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Motoko

The Programming Language of the Internet Computer

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What is Motoko?

A programming language specialized for the Internet Computer blockchain

IC 	**Motoko** 
General-purpose	Feature richness like JavaScript, Rust, and ML
Secure	Rigorous memory, type, and numeric safety
Decentralized	Actor model and asynchrony
Unstoppable	Orthogonal persistence

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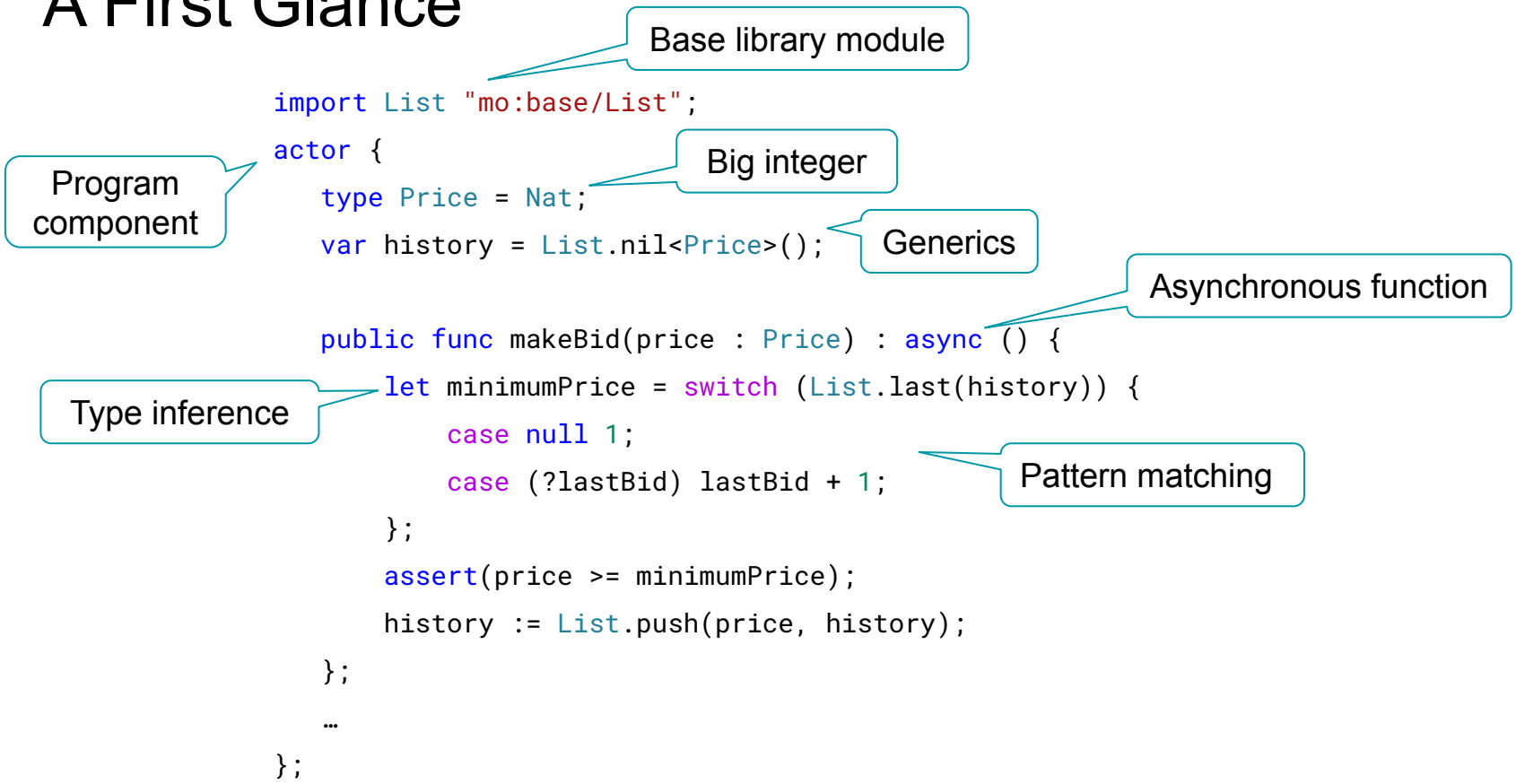
A First Glance




```
import List "mo:base/List";
actor {
   type Price = Nat;
   var history = List.nil<Price>();

   public func makeBid(price : Price) : async () {
       let minimumPrice = switch (List.last(history)) {
           case null 1;
           case (?lastBid) lastBid + 1;
       };
       assert(price >= minimumPrice);
       history := List.push(price, history);
   };
   …
};
```

