Compile-time Deadlock Detection in Rust using Petri Nets

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October 9, 2025

Agenda

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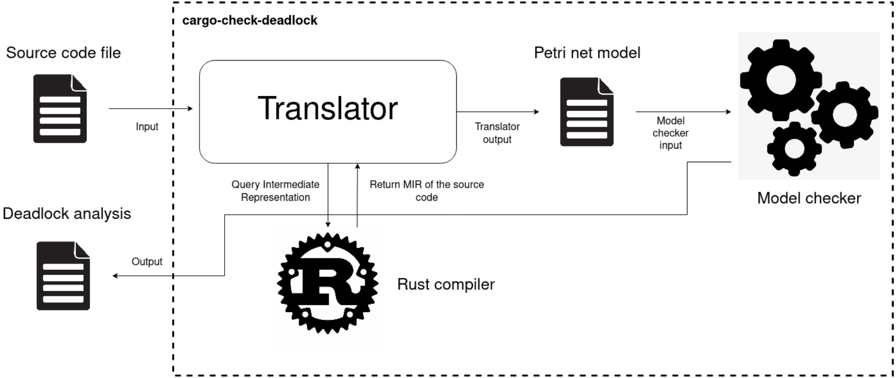
A bird's-eye view of the tool

The Translator is the core component. The model checker and the Rust compiler, *rustc*, are dependencies.



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Informal definition

A Petri net is a mathematical modeling tool used to describe and analyze the behavior of concurrent systems. It provides a graphical representation of the system's state and its transitions, allowing for visual and formal analysis of complex processes.

- Places: Represent states in the system (*circles*)
- Transitions: Represent usually events or actions that occur in the system (*rectangles*)
- Tokens: Marks inside of places that are created and consumed by transitions (*points inside of places*)

Mathematical definition

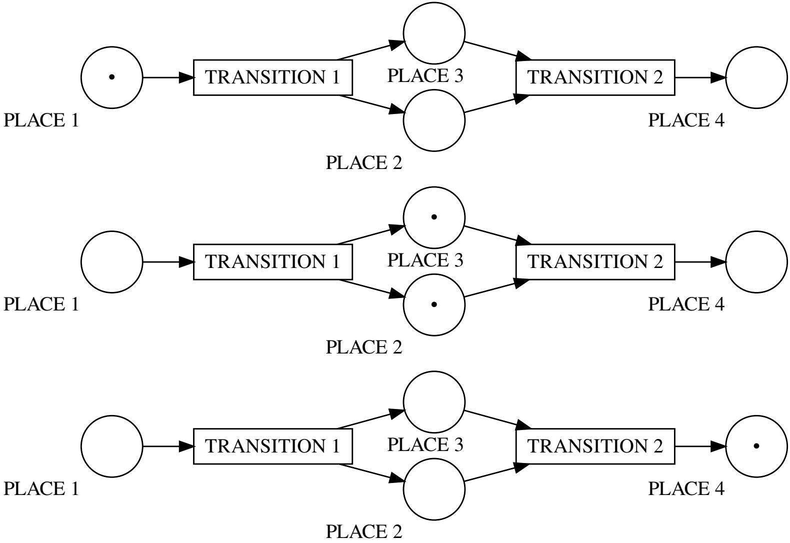
A Petri net is a 5-tuple, $PN = (P, T, F, W, M_0)$ where:

- $P = \{p_1, p_2, \ldots, p_m\}$ *is a finite set of places,*
- $T = \{t_1, t_2, \ldots, t_n\}$ *is a finite set of transitions,*
- $F \subseteq (P \times T) \cup (T \times P)$ *is a set of arcs (flow relation),*
- $W : F \rightarrow \{1, 2, 3, ...\}$ *is a weight function for the arcs,*
- $M_0 : P \rightarrow \{0, 1, 2, 3, ...\}$ *is the initial marking,*
- $P \cap T = \varnothing$ *and* $P \cup T \neq \varnothing$

The graph is by definition *bipartite*. There can only be edges:

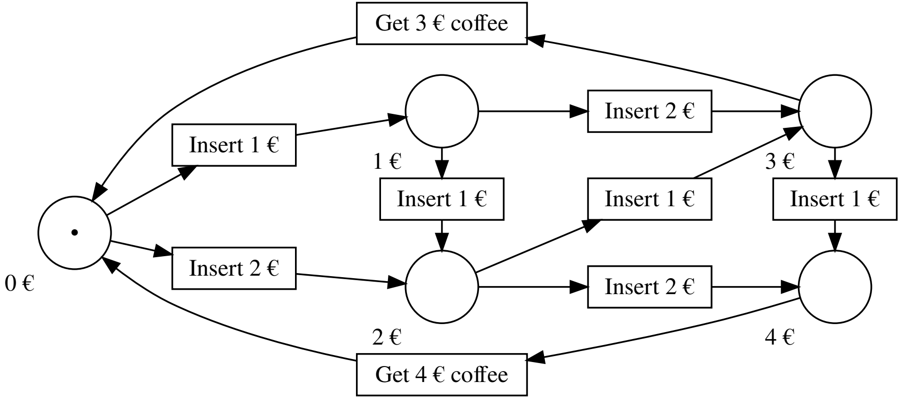
- from places to transitions or
- from transitions to places

