(2)

Moreover, a schedule must satisfy the data dependences \( (i, j) \rightarrow (i', j') \), abstraced by a dependence polyhedron \( \Delta_N \):

\[ \theta(i', j', N) > \theta(i, j, N) \] \( \forall (i, j, i', j') \in \Delta_N \)

(3)

This is explicitly written as the positivity of the affine form \( (i, j, i', j', N) \rightarrow (i', j', N) \) over \( \Delta_N \) as affine polyhedron. Applying Farkas lemma:

\[ \exists \mu_0, \mu_0, \mu_0 \geq 0 \text{ such that} \]

\[ \theta(i', j', N) - \theta(i, j, N) - 1 = \gamma(\mu_0 C, \mu_0 C, \mu_0 C) \]

Substituting \( \theta \) using Equation (2), this translates to solving

\[ \forall (i, j, i', j', N) : S(i, j, i', j', N) = 0 \], where \( S(i, j, i', j', N) \) is the summation:

\[ \gamma(\lambda_0 A, \lambda_0 A, \lambda_0 A) \] \( (i, j, i', j', N) \) \( \gamma(\mu_0 C, \mu_0 C, \mu_0 C) \)

Since \( \gamma(\lambda_0 A, \lambda_0 A, \lambda_0 A) = \gamma(\lambda_0 A, \lambda_0 A, \lambda_0 A) \), we may apply theorem 2.2 to obtain a system of affine constraints with \( \lambda_0 A, \lambda_0 A, \lambda_0 A \). Linear programming may then be employed to find the desired schedule [3, 6].

3 FKCC at a glance

This section outlines briefly the input syntax of FKCC on our motivating example. For a detailed description, the reader is referred to [1].

Program, instructions, polyhedra An FKCC program consists of a sequence of instructions. There is no other control structure than the sequence. An instruction may assign an FKCC object (polyhedron, affine form or affine function) to an FKCC identifier, or may be an FKCC object alone. In the latter case, the FKCC object is streamed out to the standard output. FKCC objects are expressed with the same syntax as SC7:

\[ \text{parameters} := \{ M, eps \}; \]

\[ \text{parametersized_iterations} := \{ M \} \rightarrow \{ [i] : 0 \leq i \text{ and } i < M \}; \]

Parameters must be declared with the parameters construct. The parameters of a polyhedron may optionally be declared on preceding brackets \( [M] \rightarrow \ldots \). The set intersection of two polyhedra \( P \) and \( Q \) is obtained with \( P \cap Q \).
When the summation contains affine forms with parameters (as \( \text{sum}_\text{eps} \)), the resolution interprets parameters as constants. In particular, this makes it possible to tune dependence satisfaction: \( \theta(i', j') \geq \theta(i, j) + \varepsilon_q \) with \( 0 \leq \varepsilon_q \leq 1 \).

At this point, we need to recover the coefficients of our affine form \( \theta \) in terms of \( \lambda \) (\( \lambda_0, \ldots, \lambda_3 \)) and \( \lambda_0 \) (\( \lambda_4 \)). Observe that \( \theta(\bar{x}) = \overline{\lambda_0, \lambda, A, b}(\bar{x}) \), in turn equal to \( \sum \bar{\lambda} \bar{x} = \overline{\lambda_0} \bar{x} + \sum \bar{\lambda} \bar{b} + \lambda_0 \). If the coefficients of \( \theta \) are written: \( \theta(\bar{x}) = \bar{\lambda} \cdot \bar{x} + r_0 \), we simply have: \( \bar{\lambda} = \sum \bar{\lambda} \) and \( r_0 = \overline{\lambda_0} \bar{b} + \lambda_0 \). This is obtained with define:

**define theta with tau;**

The result is a conjunction of definition equalities, gathered in a polyhedron:

\[
\begin{align*}
\lambda_0, \lambda_1, \lambda_2, \lambda_3 :&= \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3; \\
\text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 :&= \text{tau}_0 + \text{tau}_1 + \text{tau}_2 + \text{tau}_3; \\
\text{tau}_0 &= \lambda_0; \\
\text{tau}_1 &= \lambda_1; \\
\text{tau}_2 &= \lambda_2; \\
\text{tau}_3 &= \lambda_3; \\
\text{tau}_4 &= \lambda_4; \\
\end{align*}
\]