Design Goals

Suitability for blockchain

- Safety
- Expressiveness

Programming productivity

- Expressiveness
- Resemblance to JavaScript, C#, Rust

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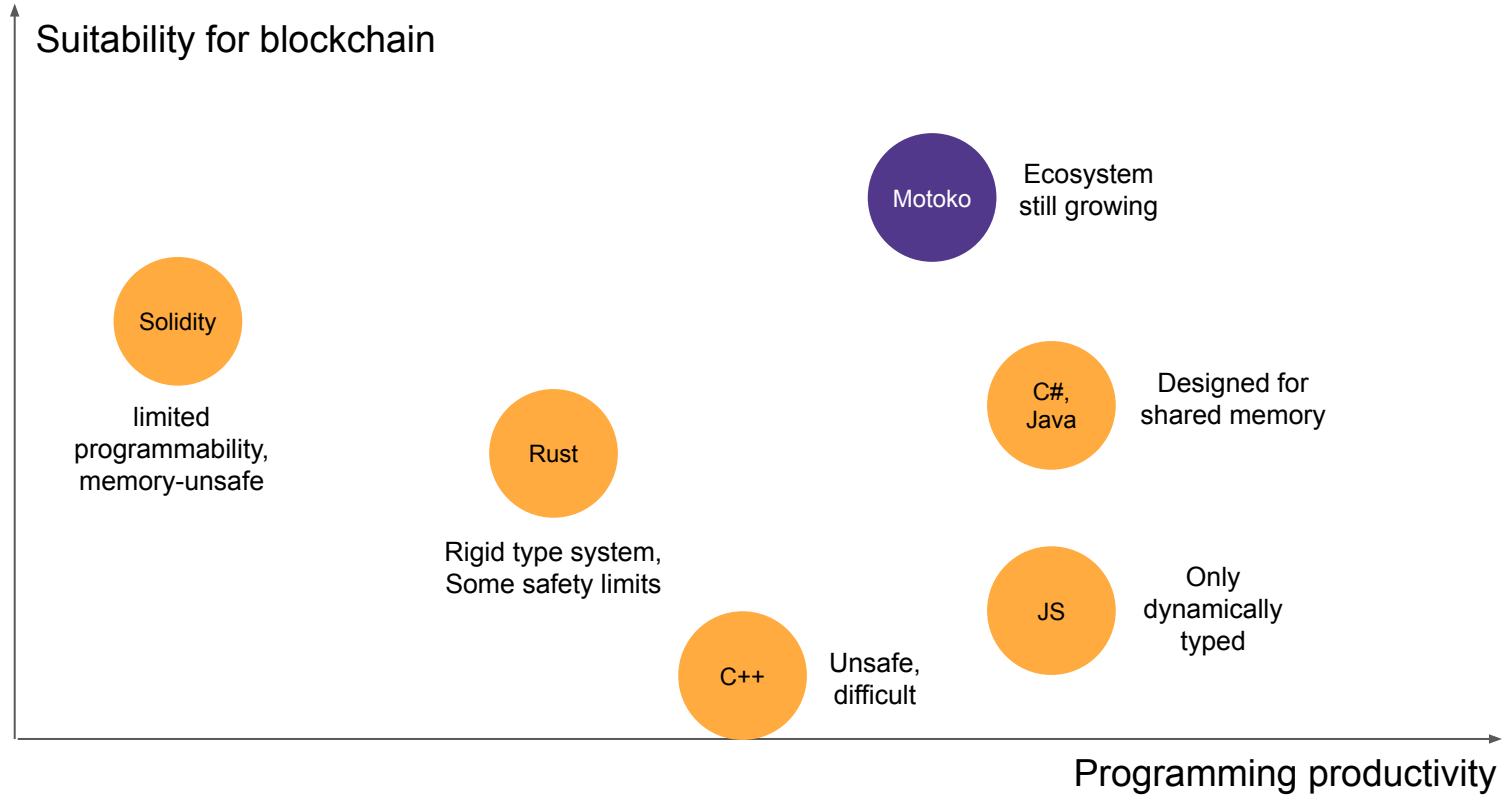
Language Landscape



