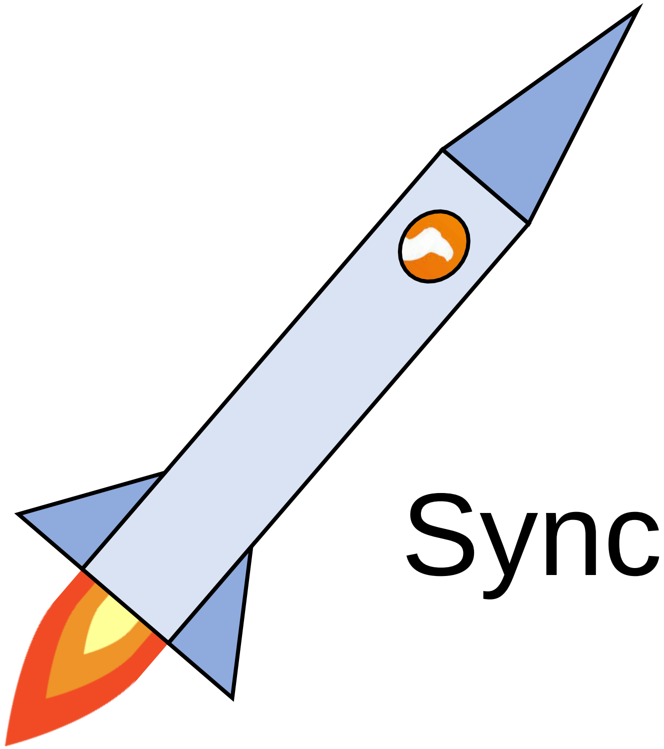


Synchronous Programming with Refinement Types

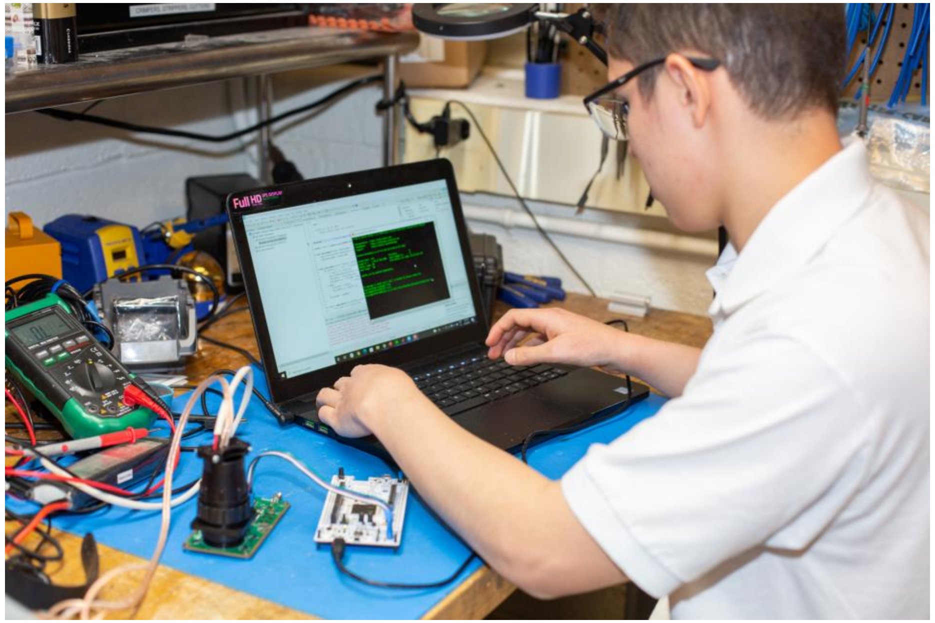
Honors Capstone – Fall 2023

José Luiz Vargas de Mendonça

April 23rd, 2023

Nice to meet you!