The first coefficients \( \text{tau}_k \) define \( \bar{\lambda} \), the last one defines the constant \( r_0 \). On our example, \( \text{tau}(i, j, N) = \text{tau}_0 \cdot i + \text{tau}_1 \cdot j + \text{tau}_2 \cdot N + \text{tau}_3 \). Now we may gather the results and eliminate the \( \lambda \) to keep only \( \bar{\lambda} \) and \( r_0 \):

\[
\begin{align*}
\text{keep tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 \text{ in } \\
\text{(solve sum = 0) * (define theta with tau)}; \\
\end{align*}
\]

The result is a polyhedron with all the valid schedules:

\[
\begin{align*}
\lambda_0, \lambda_1, \lambda_2, \lambda_3 :&= \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3; \\
\text{tau}_0 &= \lambda_0; \\
\text{tau}_1 &= \lambda_1; \\
\text{tau}_2 &= \lambda_2; \\
\text{tau}_3 &= \lambda_3; \\
\text{tau}_4 &= \lambda_4; \\
\end{align*}
\]

All these steps may be applied at once with the \text{find} command:

\[
\begin{align*}
\text{find theta s.t. sum = 0;} \\
\quad \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 \text{ in } \\
\quad \text{(solve sum = 0) * (define theta with tau)}; \\
\end{align*}
\]

This is typically used to compute schedules for programs with multiple assignments (here \( S \) and \( T \) with dependences from iterations of \( S \) to iterations of \( T \)). Finally, note that keep \( \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 \) in \( P \); projects \( P \) on variables \( \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 \): the result is a polyhedron with integral points of coordinates \( \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 \). This way, the order in which \( \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 \) are specified to keep impacts directly a further lexicographic optimization. As in \( \text{isc} \), the lexicographic minimum of a polyhedron is obtained with the command \text{l}ex\text{min} this. Example, however, does not admit a lexic-minimum solution. We can find a solution by forcing positive coefficients:

\[
\begin{align*}
\text{positive_theta := [] -> } \{ \text{tau}_0, \text{tau}_1, \text{tau}_2, \text{tau}_3 \}; \\
\text{theta_0} \gg 0 \text{ and theta_1} \gg 0 \text{ and theta_2} \gg 0 \text{ and theta_3} \gg 0; \\
\text{lexmin (find theta s.t. sum = 0) * positive_theta}; \\
\end{align*}
\]

Using the \text{-pretty} option, we obtain:

\[
\begin{align*}
\text{theta}_0 &= 1 \\
\text{theta}_1 &= 0 \\
\text{theta}_2 &= 0 \\
\text{theta}_3 &= 0 \\
\end{align*}
\]

Which corresponds to the schedule \( \theta(i, j, N) = i \). We point out that it is also possible to write in a few lines of \( \text{fkc} \) the latency minimization as in [5]. A complete description may be found in [1].

### 4 Conclusion

\( \text{fkc} \) is a scripting tool to prototype program analyses using the affine form of Farkas lemma. The script language of \( \text{fkc} \) is powerful enough to write in a few lines sophisticated scheduling algorithms. The object representation (polyhedral, affine functions) is compatible with \( \text{isc} \), a widespread polyhedral tool featuring manipulation of affine relations. \( \text{fkc} \) provides features to generate \( \text{isc} \) code, and conversely, the output of \( \text{isc} \) might be injected in \( \text{fkc} \). This will allow to take profit of both worlds.

We believe that scripting tools are mandatory to evaluate rapidly research ideas. So far, Farkas lemma-based approaches were locked by two facts: applying by hand Farkas Lemma is notorious time consuming and bug prone. With \( \text{fkc} \), computer scientists are now freed from these constraints.

Let the power of \( \text{fkc} \) be with you!