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Security Aspects

Blockchain-inherent security:

- Byzantine fault-tolerant execution
- Higher DOS resistance by replication and scalability
- Inbuilt authentication mechanism

Language-inherent safety:

- Reducing chances for bugs - and thus security vulnerabilities

Out of scope for this tutorial:

- Threshold ECDSA signing, blockchain data encryption, …

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Learning Goals

Tutorial:

- Know the main concepts of the Motoko language
- Get ready for the subsequent Motoko workshop

Workshop:

- Experience how the blockchain can be programmed - and thus its inherent security be seamlessly applied

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A Top-Down Language Tour

- Actors
- Asynchrony
- Types
- Objects
- Functions
- Persistence

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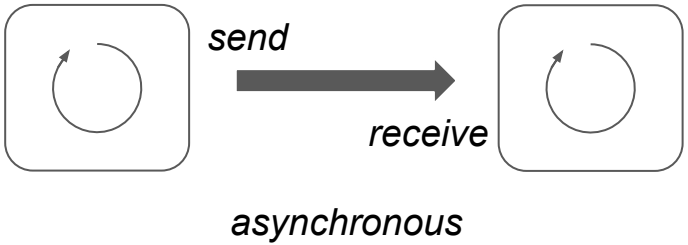
Actors

Program is a set of components = actors that

- carry their encapsulated state
- run concurrently to each other
- communicate by message passing (no shared state)



C. Hewitt, P. Bishop, and R. Steiger. A Universal Modular Actor Formalism for Artificial Intelligence. IJCAI. 1973.

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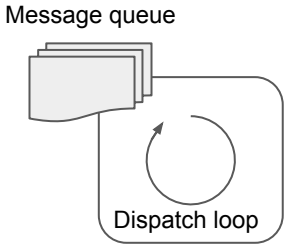
An Implementation Look

Each actor consists of:

- Local memory
- Incoming message queue
- Dispatch loop
  - Processing the queue sequentially
  - Executing code per message



Actors run sequentially on the inside and concurrently on the outside

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Asynchrony

In Motoko, actor communication is realized by asynchronous functions

Async function call	Send
Async function execution	Receive
Return from `async` function	Send (reply)
`await` expression	Receive (reply)

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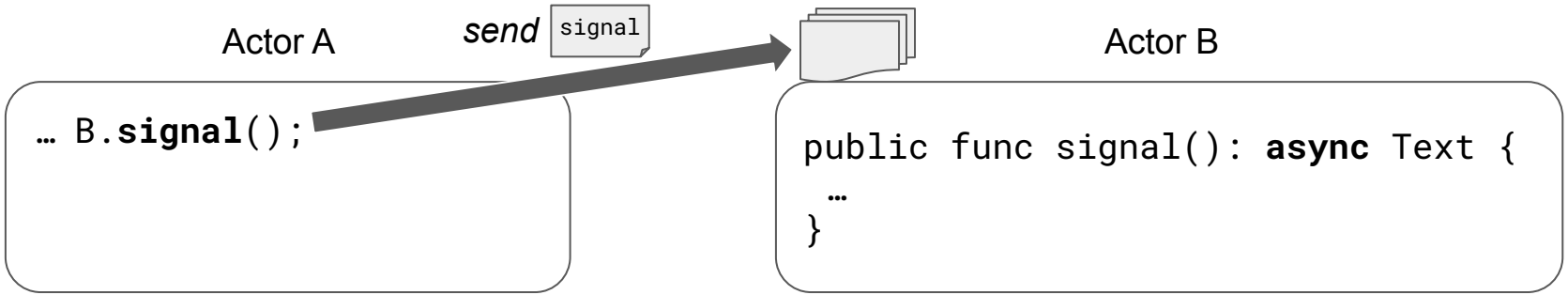
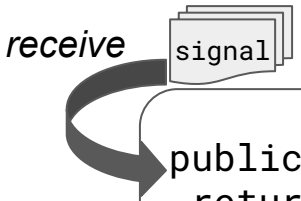
Async Function Call



