Research vision

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Programming Languages

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let r = alloc 0 in r := !r + 1; r
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Typed Programming Languages

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let r = alloc 0 in r := !r + 1; r : ref Nat
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lightweight and modular [specification / verification / documentation]

correct by construction

In today's world software is everywhere!

Typed Programming Languages

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Typed Programming Languages

But what about behaviour?

```
let r = alloc 0 in r := !r + 1; r : ref Nat
```

r is fresh

!r > 0

other effects like I/O ?

user-defined effects ?

...

State of affairs in type-based reasoning

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Values

Well-understood, uniform,

and thoroughly studied! :)

- **Refinement types**

```
Odd ⊑ Nat     Even ⊑ Nat
Vec A n = { l:List A | len l = n }
```

- **Dependent types**

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Vec a n = Σ l:List A.(len l = n)
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- **Homogeneous implementations**
  - Agda, Coq, Idris, F*, L.Haskell, ...

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Effects and behaviour

Scattered landscape, effect-specific, little uniformity! :(

- **Hoare Type Theory** (state)

  `M : Ψ.X.{P}x:A{Q}`

- **F*** (state, exceptions, but no I/O)

  $M : ST\ A\ wp_{ST}$

  ~~$M : IO\ A\ wp_{IO}$~~

- **Session Types** (I/O & channels)

  `c : ?Nat.!String.!Nat.T`

- **Graded monads, param. monads**

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  - operations and equations
  - reveal the fundamental underlying tree-like structure of effects
  - effect handlers are algebras; handling is homomorphism application

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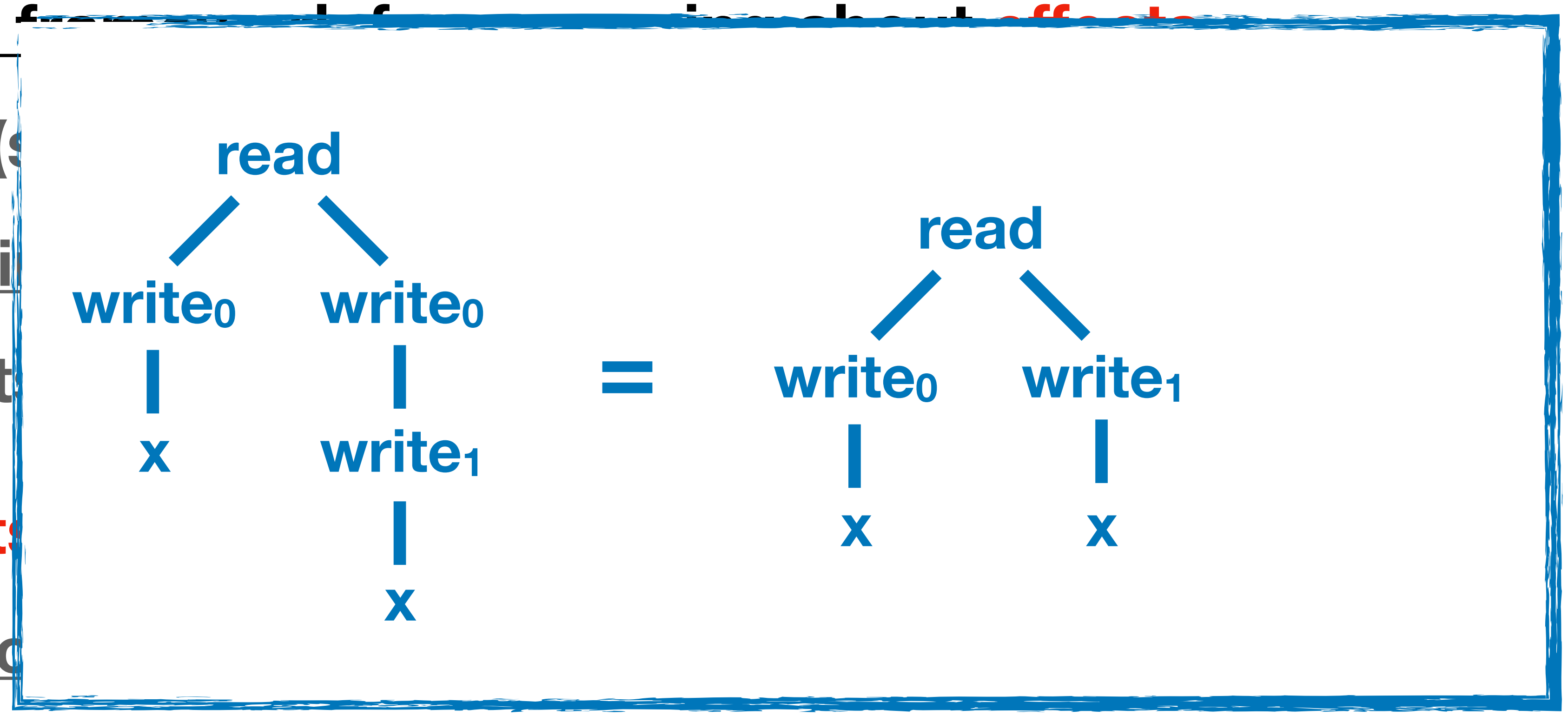