Transition firing rule



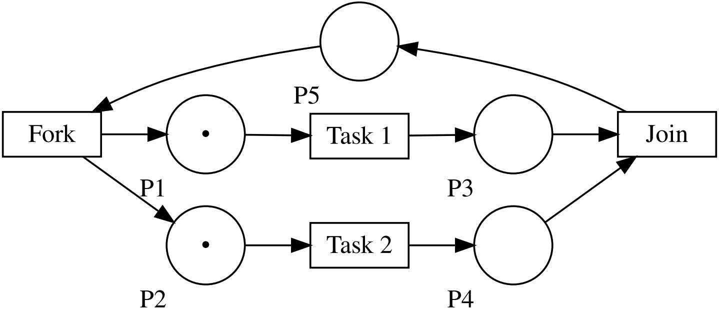
Vending machine

This is a finite-state machine (FSM), a subclass of Petri nets.



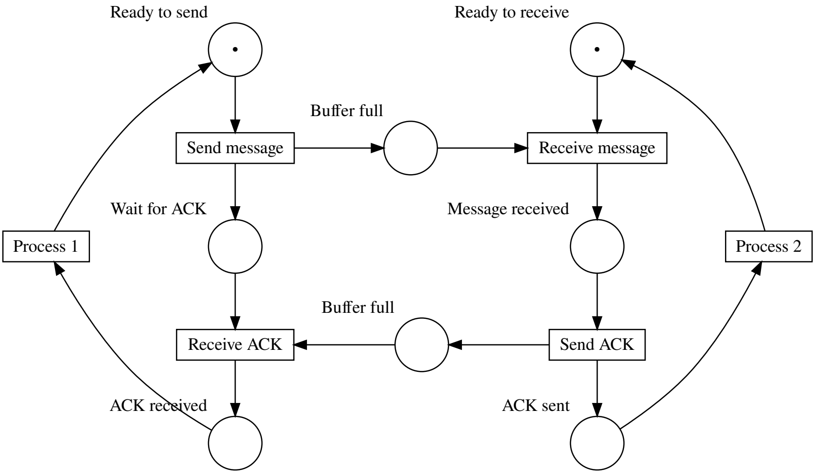
Parallel activities: Fork/Join

This is a marked graph (MG), a subclass of Petri nets. Observe the concurrency between Task 1 and Task 2. This cannot be modeled by a single finite-state machine.



Communication protocols: Send with ACK

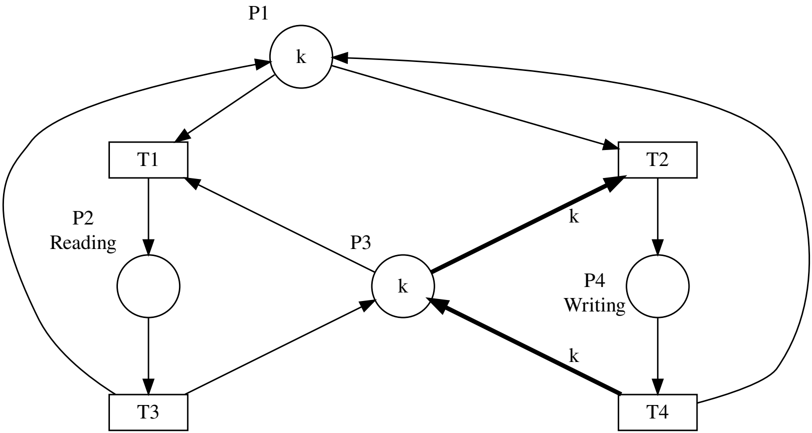
A simple protocol in which Process 1 sends messages to Process 2 and waits for an acknowledgment to be received before continuing. For simplicity, no timeout mechanism was included.



Synchronization control: Readers and writers

A Petri net system with k processes that either read or write a shared value.

- If one process writes, then no process may read.
- If a process is reading, then no process may write.
- There can only be zero or one process writing at any given time.



Reachability analysis

Petri nets can be analyzed using formal methods to conclude whether the net can reach a deadlock or not. There is a notion of liveness analogous to the one found in computer systems.