Async Function Execution

```
… B.signal();
```




```
public func signal(): async Text {
 return "received";
}
```

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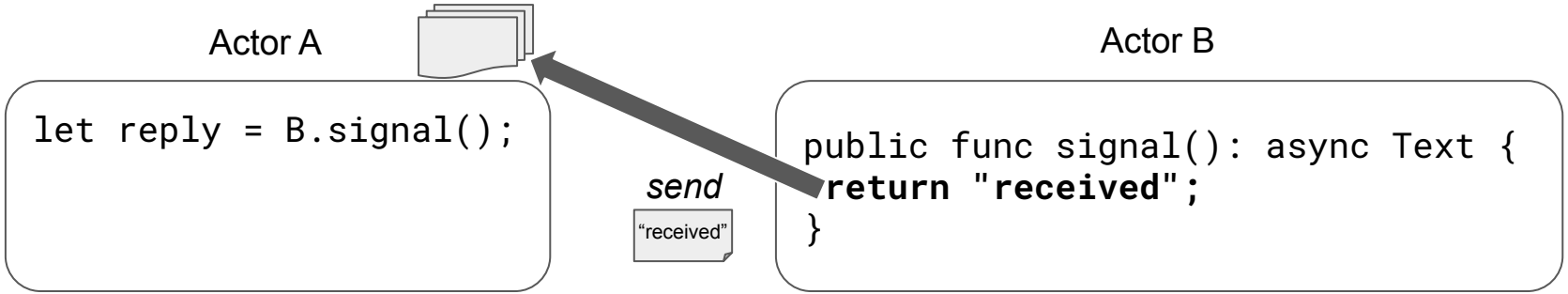
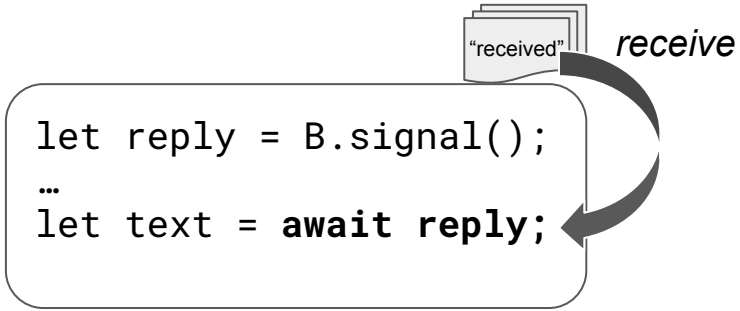
Async Function Return

