

Mastering Michelson

Part 0: Outline

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Nomadic Labs training

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Outline

- 1 Part 1: Getting started
- 2 Part 2: Michelson by example
- 3 Part 3: Formal Methods



Mastering Michelson

Part 1: Getting started

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Outline

- 1 Introduction
- 2 Type System
- 3 Tooling
- 4 Reference manual

Smart contracts in Tezos

Smart contracts are:

- a bag of tokens (the **balance**), a piece of **code**, a **storage** space
- all stored on the blockchain at a specific **address**

They:

- decide whether a transaction is accepted or rejected
- keep track of transactions in their storage,
- initiate transfers to other smart contracts,
- take a **parameter** and emit **operations**

Michelson vs. EVM

- Like EVM:
 - stack language
 - on-chain storage
 - gas model
 - Turing complete
- Unlike EVM:
 - static typing
 - atomic computations
 - explicit failure
 - strict syntax

Stack language

- low level enough for good intuition on gas consumption,
- ideal underlying model for formal verification,
- between a high level language and a typed bytecode,

Stack language

- instructions rewrite an input stack into an output stack,
- do not modify input values (immutable data structures),
- the contract rewrites the stack
 - from pair parameter storage
 - to pair (list operation) storage

Static typing

Instructions operate on a *stack*.

Each instruction pops 0, 1, or several elements on the top of the stack and pushes back 0, 1, or several elements on the stack.

For example:

- SWAP pops two elements *a* and *b* and pushes back *a*, and *b* on top of *a*
- UNIT pops nothing and pushes the constant `Unit`
- DROP pops an element and pushes nothing
- NOT pops a boolean and pushes its negation

The number and nature of the element popped and pushed can be seen in the type of the instruction

SWAP	::	'a : 'b : 'A	→	'b : 'a : 'A
SENDER	::	'A	→	address : 'A
DROP	::	'a : 'A	→	'A
NOT	::	bool : 'A	→	bool : 'A

Static typing

Data are typed.

- `PUSH int 2` vs. `PUSH mutez 2`
- `PUSH (list int) { 1 ; 2 ; 3 }`
vs. `PUSH (set int) { 1 ; 2 ; 3 }`

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Each time a piece of data enters a Michelson contract, its type must be given

- `PUSH` (and variants)
- `storage`
- `parameter`

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The type of each instruction is determined by the type of its input

<code>ADD ::</code>	<code>int : int : 'S</code>	<code>→</code>	<code>int : 'S</code>
<code>ADD ::</code>	<code>mutez : mutez : 'S</code>	<code>→</code>	<code>mutez : 'S</code>
<code>SWAP ::</code>	<code>'a : 'b : 'S</code>	<code>→</code>	<code>'b : 'a : 'S</code>

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type-checking at origination + each call

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<code>SWAP ::</code>	<code>'a : 'b : 'S</code>	\rightarrow	<code>'b : 'a : 'S</code>

type-checking at origination + each call

Michelson interpreter cannot run on an ill-typed contract

Static typing

- sound: well-typed contracts do not go wrong,
- inter-contract type safety checks!

Strong type system:

- no nulls, no implicit casts, no overflow, no division by 0 etc.
- high level types: \mathbb{Z} , options, pairs, lists, immutable sets and maps,

Atomic computation

A Michelson contract runs completely before calling other contracts.

This avoids many re-entrancy bugs.

Contracts are not functions, they do not return values.

To get a value from another contract, we need continuation passing style.

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To get a value from another contract, we need continuation passing style.

$$A \rightarrow B(\text{request}, \text{address of } A) \rightarrow A(\text{answer})$$

Explicit failure

All possible runtime failures:

- Explicit failure (`FAILWITH` instruction)
- Gas exhaustion
- Mutez overflow

No modular arithmetic, invalid opcode, invalid instruction, stack over/underflow at runtime.