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Translating source code to a Petri net has been done before for other programming languages [1, 2] and also for Rust [3, 4]. The difficulty lies in supporting more synchronization primitives than simple mutexes and translating code from real-world applications.

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  - Desugar loops: `while` and `for` to simple `loop`.
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- Code generation:
  - *rustc* relies on LLVM as a backend.
  - It leverages many optimizations of the LLVM intermediate representation.
  - LLVM takes over from this point on.
  - At the end, object files are linked to create an executable.

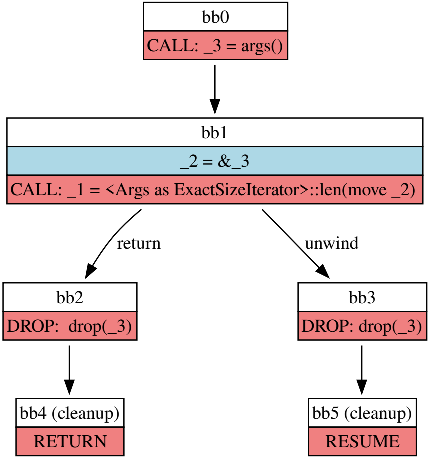
Hello World in MIR

BB means "basic block". Each one is formed by statements and one terminator statement. The terminator statement is the only place where the control flow can jump to another basic block.

```
fn main() -> () {
    let mut _0: ();
    let _1: ();
    let mut _2: std::fmt::Arguments<'_>;
    let mut _3: &[&str];
    let mut _4: &[&str; 1];

    bb0: {
        _4 = const _;
        _3 = _4 as &[&str] (Pointer(Unsize));
        _2 = Arguments::<'_>::new_const(move _3) -> bb1;
    }

    bb1: {
        _1 = _print(move _2) -> bb2;
    }

    bb2: {
        return;
    }
}
```

MIR as a graph that shows the flow of execution

The MIR is a form of control flow graph (CFG) used in compilers. In this form, the translation to a Petri net becomes evident.



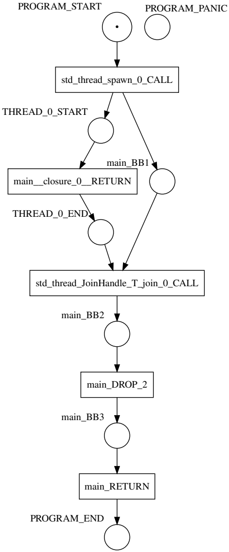
Example program

Let's consider a trivial program that spawns a thread that does nothing and immediately joins it.

```
fn main() {
  let thread_join_handle = std::thread::spawn(move || {
      // some work here
  });
  // some work here
  let _res = thread_join_handle.join();
}
```

- `std::thread::spawn` should create an additional token that models the program counter of the second thread.
- The joining thread should wait until the spawned thread finishes.

Petri net model for a thread



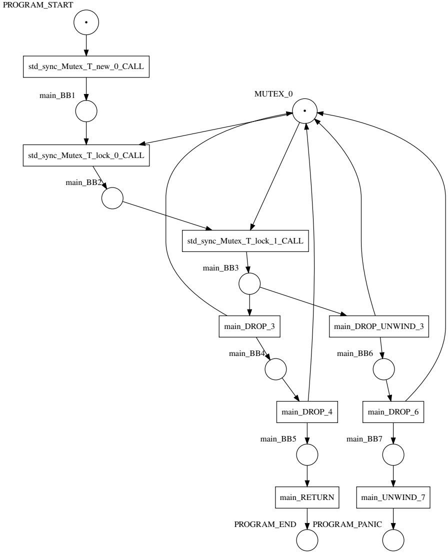
Example program

Consider a simple program that locks a mutex twice. The second lock operation will deadlock because the lock handle returned by the first call to `std::sync::Mutex::lock` is not dropped until it falls out of scope.

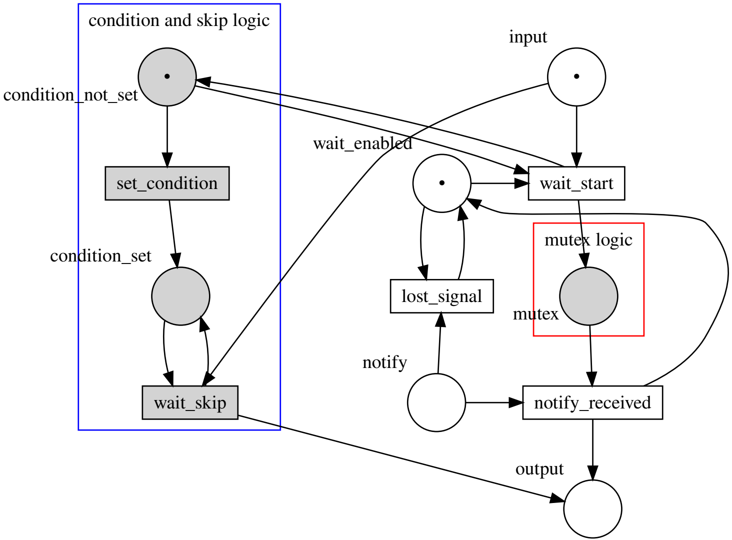
```
fn main() {
  let data = std::sync::Mutex::new(0);
  let _d1 = data.lock();
  let _d2 = data.lock(); // cannot lock, since d1 is still active
}
```