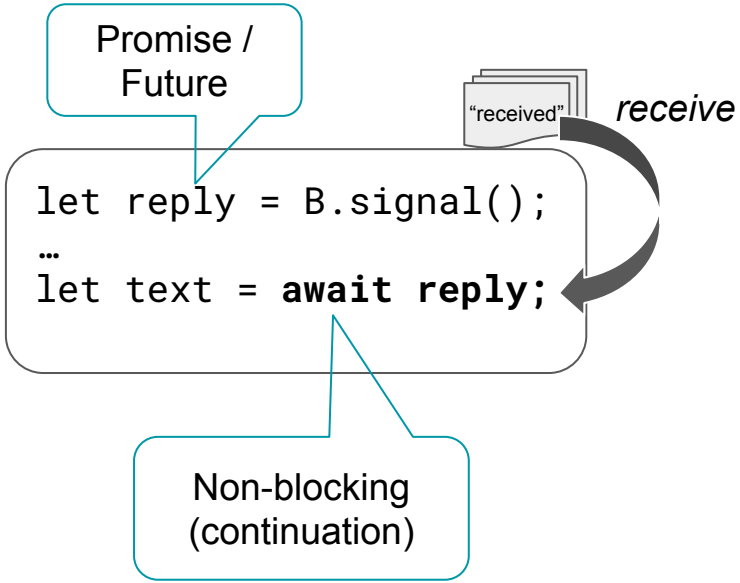


Await Expression




```
public func signal(): async Text {
  …
}
```

Continuation-Style Programming



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Async/Await Constructs

Similar to JavaScript, C#, or C++ 20

Function with an **`async`** return type

- Caller is not blocked during invocation
- Caller obtains a promise = handle for async function

`await` a promise

- Pause the current execution and let other code run
- Resume later when the function behind the promise has completed
- Obtain the result value of the awaited function

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Seamless Integration to the IC

The software components of the IC are canisters:

- A canister is also an actor
- Async/await → actor → canister

Message encoding:

- Standard format on the IC: Candid
- Automatic encoding/decoding by Motoko

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Types

Primitive	`Bool, Nat, Int, Float, Text, Blob, …`	
Tuple	`(Nat, Text, Bool)`	`(123, "Motoko", true)`
Record	`{ name: Text; year: Nat }`	`{ name="CySeP"; year=2023 }`
Array	`[Nat]`	`[1, 2, 3]`
Option	`?Bool`	`null, ?true`
Variant	`{ #North; #South; #East; #West }`	`#North`
Function	`Int -> Bool`	`func (x) { x % 2 == 0 }`

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Mutable State

Mutable fields/arrays must be explicitly declared as `var`

{
name: Text;
var year: Nat;
}
	{
	name = "CySeP";
	var year = 2023;
	}

[var Nat]	[var 1, 2, 3]

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Semantics

Value semantics (copying) for primitive types

```
var x = 0;
let y = x;
x += 1;
Debug.print(debug_show(y));
// Output: 0
```

Reference semantics (sharing) for composite types

```
let x = { var value = 0 };
let y = x;
x.value += 1;
Debug.print(debug_show(y));
// Output: {value = 1}
```

Like JavaScript and Java

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Shareable Types = Serializable

Types that can be sent across actors:

- Primitive types
- Immutable composed types
- No `var` components
- No function types

For immutability: Reference semantics = Value semantics

Also shareable: Remote calls (“shared functions”), actor references

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Structural Typing

Type x is compatible to y if

- They have identical structure
- Record x declares more fields than record y (subtyping)

```
type Work = { author: Text; };
type Picture = { author: Text; image: Blob; };
type Literature = { author: Text; content: Text; };

let book = { name = "Shakespeare"; content = "...to be or not to be..."};
// implicitly compatible to Literature and Work
```

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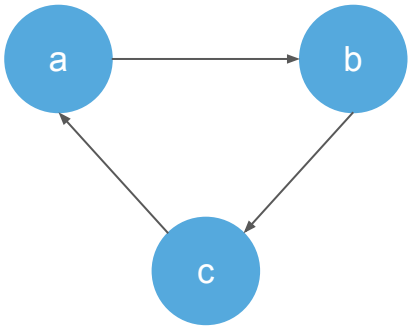
Object-Orientation

```
class Website(url: Text) {
    var links: [Website] = [];

    public func addLink(to: Website) {
        links := Array.append(links, [to]);
    }
};
```

```
type Website = {
  url: Text;
  var links: [Website];
  addLink: Website -> ();
}
```

```
let a = Website("dfinity.org");
let b = Website("internetcomputer.org");
let c = Website("cysep.conf.kth.se");
a.addLink(b);
b.addLink(c);
c.addLink(a);
```