Syntax

- as unambiguous as possible for humans,
- enforced indentation (alignment of sequences and arguments),
- enforced case: (INSTR, Data, type),
- enforced delimitation of code blocks

Types

- Arithmetic:
int, nat, mutez, timestamp
- Compound types:
unit, bool, pair _ _, or _ _, option _
- Addresses:
key_hash, address, contract _
- Data structures:
list _, set _, map _ _, big_map _ _
- Crypto:
bytes, key, signature
- Other:
string, lambda _ _, operation

Casts

```
INT   ::   nat   →   int
ISNAT ::   int   →   option nat
ABS   ::   int   →   nat
```

Casts

```
INT    ::    nat    →    int
ISNAT  ::    int    →    option nat
ABS    ::    int    →    nat
```

```
IMPLICIT_ACCOUNT :: key_hash → contract unit
ADDRESS          :: contract _ → address
CONTRACT 'ty     :: address → option (contract 'ty)
```

Casts

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```

```
IMPLICIT_ACCOUNT :: key_hash → contract unit
ADDRESS          :: contract _ → address
CONTRACT 'ty     :: address → option (contract 'ty)
```

```
PACK      ::      _      →    bytes
UNPACK 'ty :: bytes      →    option 'ty
```


CLI

- `tezos-client typecheck script <file>`
- `tezos-client run script <file> on storage <data>
and input <data> [--trace-stack]`
- `tezos-client originate contract <contract_name>
transferring <balance> from <payer> running
<file> --init <storage> --burn-cap <cap>`
- `tezos-client transfer <amount> from <sender> to
<contract> --arg <parameter> [--burn-cap <cap>]`

Editors

- Emacs
<https://gitlab.com/tezos/tezos/tree/master/emacs>
- IntelliJ (and derived editors like PyCharm)
<https://www.plugin-dev.com/plugins/tezos-michelson/>

Try-Michelson

<https://try-michelson.tzalpha.net/>
(or locally on the Training VM)

- Web editor
- Type-checking
- Simulation (incl. inter-contract interaction)

Reference manual

Michelson whitepaper:

- Athens: `https://tezos.gitlab.io/master/whitedoc/michelson.html`
- Babylon: `https://tezos.gitlab.io/zeronet/whitedoc/michelson.html`

WIP Michelson reference:

- `https://arvidj.eu/michelson/`

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Questions?

Mastering Michelson

Part 2: Michelson by example (and Babylon novelties)

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Outline

- 1 First example: Deposit
- 2 Second example: Voting
- 3 What's new in Babylon
- 4 Third example: Multisig
- 5 Fourth example: Weather Insurance

Deposit contract

First example: a **deposit** contract

- Storage contains the owner's address
- Can receive tokens from anybody
- The owner can withdraw tokens

Goal

- Starting example
- Simple authentication
- Token transfers

Base types

- `unit`: trivial type (the only value is `Unit`)
- `bool`: either `True` or `False`
- `string`: character strings surrounded by double quotes `"`

Control structures

- No operation: $\{ \} :: 'A \rightarrow 'A$
- Sequence: $\{ \text{code}_1 ; \text{code}_2 ; \dots ; \text{code}_n \} :: A_1 \rightarrow A_{n+1}$
if $\text{code}_i :: A_i \rightarrow A_{i+1}$
- Explicit failure: $\text{FAILWITH} :: 'a : 'A \rightarrow 'B$
- Conditional: $\text{IF } \{ \text{bt} \} \{ \text{bf} \} :: \text{bool} : 'A \rightarrow 'B$
if $\text{bt}, \text{bf} :: 'A \rightarrow 'B$
- loop: $\text{LOOP } \{ \text{body} \} :: \text{bool} : 'A \rightarrow 'A$
if $\text{body} :: 'A \rightarrow \text{bool} : 'A$