### References


A Pluto-style tiling with fkcc

We give here the fkcc script discussed in the demo session to compute a Pluto-style tiling [3] for the Jacobi-1D kernel. Note the sections expressing successively the data dependences (→), the correctness condition \((S, i) \rightarrow (T, j) \Rightarrow \phi_T(j) - \phi_S(i) \geq 0\), the laziness (minimal dependence distance \(\delta_{ST} = \phi_T(j) - \phi_S(i)\)), and finally the computation of non-null and linearly independent affine tiling hyperplanes in \(\phi_S\) and \(\phi_T\). Applying fkcc with the -pretty option, we obtain:

\[
\begin{align*}
\phi_{S,0} &= 1 & \phi_{S,0} &= 2 \\
\phi_{S,1} &= 0 & \phi_{S,1} &= 1 \\
\phi_{S,2} &= 0 & \phi_{S,2} &= 0 \\
\phi_{S,3} &= 0 & \phi_{S,3} &= 0 \\
\phi_{S,4} &= 0 & \phi_{S,4} &= 0 \\
\phi_{T,0} &= 1 & \phi_{T,0} &= 2 \\
\phi_{T,1} &= 0 & \phi_{T,1} &= 1 \\
\phi_{T,2} &= 0 & \phi_{T,2} &= 0 \\
\phi_{T,3} &= 0 & \phi_{T,3} &= 0 \\
\phi_{T,4} &= 0 & \phi_{T,4} &= 1 \\
\text{latency}_0 &= 0 & \text{latency}_0 &= 0 \\
\text{latency}_1 &= 0 & \text{latency}_1 &= 0 \\
\text{latency}_2 &= 1 & \text{latency}_2 &= 2
\end{align*}
\]

Which corresponds to the affine tiling \(\phi_S(t, i) = (t, 2t + i)\) and \(\phi_T(t, i) = (t, 2t + i + 1)\) with a maximum dependence distance 1 for the first tiling hyperplane and 2 for the second tiling hyperplane.

# # jacobi-1D non-perfect #
# # for (t = 1; t <= T; t++)
# # {
# #   # for (i = 1; i < N - 1; i++)
# #   # for (i = 1; i < N - 1; i++)
# #     A[i] = B[i]; //T
# # }

D_S := [ ] \rightarrow \{ [t, i, T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 \};
D_T := [ ] \rightarrow \{ [t, i, T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 \};
phi_S := positive_on D_S;
phi_T := positive_on D_T;

#\$ \rightarrow \$\$
Delta_{ST} := [ ] \rightarrow \{ [t, i, t', i', T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 and 1 \leq t' and t' \leq T and 1 \leq i' and i' \leq N-1 and t=t' and i=i' \};

#\$ \rightarrow \$\$
Delta_{ST_anti_1} := [ ] \rightarrow \{ [t, i, t', i', T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 and 1 \leq t' and t' \leq T and 1 \leq i' and i' \leq N-1 and t+1=t' and i=i'-1 \};

#\$ \rightarrow \$\$
Delta_{ST_anti_2} := [ ] \rightarrow \{ [t, i, t', i', T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 and 1 \leq t' and t' \leq T and 1 \leq i' and i' \leq N-1 and t+1=t' and i=i'+1 \};

#\$ \rightarrow \$\$
Delta_{TS_1} := [ ] \rightarrow \{ [t, i, t', i', T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 and 1 \leq t' and t' \leq T and 1 \leq i' and i' \leq N-1 and t+1=t' and i=i' \};

#\$ \rightarrow \$\$
Delta_{TS_2} := [ ] \rightarrow \{ [t, i, t', i', T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 and 1 \leq t' and t' \leq T and 1 \leq i' and i' \leq N-1 and t+1=t' and i=i' \};