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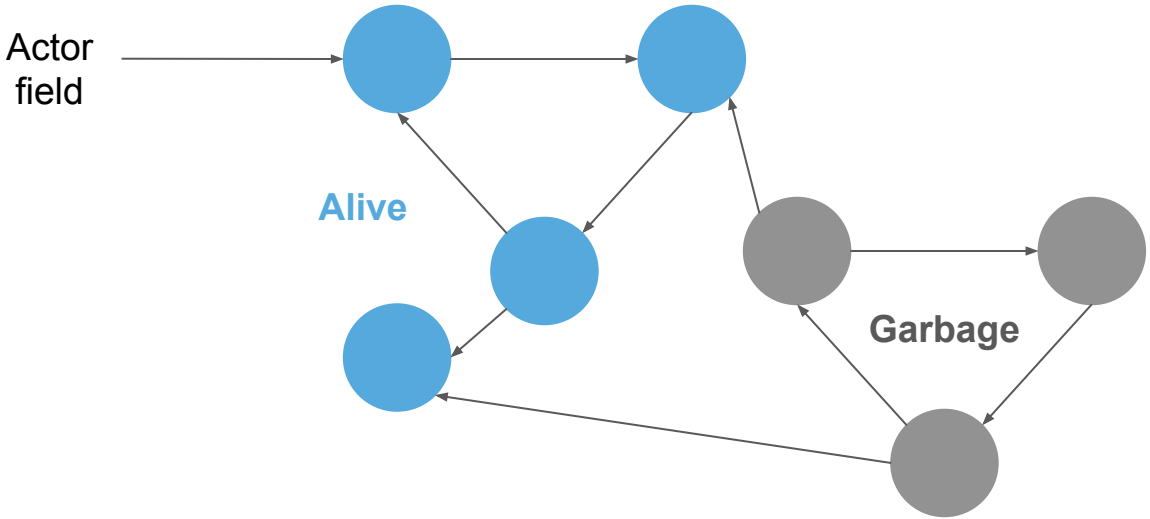
Garbage Collection

Automatic reclamation of unreachable objects inside the actor



Motoko features a powerful incremental GC

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A Word about Safety

Type safety

- Static types
- Dynamic types
- No implicit null deref

Memory safety

- Garbage collection

Numeric safety

- Unbound integers
- Overflow always checked

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Comparison to Other Languages

Rust

- Memory leaks with reference counters possible
- Overflow not checked in production mode
- “Unsafe” mode

C#, Java, JavaScript

- Unchecked overflows (in production mode)
- BigInt is not the default integer type
- Prone to null deref exceptions

→ Safety is particularly important on blockchain

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Functions

```
public func translate(input: Text): async Text { … }
public func store(content: Blob): async () { … }
func max(x: Nat, y: Nat): Nat = x + y;
func printArray(array: [?Int]) { … }
```

Support both imperative and functional programming

- `switch` (with pattern matching), `if-else`
- `if`, `while`, `loop`, `for`, `return`
- function calls, `await`
- Local variables, local functions

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Imperative Programming

```
let array: [?Int] = …;
var sum = +0;
var gaps = false;
for (entry in array.vals()) {
    switch entry {
        case (?number) { sum += number };
        case null { gaps := true }
    }
};
Debug.print("Sum " # debug_show(sum) # " gaps: " # debug_show(gaps));
```

Iterator

null test with pattern matching

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Functional Programming

```
let (sum, gaps) = Array.foldLeft<?Int, (Int, Bool)>(
   array,
   (+0, false),
   func((leftSum, leftGaps), entry) {
       switch entry {
           case (?number) (leftSum + number, leftGaps);
           case null (leftSum, true);
       };
   }
);
Debug.print("Sum " # debug_show (sum) # " gaps: " # debug_show (gaps));
```

Anonymous function (lambda)

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Orthogonal Persistence

IC canisters and thus actors live conceptually perpetually

- State is automatically persisted
- No need for a database, file system, external storage

Special aspect: Upgrade

- Changing the program implementation
- Requires evolving the existing data

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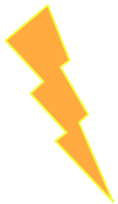
Persistent Program

```
actor {
   …
   type Auction = {
       id : AuctionId;
       item : Item;
       var bidHistory : List.List<Bid>;
       var remainingTime : Nat;
   };

   var auctions = List.nil<Auction>();
   var idCounter = 0;
   …
};
```