Stack manipulation

```

PUSH 'a x      ::                'A      →      'a : 'A
DROP           ::                'a : 'A      →      'A
DUP            ::                'a : 'A      →      'a : 'a : 'A
SWAP           ::      'a : 'b : 'A      →      'b : 'a : 'A
DIP { code } ::      'a : 'A      →      'a : 'B

```

```

if code :: 'A → 'B

```

Stack manipulation example

```
PUSH string "foo"; PUSH string "bar";  
DIP { DUP; PUSH string "baz"}; SWAP; DROP
```

Stack manipulation example

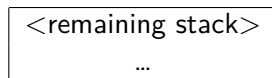
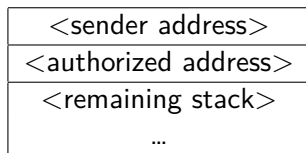
```
PUSH string "foo"; PUSH string "bar";  
DIP { DUP; PUSH string "baz"}; SWAP; DROP
```

"bar"
"foo"
"foo"

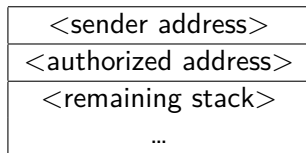
Comparison

- `COMPARE :: 'a : 'a : 'A → int : 'A` Returns -1, 0, or 1
- `EQ, NEQ, LT, GT, LE, GE :: int : 'A → bool : 'A`

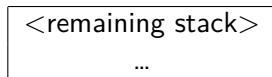
Sender authentication



Sender authentication



→



```
COMPARE; EQ; IF { FAILWITH } {}
```

Operations

- address: untyped address
- contract 'a: smart contract expecting a parameter of type 'a
- mutez: amount of tokens (in μtz)

```
TRANSFER_TOKENS :: 'a : mutez : contract 'a : 'A →  
  operation : 'A
```

```
AMOUNT, BALANCE :: 'A → mutez : 'A  
SENDER          :: 'A → address : 'A  
SELF            :: 'A → contract 'a : 'A
```

```
CONTRACT 'a :: address : 'A → option (contract 'a) : 'A
```

```
ADDRESS :: contract 'a : 'A → address : 'A
```

Pairs, ors, and options

- `pair 'a 'b`: a pair of values `Pair x y` with `x :: 'a` and `y :: 'b`
- `or 'a 'b`: either `Left x` with `x :: 'a` or `Right y` with `y :: 'b`
- `option 'a`: either `Some x` with `x :: 'a` or `None`

Constructors

PAIR	::	'a : 'b : 'A	→	pair 'a 'b : 'A
LEFT 'b	::	'a : 'A	→	or 'a 'b : 'A
RIGHT 'a	::	'b : 'A	→	or 'a 'b : 'A
NONE 'a	::	'A	→	option 'a : 'A
SOME	::	'a : 'A	→	option 'a : 'A

Destructors

CAR :: pair 'a 'b : 'A → 'a : 'A

CDR :: pair 'a 'b : 'A → 'b : 'A

IF_LEFT { bl } { br } :: or 'a 'b : 'A → 'B

if bl :: 'a : 'A → 'B, br :: 'b : 'A → 'B

IF_NONE { bn } { bs } :: option 'a : 'A → 'B

if bn :: 'A → 'B, bs :: 'a : 'A → 'B

LOOP_LEFT { body } :: or 'a 'b : 'A → 'b : 'A

if body :: 'a : 'A → or 'a 'b : 'A

Parameters and storage

3 sections: *storage*, *parameter*, *code*

- *storage* and *parameter* are types.
- *code* :: pair parameter storage : [] → pair (list operation) storage

Example: deposit contract

Example: deposit contract

```

parameter: (or unit mutez);
storage: address;
code:
  { DUP; CAR; DIP {CDR};
    IF_LEFT
      { # Deposit
        DROP; NIL operation }
      { # Withdraw
        DIP { DUP;
          # Access control:
          #   only the stored address can withdraw
          DUP; SENDER; COMPARE; EQ; IF {FAILWITH} {}
          CONTRACT unit; IF_NONE {FAILWITH} {} };
        PUSH unit Unit; TRANSFER_TOKENS;
        NIL operation; SWAP; CONS};
    PAIR}