#\$ \rightarrow \$\$
Delta_{TS_3} := [ ] \rightarrow \{ [t, i, t', i', T, N]: 1 \leq t and t \leq T and 1 \leq i and i \leq N-1 and 1 \leq t' and t' \leq T and 1 \leq i' and i' \leq N-1 and t+1=t' and i=i' \};
Correctness: $s \rightarrow t \implies \phi(s) \leq \phi(t)$

to_target := \{[t,i,t',i',T,N] \rightarrow [t',i',T,N]\};
to_source := \{[t,i,t',i',T,N] \rightarrow [t,i,T,N]\};

\[ \phi_{\text{correct}} := \]
\[ \# S \rightarrow T \]
\[ (\text{find } \phi_S,\phi_T \text{ s.t. } (\phi_T \cdot \text{to_target}) - (\phi_S \cdot \text{to_source}) - \text{positive_on } \Delta_{ST} = 0) \]
\[ \# S \rightarrow T, \ (\text{anti read}(a[i-1]) \rightarrow \text{write}(a[i])) \]
\[ (\text{find } \phi_S,\phi_T \text{ s.t. } (\phi_T \cdot \text{to_target}) - (\phi_S \cdot \text{to_source}) - \text{positive_on } \Delta_{ST-\text{anti-1}} = 0) \]
\[ \# S \rightarrow T, \ (\text{anti read}(a[i+1]) \rightarrow \text{write}(a[i])) \]
\[ (\text{find } \phi_S,\phi_T \text{ s.t. } (\phi_T \cdot \text{to_target}) - (\phi_S \cdot \text{to_source}) - \text{positive_on } \Delta_{ST-\text{anti-2}} = 0) \]
\[ \# T \rightarrow S, \ \text{read } a[i-1] \]
\[ (\text{find } \phi_S,\phi_T \text{ s.t. } (\phi_S \cdot \text{to_target}) - (\phi_T \cdot \text{to_source}) - \text{positive_on } \Delta_{TS-1} = 0) \]
\[ \# T \rightarrow S, \ \text{read } a[i] \]
\[ (\text{find } \phi_S,\phi_T \text{ s.t. } (\phi_S \cdot \text{to_target}) - (\phi_T \cdot \text{to_source}) - \text{positive_on } \Delta_{TS-2} = 0) \]
\[ \# T \rightarrow S, \ \text{read } a[i+1] \]
\[ (\text{find } \phi_S,\phi_T \text{ s.t. } (\phi_S \cdot \text{to_target}) - (\phi_T \cdot \text{to_source}) - \text{positive_on } \Delta_{TS-3} = 0) \];

Efficiency: $s \rightarrow t \implies \phi(t) - \phi(s) \leq \text{latency}(N)$, then min latency(N)

\[ \# L(N) \geq 0 \text{ on the parameter domain} \]
\[ \text{latency} := \text{positive_on } ([] \rightarrow \{[T,N]: T \geq 0 \text{ and } N \geq 0\}); \]
\[ \text{latency_def} := \text{define latency with latency}; \]
\[ \text{to_param} := \{[t,i,t',i',T,N] \rightarrow [T,N]\}; \]

\[ \# \phi(t) - \phi(s) \leq L(N) \forall s \rightarrow t \]
\[ \phi_{\text{bounded}} := \]
\[ \# S \rightarrow T \]
\[ (\text{find } \text{latency},\phi_S,\phi_T \text{ s.t. } \text{to_param} - (\phi_T \cdot \text{to_target}) + (\phi_S \cdot \text{to_source}) - \text{positive_on } \Delta_{ST} = 0) \]
\[ \# S \rightarrow T, \ (\text{anti read}(a[i-1]) \rightarrow \text{write}(a[i])) \]
\[ (\text{find } \text{latency},\phi_S,\phi_T \text{ s.t. } \text{to_param} - (\phi_T \cdot \text{to_target}) + (\phi_S \cdot \text{to_source}) - \text{positive_on } \Delta_{ST-\text{anti-1}} = 0) \]
\[ \# S \rightarrow T, \ (\text{anti read}(a[i+1]) \rightarrow \text{write}(a[i])) \]
\[ (\text{find } \text{latency},\phi_S,\phi_T \text{ s.t. } \text{to_param} - (\phi_T \cdot \text{to_target}) + (\phi_S \cdot \text{to_source}) - \text{positive_on } \Delta_{ST-\text{anti-2}} = 0) \]
\[ \# T \rightarrow S, \ \text{read } a[i-1] \]
\[ (\text{find } \text{latency},\phi_S,\phi_T \text{ s.t. } \text{to_param} - (\phi_S \cdot \text{to_target}) + (\phi_T \cdot \text{to_source}) - \text{positive_on } \Delta_{TS-1} = 0) \]
\[ \# T \rightarrow S, \ \text{read } a[i] \]
\[ (\text{find } \text{latency},\phi_S,\phi_T \text{ s.t. } \text{to_param} - (\phi_S \cdot \text{to_target}) + (\phi_T \cdot \text{to_source}) - \text{positive_on } \Delta_{TS-2} = 0) \]
\[ \# T \rightarrow S, \ \text{read } a[i+1] \]
\[ (\text{find } \text{latency},\phi_S,\phi_T \text{ s.t. } \text{to_param} - (\phi_S \cdot \text{to_target}) + (\phi_T \cdot \text{to_source}) - \text{positive_on } \Delta_{TS-3} = 0) \];