- I'm José Vargas
- Hometown: Manaus, Brazil
- Major: Aerospace 🚀 and Computer Engineering 💻
- Hobbies: Learning languages (spoken and programming)



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Research

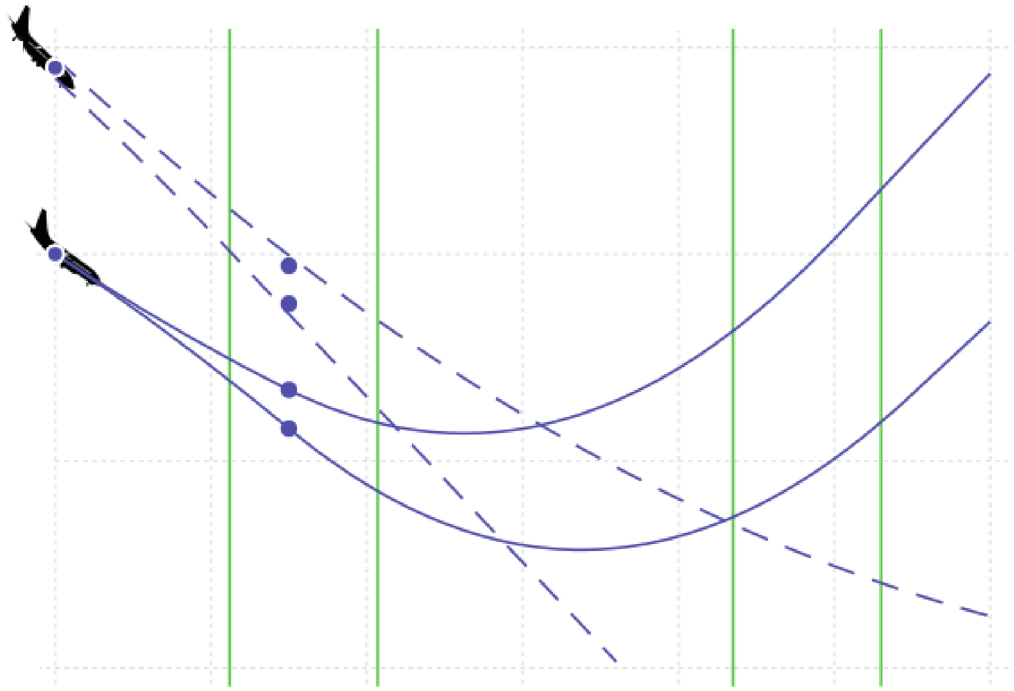
1. Background

- **Cyber-physical systems (CPSs)** are composed of software that interacts with the environment.
- Unit testing complex software might not cover all scenarios.
- Formal verification provides rigorous tools to prove **software safety**.
- **Refinement types** can add **constraints** to base types on programming languages.