```


Vote contract

- User can pay 5_{tz} to vote
- Fixed set of options to vote for

Goal

- paywall
- arithmetics
- manipulation of a map

Integer arithmetics

- `int`: arbitrary-precision integers
- `nat`: arbitrary-precision naturals

Arithmetics

- $\text{ABS} :: \text{int} : 'A \rightarrow \text{nat} : 'A$
- $\text{NEG} :: \text{nat} : 'A \rightarrow \text{int} : 'A$
- $\text{NEG} :: \text{int} : 'A \rightarrow \text{int} : 'A$
- $\text{ADD} :: \text{nat} : \text{nat} : 'A \rightarrow \text{nat} : 'A$
- $\text{ADD} :: \text{nat} : \text{int} : 'A \rightarrow \text{int} : 'A$
- $\text{ADD} :: \text{int} : \text{nat} : 'A \rightarrow \text{int} : 'A$
- $\text{ADD} :: \text{int} : \text{int} : 'A \rightarrow \text{int} : 'A$
- SUB, MUL
- $\text{EDIV} :: \text{nat} : \text{nat} : 'A \rightarrow \text{option}(\text{pair nat nat}) : 'A$
- $\text{EDIV} :: \text{nat} : \text{int} : 'A \rightarrow \text{option}(\text{pair int nat}) : 'A$
- $\text{EDIV} :: \text{int} : \text{nat} : 'A \rightarrow \text{option}(\text{pair int nat}) : 'A$
- $\text{EDIV} :: \text{int} : \text{int} : 'A \rightarrow \text{option}(\text{pair int nat}) : 'A$
- bitwise operations
- $\text{LSL}, \text{LSR} :: \text{nat} : \text{nat} : 'A \rightarrow \text{nat} : A$

Data structures

- `list 'a`: a list with elements of type `'a`
- `set 'a`: a finite set of elements of type `'a`
- `map 'key 'val`: a finite map
- `big_map 'key 'val`: same but lazily deserialized

Instructions

- `NIL 'a`
- `EMPTY_SET 'elt`
- `EMPTY_MAP 'key 'val`
- `CONS`
- `UPDATE`
- `IF_CONS { bc } { bn }`
- `MEM`
- `MAP { body }`
- `SIZE`
- `ITER { body }`

Example: vote contract

Example: vote contract

```

storage (map string nat);
parameter string;
code { DUP; DIP {CDR; DUP}; CAR; DUP;
      DIP { GET;
            IF_NONE
              { PUSH string "Not a valid option";
                FAILWITH }
            {} };
      PUSH nat 1; ADD; SOME };
UPDATE;
NIL operation; PAIR }

```


Overview of Michelson changes in Babylon

More details here:

https:

[//blog.nomadic-labs.com/michelson-updates-in-005.html](https://blog.nomadic-labs.com/michelson-updates-in-005.html)

Gas

- Micro bench-marking
- Better gas computation
- STEPS_TO_QUOTA is deprecated

Account reorganisation

- CREATE_ACCOUNT is deprecated
- CREATE_CONTRACT now takes fewer arguments

```
CREATE_CONTRACT { storage 'g ; parameter 'p ; code  
... } Parameters
```

Parameter type	Parameter	in Athens	in Babylon
key_hash	manager	Yes	No
option key_hash	initial delegate	Yes	Yes
bool	spendable flag	Yes	No
bool	delegatable flag	Yes	No
mutez	initial balance	Yes	Yes
'g	initial storage	Yes	Yes

Stack instructions

DIG n :: 'a{1} : ... : 'a{n-1} : 'a{n} : 'C
 → 'a{n} : 'a{1} : ... : 'a{n-1} : 'C