First hyperplane: avoid the null solution

\[ \phi_{\text{filter level-1}} := [] \rightarrow \{[\phi_S_0,\phi_S_1,\phi_S_2,\phi_S_3,\phi_S_4,\phi_T_0,\phi_T_1,\phi_T_2,\phi_T_3,\phi_T_4]\}; \]

\#phi_S: positive coefficients + no parameters
\[ \phi_S_0 \geq 0 \text{ and } \]
\[ \phi_S_1 \geq 0 \text{ and } \]
\[ \phi_S_2 \geq 0 \text{ and } \]
\[ \phi_S_3 \geq 0 \text{ and } \]
\[ \phi_S_4 \geq 0 \text{ and } \]

\#phi_T: positive coefficients + no parameters
\[ \phi_T_0 \geq 0 \text{ and } \]
\[ \phi_T_1 \geq 0 \text{ and } \]
\[ \phi_T_2 \geq 0 \text{ and } \]
\[ \phi_T_3 \geq 0 \text{ and } \]
\[ \phi_T_4 \geq 0 \text{ and } \]
#phi_S != 0 and phi_T != 0
phi_S_0 + phi_S_1 + phi_S_2 + phi_S_3 >= 1 and
phi_S_0 + phi_T_1 + phi_T_2 + phi_T_3 >= 1 
};

all_level_1 := keep latency_0, latency_1, latency_2, phi_S_0, phi_S_1, phi_S_2, phi_S_3, phi_S_4, phi_T_0, phi_T_1, phi_T_2, phi_T_3, phi_T_4
    in phi_correct * phi_bounded * phi_filter_level_1;
lexmin all_level_1;

# Second hyperplane: avoid the null solution + linear independence with the first hyperplane
#
phi_filter_level_2 := [] -> {
    [phi_S_0, phi_S_1, phi_S_2, phi_S_3, phi_S_4, phi_T_0, phi_T_1, phi_T_2, phi_T_3, phi_T_4]:

    #phi_S: positive coefficients + no parameters + lin. ind (coef(i) > 0)
    phi_S_0 >= 0 and
    phi_S_1 > 0 and
    phi_S_2 = 0 and
    phi_S_3 = 0 and
    phi_S_4 >= 0 and

    #phi_T: positive coefficients + no parameters + lin. ind (coef(i) > 0)
    phi_T_0 >= 0 and
    phi_T_1 > 0 and
    phi_T_2 = 0 and
    phi_T_3 = 0 and
    phi_T_4 >= 0 and

    #phi_S != 0 and phi_T != 0
    phi_S_0 + phi_S_1 + phi_S_2 + phi_S_3 >= 1 and
    phi_S_0 + phi_T_1 + phi_T_2 + phi_T_3 >= 1 
};

all_level_2 := keep latency_0, latency_1, latency_2, phi_S_0, phi_S_1, phi_S_2, phi_S_3, phi_S_4, phi_T_0, phi_T_1, phi_T_2, phi_T_3, phi_T_4
    in phi_correct * phi_bounded * phi_filter_level_2;
lexmin all_level_2;