$$let\ (x : int) = 4$$

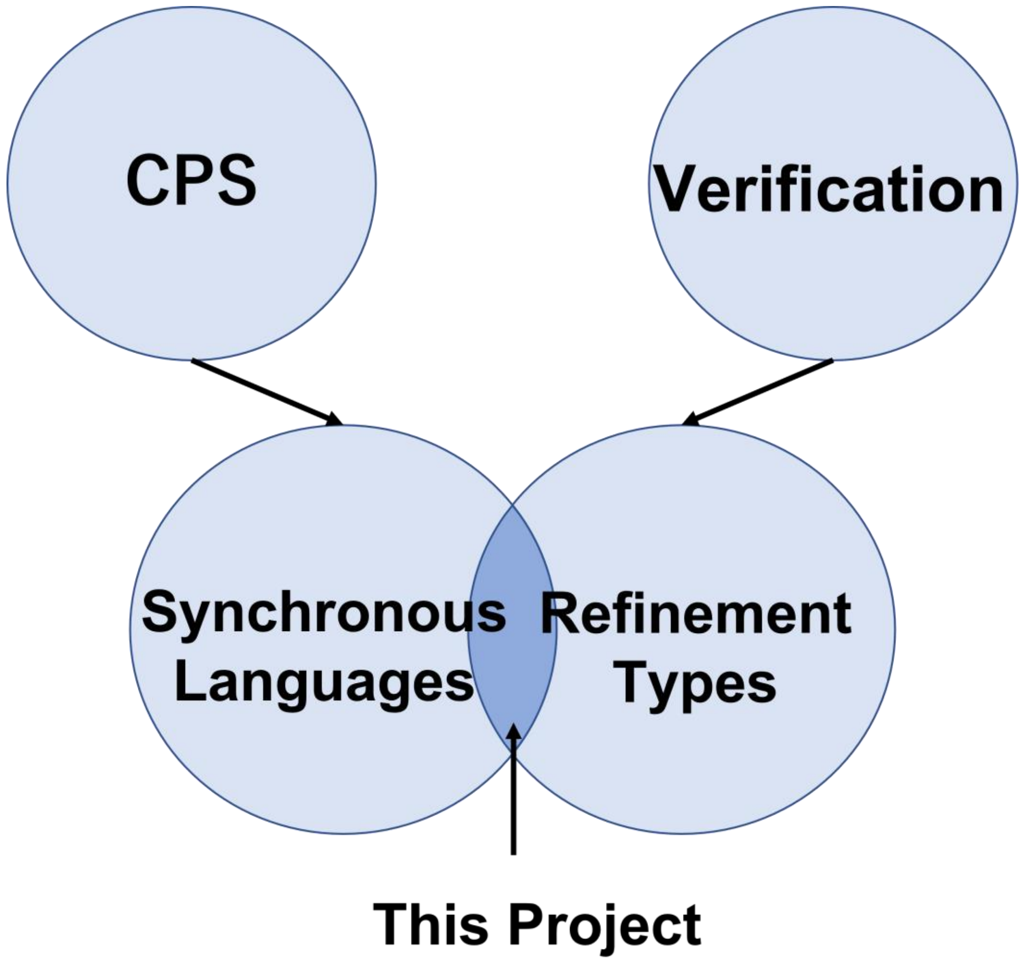
vs

$$let\ (x : \{v : int \mid v \geq 0\}) = 4$$



2. Motivation

- **Synchronous languages** are used to program **Cyber-Physical Systems** (CPSs)
- **Refinement types** are used for formal verification



2. Motivation

- Unit tests are **not enough** to show that software is safe!
- **MARVeLus** tells you what you need to know to check that a critical software follows its **specifications**.

3. Zelus Compiler Architecture

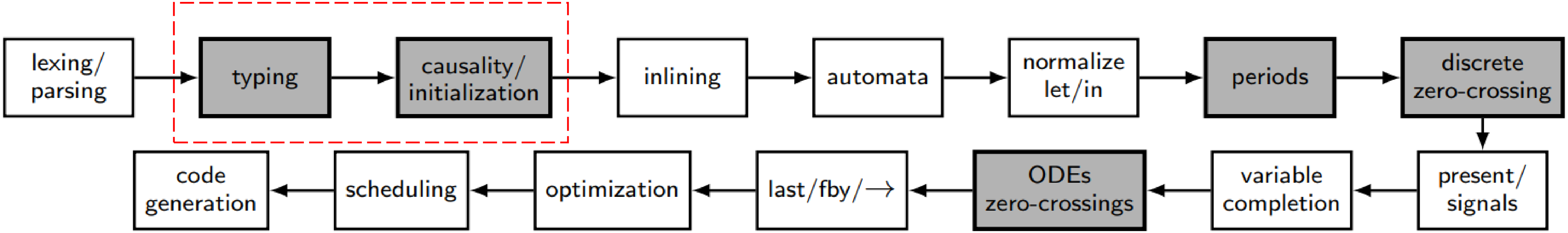
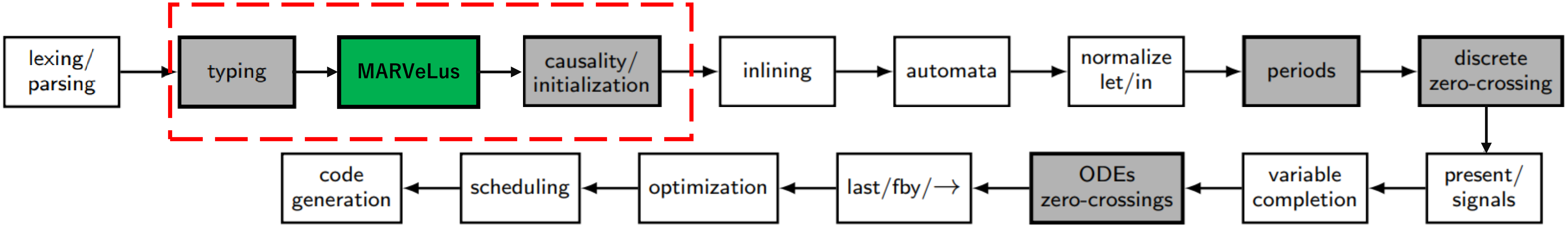