DUG n :: 'a{1} : 'a{2} : ... : 'a{n} : 'C
 → 'a{2} : ... : 'a{n} : 'a{1} : 'C

DROP n :: 'a{1} : ... : 'a{n} : 'C
 → 'C

DIP n { code } :: 'a{1} : 'a{2} : ... : 'a{n} : 'C
 → 'a{1} : 'a{2} : ... : 'a{n} : 'D

if code :: 'C → 'D

Partial application

Already in Athens:

EXEC :: 'a : lambda 'a 'b : 'C → 'b : 'C

New in Babylon:

APPLY :: 'a : lambda (pair 'a 'b) 'c : 'C
→ lambda 'b 'c : 'C

Multiple big maps

In Athens:

- Each contract can store at most one `big_map`,
storage pair `(big_map 'a 'b) 'c`
- `big_maps` can not be transferred

In Babylon:

- Both restrictions removed

Entrypoints

Already in Athens:

- A contract with 3 entrypoints of type 'a', 'b', and 'c' can be encoded as:

(or 'a (or 'b 'c)).

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`(or 'a (or 'b 'c)).`

- Entrypoints can be named using %-annotations:

`(or ('a %entry_A) (or ('b %entry_B) ('c %entry_C))).`

Entrypoints

Already in Athens:

- A contract with 3 entrypoints of type 'a', 'b', and 'c' can be encoded as:

(or 'a (or 'b 'c)).

- Entrypoints can be named using %-annotations:

(or ('a %entry_A) (or ('b %entry_B) ('c %entry_C))).

- But two problems:

- To call an entrypoint of a contract, we need to know **where** the entrypoint is in the or-tree
- and **the types** of all entrypoints
- interfaces are not extensible

Entrypoints

In Athens:

```
CONTRACT 'ty    ::                address : 'S
                → option (contract 'ty) : 'S
SELF           ::                'S
                → contract <param_type> : 'S
```

In Babylon:

```
CONTRACT %<entry> 'ty    ::                address : 'S
                        → option (contract 'ty) : 'S
SELF %<entry>           ::                'S
                        → contract <entry_ty> : 'S
```

%default is used if %<entry> is omitted.

The multisig contract

- n persons share the ownership of the contract.
- they agree on a threshold t (an integer).
- to do anything with the contract, at least t owners must agree.
- possible actions:
 - list of operations (to be run atomically)
 - changing the list of owners and the threshold

Goal

- advanced, signature-based authentication
- security

Types

- bytes: non-readable sequence of bytes
- key: cryptographic public key
- signature: cryptographic signature

Instructions

- `PACK :: 'a : 'A → bytes : 'A`
- `UNPACK 'a :: bytes → option 'a : 'A`
- `BLAKE2B, SHA256, SHA512 :: bytes : 'A → bytes : 'A`
- `CHECK_SIGNATURE :: key : signature : bytes : 'A →
bool : 'A`

First example: Deposit
oooooooooooooooo

Second example: Voting
ooooooo

What's new in Babylon
oooooooo

Third example: Multisig
oooo●

Fourth example: Weather Insur
ooooo

Example: multisig

Example: multisig

```

parameter (pair (lambda unit (list operation)) (list (option signature)));
storage (pair nat (list key));
code
{ DUP; CDR; DIP {CAR}; DUP;
  DIP { SWAP; DUP; CAR; DIP {CDR}; DUP; DIP {SWAP}; PACK; SWAP };
  DUP; CAR;
  DIP
    { CDR; PUSH nat 0; SWAP;
      ITER
        { DIP {SWAP}; SWAP;
          IF_CONS
            { IF_SOME
              { SWAP;
                DIP { SWAP ; DIP {DIP {DIP {DUP}; SWAP}};
                  DIP {DIP {DIP {DUP}; SWAP}; SWAP}; SWAP;
                  DIP {CHECK_SIGNATURE}; SWAP;
                  IF {DROP} {PUSH string "bad signature"; FAILWITH};
                  PUSH nat 1; ADD }}
              { SWAP; DROP }}
            { PUSH string "signature list is too short"; FAILWITH };
          SWAP }};
        COMPARE; LE; IF {} {PUSH string "not enough signatures"; FAILWITH};
        IF_CONS {PUSH string "signature list is too long"; FAILWITH} {}; DROP;
        UNIT; EXEC; PAIR }