However, state is discarded on program change (upgrade)

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Prepare for Upgrade

```
actor {
   …
   type Auction = {
       id : AuctionId;
       item : Item;
       var bidHistory : List.List<Bid>;
       var remainingTime : Nat;
   };

   stable var auctions = List.nil<Auction>();
   stable var idCounter = 0;
   …
};
```

Survive upgrade to future program version

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Stable Modifier

Everything transitively reachable from `stable` fields is upgraded

- Motoko automatically transitions the stable sub-graph of the heap

Only certain types can be upgraded

- No function types

Can also upgrade non-stable variables with upgrade hooks

- See documentation

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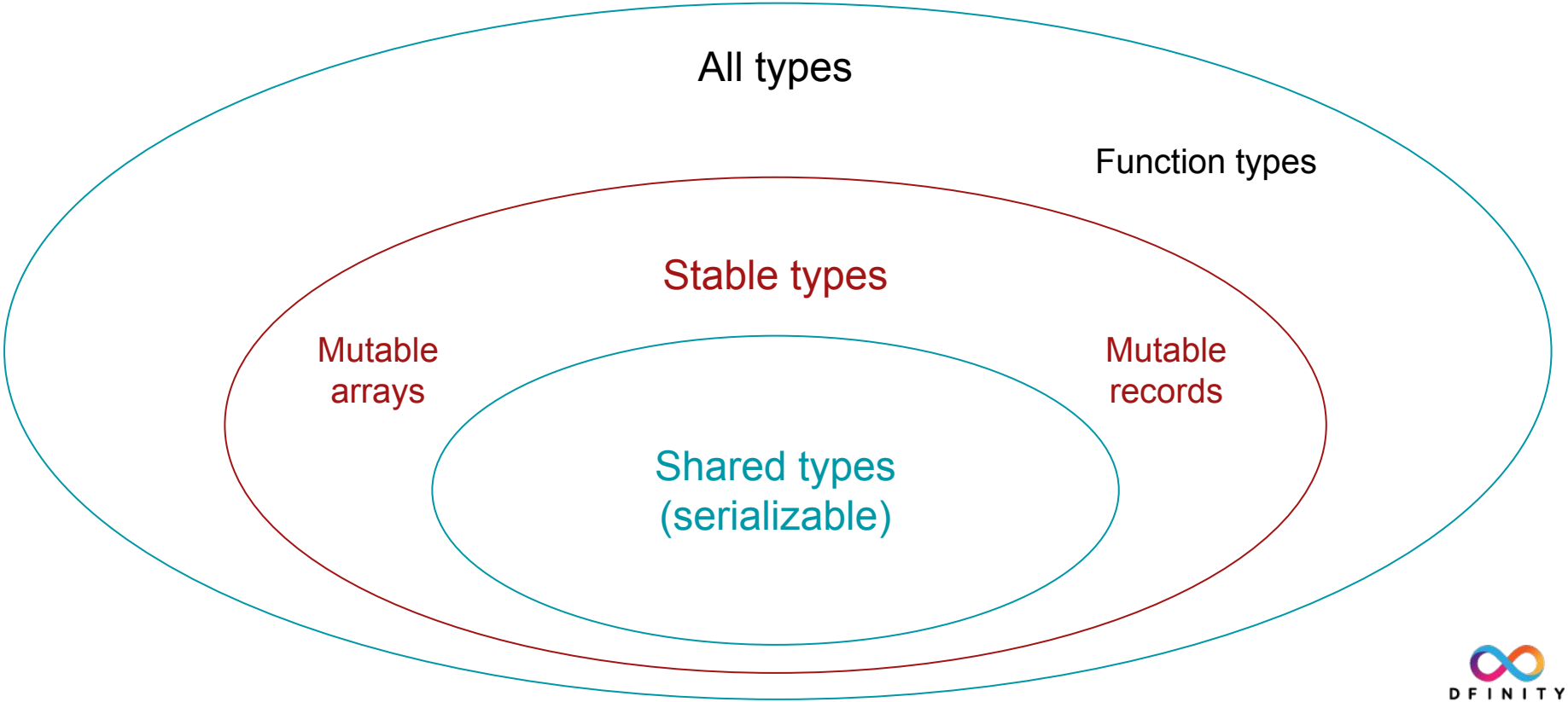
Type Categories



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Modules

Set of functionality that can be imported to actors and other modules.