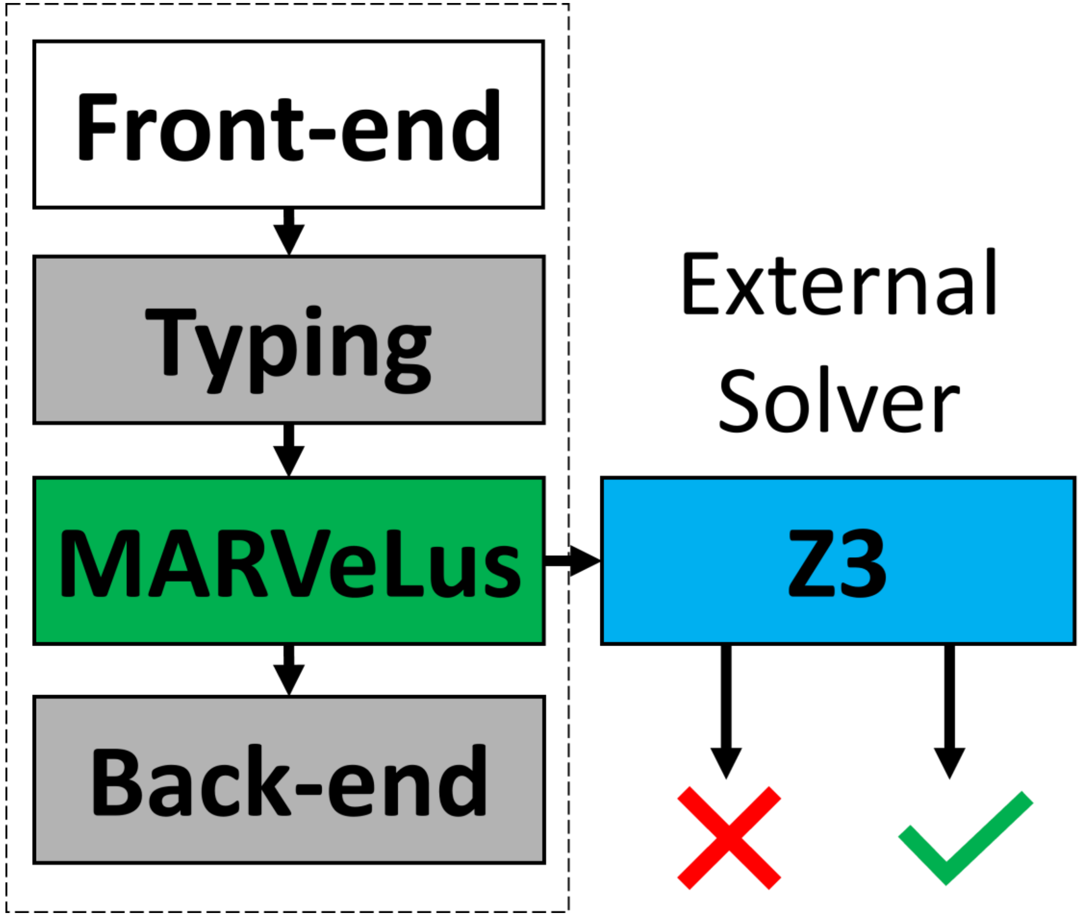
Figure 3: Compiler architecture

Source: Timothy Bourke and Marc Pouzet. Zélus: A synchronous language with ODEs. In *16th International Conference on Hybrid Systems: Computation and Control (HSCC'13)*, pages 113–118, Philadelphia, USA, March 2013.

3.1 Introducing MARVeLus: a refinement type verifier for Zelus



3.2 MARVeLus workflow



4. Refinement variable declaration

variable reference

variable name — base type — rhs expression

$$let\ var : \{v : t \mid \phi(v)\} = e$$

refinement type constraint

- Refinement type requires a base type and a type predicate
- Once the variable is declared, rhs expression is checked against predicate
- Predicate can depend on previously defined variables

4.1 Refinement variable check

Verification condition: $\neg(\bigwedge^{E} \phi_i \rightarrow \phi(var))$

where

E, is the program environment

ϕ_i, are constraints associated with previously defined variables

$\phi(var)$, is the constraint we want to satisfy

4.2 Refinement variable declaration example

```
let pi = 3.14159
let w = 2 .* pi
let y0 : {v : float | v >= pi} = 4.0
```

Verification condition:

$$\neg\big((pi = 3.14159) \land (w = 2pi) \land (y0 = 4.0) \rightarrow (y0 \geq pi)\big)$$

- The constraints are added to the program environment as variables are declared
- Once verification condition is checked to be true, $\phi(var)$ is added to the environment