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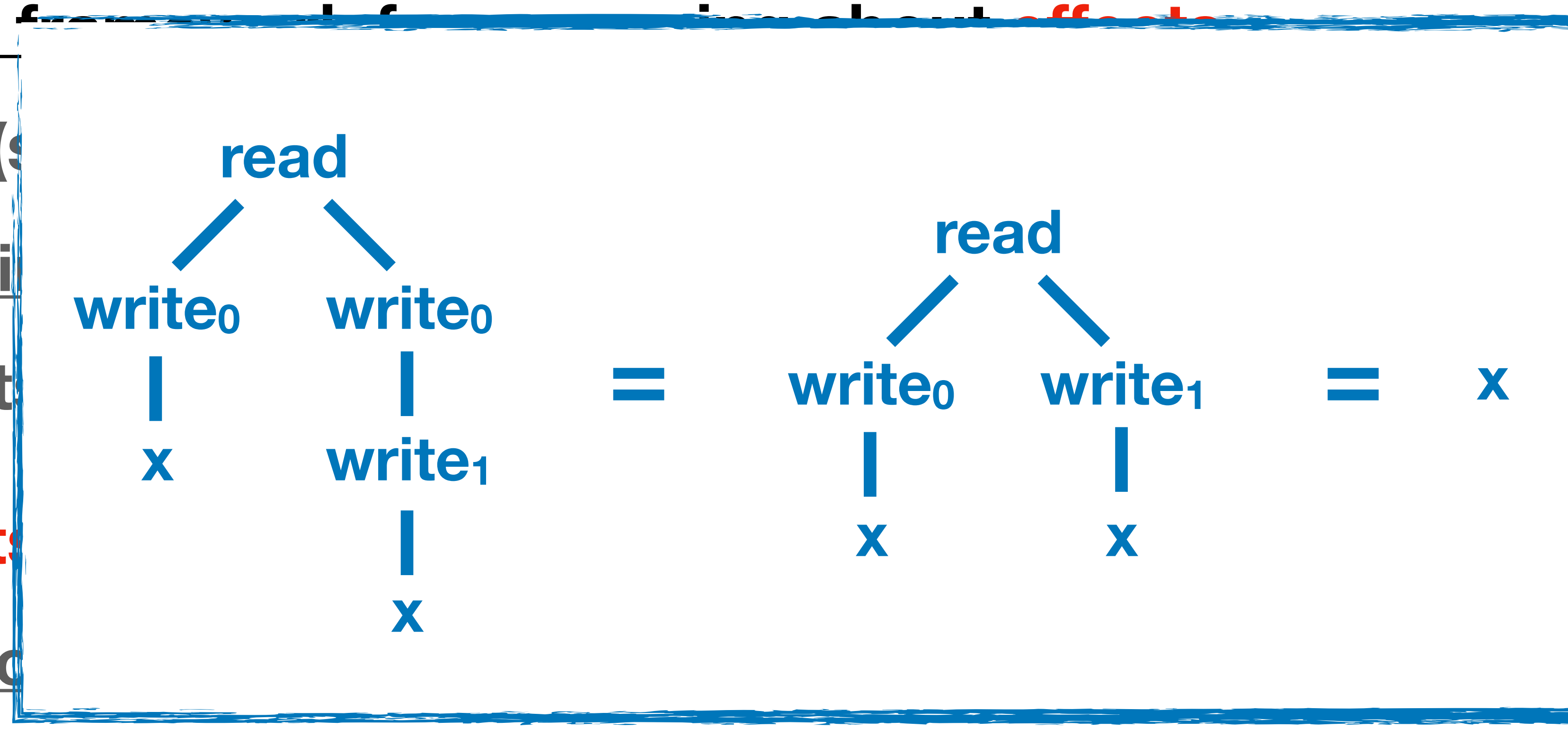