```


Weather Insurance

- Insurance contract
 - Take deposits
 - Refunds the insurance or its client depending on the rain level
- Oracle contract
 - stores rain levels
 - paid service

Goal

- communication between smart contracts
- deposits and refunds

Continuation passing style

$A \rightarrow B(\text{request}, \text{address of } A) \rightarrow A(\text{answer})$

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- Smart contract A (insurance contract) needs an extra entryptoint for receiving the answer

Continuation passing style

$A \rightarrow B(\text{request, address of } A) \rightarrow A(\text{answer})$

- Smart contract A (insurance contract) needs an extra entrypoint for receiving the answer
- Smart contract B (oracle) also needs two entrypoints

Oracle

```
https://gitlab.com/nomadic-labs/mi-cho-coq/blob/  
master/src/contracts/mutually_calling/oracle.tz
```

Insurance

```
https://gitlab.com/nomadic-labs/mi-cho-coq/blob/  
master/src/contracts/mutually_calling/weather_  
insurance_on_chain_oracle.tz
```

Mastering Michelson

Part 3: Formal Methods

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Nomadic Labs training
October 17, 2019

Outline

- 1 Formal Methods for Michelson smart contracts

Motivation

- Smart contracts manipulate money (sometimes a lot)
- They are here to stay: in case of bug, they are hard to update
- Security: bugs may become exploits

Before uploading them, we want to be sure there is no bug in them!

Motivation

- Smart contracts manipulate money (sometimes a lot)
- They are here to stay: in case of bug, they are hard to update
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Before uploading them, we want to be sure there is no bug in them!

- infinitely-many possible input values so testing cannot be exhaustive

Definition

Formal methods: methods for mathematically reasoning about programs

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Formal methods: methods for mathematically reasoning about programs

- Semantics: Description of the meaning of all instructions of the programming language
- Specification: Formula in some logic describing the expected behaviour of the program
- Goal: verify that the program satisfies the specification
 - Mathematical proof, more or less automatized

Approaches

- Model Checking
Abstract the program into a state automaton called the *model* that can be checked on all inputs.
- Abstract Interpretation
Abstract the values as *domains* (for example intervals). Refine the abstraction when needed.
- Deductive Verification
Reduce to the *theorem proving* problem.

Model Checking

Abstract the program into a state automaton called the *model* that can be checked on all inputs.

- Specifications:
 - Safety No bad state can be reached
 - Liveness Good states are reached infinitely often
 - Temporal properties
- Problem:
 - Finding the model
 - Linking it to the concrete program

Abstract Interpretation

Abstract the values as *domains* (for example intervals). Refine the abstraction when needed.

- Specifications:
 - Safety
 - Arithmetic
- Problem
 - False alarms

Deductive Verification

Reduce to the *theorem proving* problem.

- Specifications:
 - *Functional* properties { precondition } Program { postcondition }
 - Very rich logics
- Problem
 - Requires a lot of user interaction

Michelson design

Michelson has been designed to ease formal methods

- Static typing
- Explicit failure
- No overflow nor division by zero
- Clear documented semantics

Michelson contracts are necessarily small and simple

Formal methods for Michelson

- Model Checking:
 - Example: auction
 - Spec: Anybody either win the auction or lose no money
 - Tool: Cubicle Model-Checker
- Abstract Interpretation:
 - Bound on gas
 - Token freeze
- Deductive Verification:
 - Example: multisig
 - Spec: multisig succeeds IFF enough valid signatures
 - Tool: Mi-Cho-Coq