Base library modules:

`"mo:base/Timer"`	One-shot or periodic time events
`"mo:base/Principal"`	Authentication (Internet Identity)
`"mo:base/Debug"`	Debug output, raising errors (traps)
`"mo:base/List"`	List data structure (stable type)
…	

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Conclusion

Motoko aims for optimal programming on the IC blockchain

First-class support of IC-concepts

- Actors, orthogonal persistence

Easy to learn

- Resemblance to JavaScript, Rust, ML

Emphasis on safety

- Higher than in other languages

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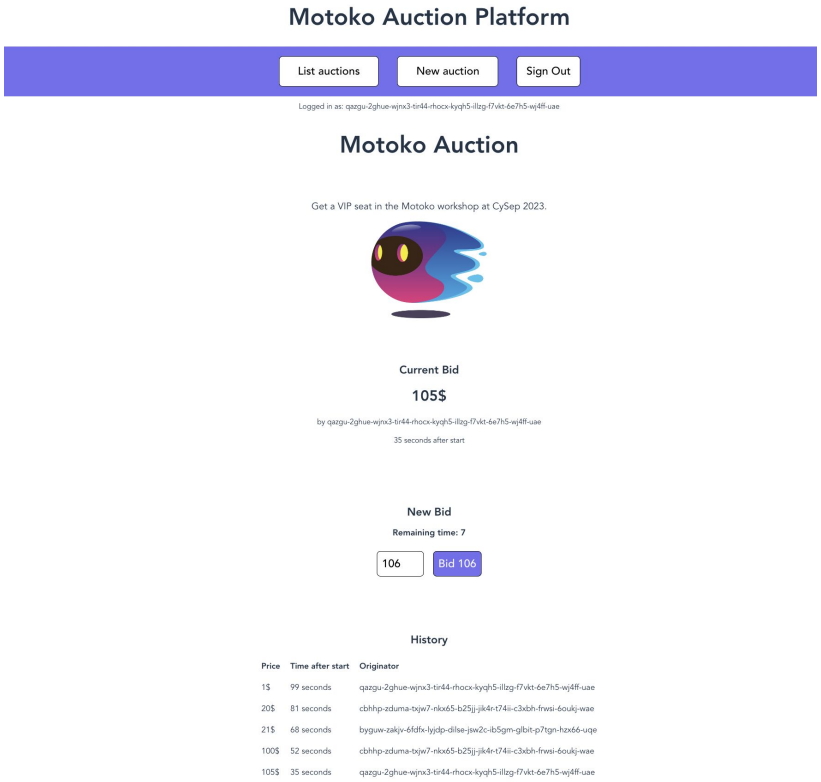
Upcoming: Motoko Workshop

Mini-Hackathon:
Developing an
Auction Platform
with Motoko on the IC



Motoko Workshop

https://github.com/luc-blaeser/auction

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Learn More

- Motoko Documentation: https://internetcomputer.org/docs/current/motoko/main/motoko
- Motoko Open Source Repository: https://github.com/dfinity/motoko

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Common Pitfalls

Using `await` carelessly	Other async code can run in meantime at await. Beware of race conditions!
Missing `stable` modifier (or upgrade hooks)	Data will be lost on program version upgrade!
Using query functions	Requires a certified variable to be secure
Blockchain transaction limit	Message runtime is limited, split into shorter messages or async / await sections
Public actor functions without return type	Onway calls (“fire and forget”), no propagation of errors, specify return type `async ( )` and await

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