4.2 Refinement variable declaration example (continued)

```
let pi = 3.14159
let w = 2 .* pi
let y0 : {v : float | v >= pi} = 4.0
let y1 : {v : float | v >= y0 * 2} = 10.0
```

```
Proving constraint: (let ((a!1 (=> (and (= y1 10.0)
                    (>= y0 pi)
                    (= y0 4.0)
                    (= w (* 2.0 pi))
                    (= pi (/ 314159.0 100000.0)))
               (>= y1 (* y0 2.0)))))
  (not a!1))
Passed
```

If constraint is satisfiable, display passed message

```
let pi = 3.14159
let w = 2 .* pi
let y0 : {v : float | v >= pi} = -4.0
```

```
Proving constraint: (let ((a!1 (=> (and (= y0 (- 4.0))
                    (= w (* 2.0 pi))
                    (= pi (/ 314159.0 100000.0)))
               (>= y0 pi))))
  (not a!1))
Counterexample found:
        w: 6.28318
        pi: 3.14159
        y0: -4
Could not prove: (>= y0 pi)
```

Counter-example

If constraint is not satisfiable, display a warning and provide counter-examples

5. Current work and next steps

- Preliminary work published at FTSCS 2022

  Jiawei Chen, José Luiz Vargas de Mendonça, Shayan Jalili, Bereket Ayele, Bereket Ngussie Bekele, Zhemin Qu, Pranjal Sharma, Tigist Shiferaw, Yicheng Zhang, and Jean-Baptiste Jeannin. 2022. Synchronous Programming and Refinement Types in Robotics: From Verification to Implementation. In Proceedings of the 8th ACM SIGPLAN International Workshop on Formal Techniques for Safety-Critical Systems (FTSCS 2022). Association for Computing Machinery, New York, NY, USA, 68–79. https://doi.org/10.1145/3563822.3568015

- Include support for the continuous part of CPSs
- Refactor compiler code for maintainability

Honors Experience

6. Starting the Project

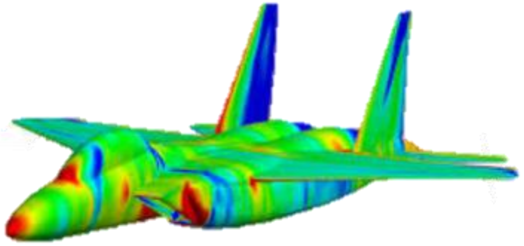
AERO 495: Fundamentals of Aerospace Computing
Fall 2020

(Currently AERO 350)

Part I: Fundamentals of Computer Science

Part III: Introduction to Embedded Systems

Part II: Fundamentals of Computational Science

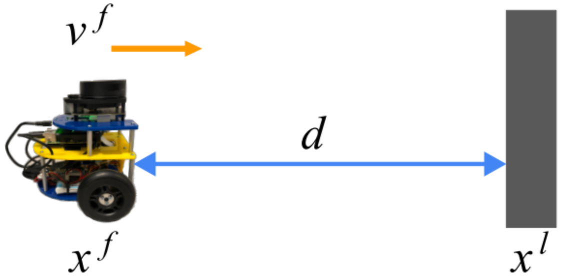


7. Focus Area Courses

- **EECS 483 – Compiler Construction** (FA22, Prof. Max New)
  - Learned how to convert a text file into assembly code
  - Runtime definitions
  - Data structures encoding

```
0 := λf.λx.x
1 := λf.λx.f x
2 := λf.λx.f (f x)
```

- **EECS 590 – Advanced Programming Languages** (FA22, Prof. Jean-Baptiste Jeannin)
  - Formal introduction to PL theory
  - Proofs by induction
  - Operational semantics and typing rules



- **AERO 490 – Directed study** (FA21, Prof. Jean-Baptiste Jeannin)
  - Develop the code base for the MARVeLus Compiler

8. Alternative Paths

- Explored CVC5 SMT Solver instead of Z3
- Start a new programming language from scratch

9. Acknowledgements

- **My family** for continuous support that allowed me to complete undergraduate education in the US
- **Professor Jean-Baptiste Jeannin** for the continuous support and mentoring over the past 2.5 years
- **Jiawei Chen** for mentoring and time dedicated to answer questions
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- **Honors Program** for academic support. Shoutout to **Rachel Armstrong** for helping me with scholarship applications!
- The **Aerospace and EECS Department** for all the challenging classes and projects
- **Dr. John Callewaert** for academic support since freshman year