- There should be a single place that models the mutex.
- Locking the mutex is taking the token from the mutex place.
- Unlocking the mutex is setting the token back in the mutex place.

Petri net model for a mutex



How to model a condition variable



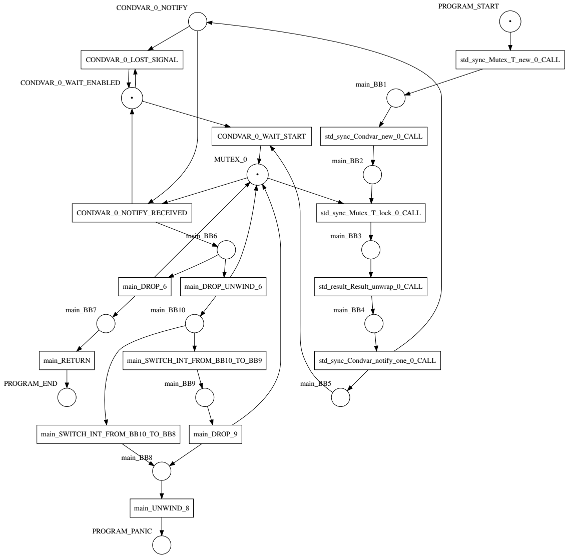
Example program

We have to use a very simple example program to keep the net small. In this case, the thread is trying to notify itself, which leads to a lost signal.

```
fn main() {
  let mutex = std::sync::Mutex::new(false);
  let cvar = std::sync::Condvar::new();
  let mutex_guard = mutex.lock().unwrap();
  cvar.notify_one();
  let _result = cvar.wait(mutex_guard);
}
```

- The model for the condition variable should appear in the Petri net.
- The notify place should be set.
- But the signal gets consumed because `std::sync::Condvar::wait` was not called.

Petri net model for the example program



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Limitations of the tool

It cannot translate everything possible in Rust / MIR...

- Closures outside of `thread:spawn` are not supported.
- Using arrays, `Vec`, and other data structures may cause the translation to give false results.
- `Channels`, `RwLock`, `Barrier` are not supported.
- Async is not supported.
- Synchronization mechanisms from external crates such as `tokio` or `semaphore` are not supported.

Limitations of the approach

Data values are not modelled...

- Deadlocks caused by certain user input
- Deadlocks that appear only when a specific number of threads is started
- Dynamic code loading and execution

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Internals of used crates are not analyzed...

- Deadlocks in calls to libraries or due to them
- Deadlocks in `std` or `core`
- Deadlocks in underlying syscalls

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Bibliography I

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A. Moshtaghi, “Modeling Multithreaded Applications Using Petri Nets,” Master’s thesis, The University of Alabama in Huntsville, 2001.

T. Meyer, “A Petri Net semantics for Rust,” Master’s thesis, Universität Rostock — Fakultät für Informatik und Elektrotechnik, 2020. `https://github.com/Skasselbard/Granite/blob/master/doc/MasterThesis/main.pdf`.

K. Zhang and G. Liua, “Automatically transform rust source to petri nets for checking deadlocks,” *arXiv preprint arXiv:2212.02754*, 2022.

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Online Petri net simulators

- A simple simulator by Igor Kim can be found on https://petri.hp102.ru/. A tutorial video on Youtube and example nets are included in the tool.
- A complement to this is a series of interactive tutorials by Prof. Wil van der Aalst at the University of Hamburg. These tutorials are Adobe Flash Player files (with extension `.swf`) that modern web browsers cannot execute. Luckily, an online Flash emulator like the one found on https://flashplayer.fullstacks.net/?kind=Flash_Emulator can be used to upload the files and execute them.
- Another online Petri net editor and simulator is http://www.biregal.com/. The user can draw the net, add the tokens, and then manually fire transitions.

Questions?

Links

Tool	https://github.com/hlisdero/cargo-check-deadlock
Presentation	https://github.com/hlisdero/thesis/tree/main/presentation_eurorust_2025
Published crate	https://crates.io/crates/cargo-check-deadlock
Thesis	https://github.com/hlisdero/thesis