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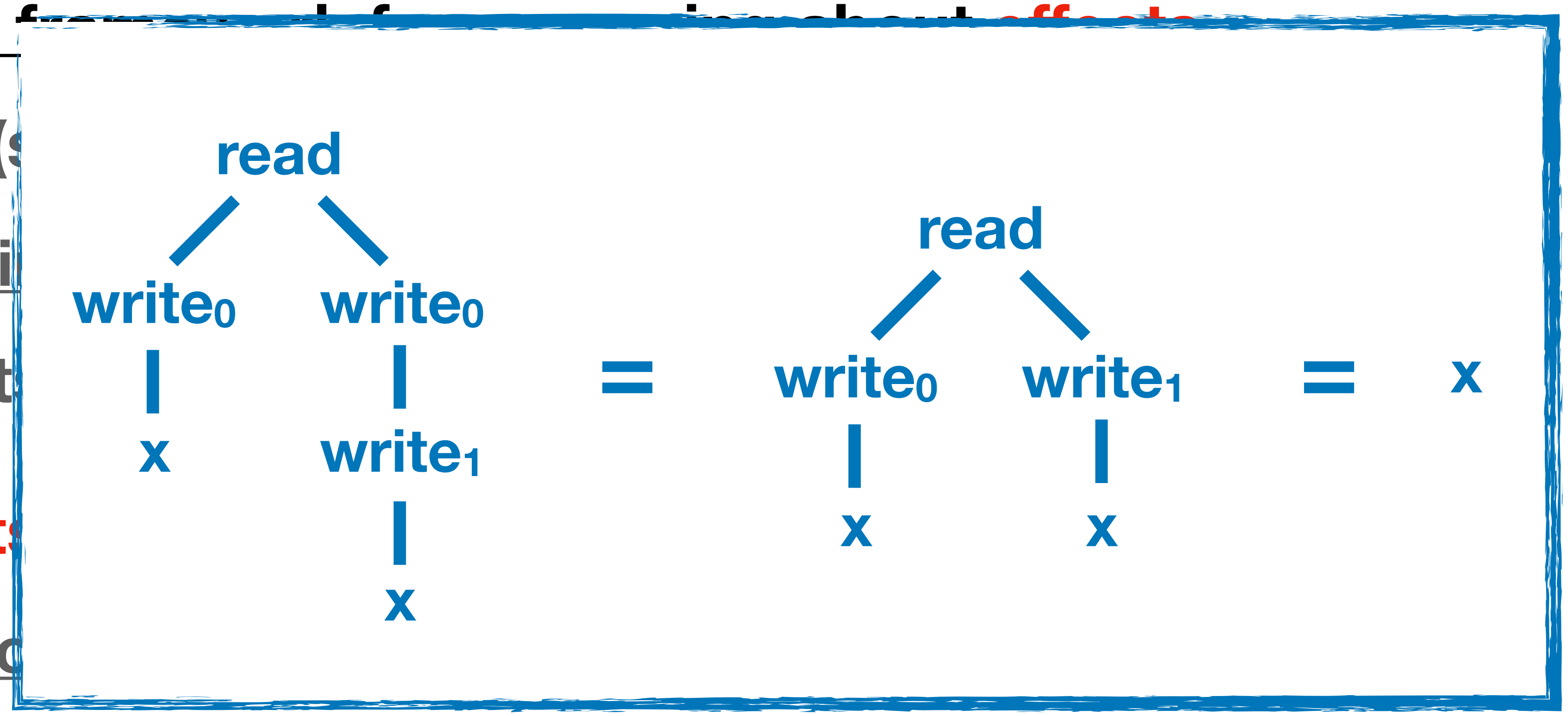

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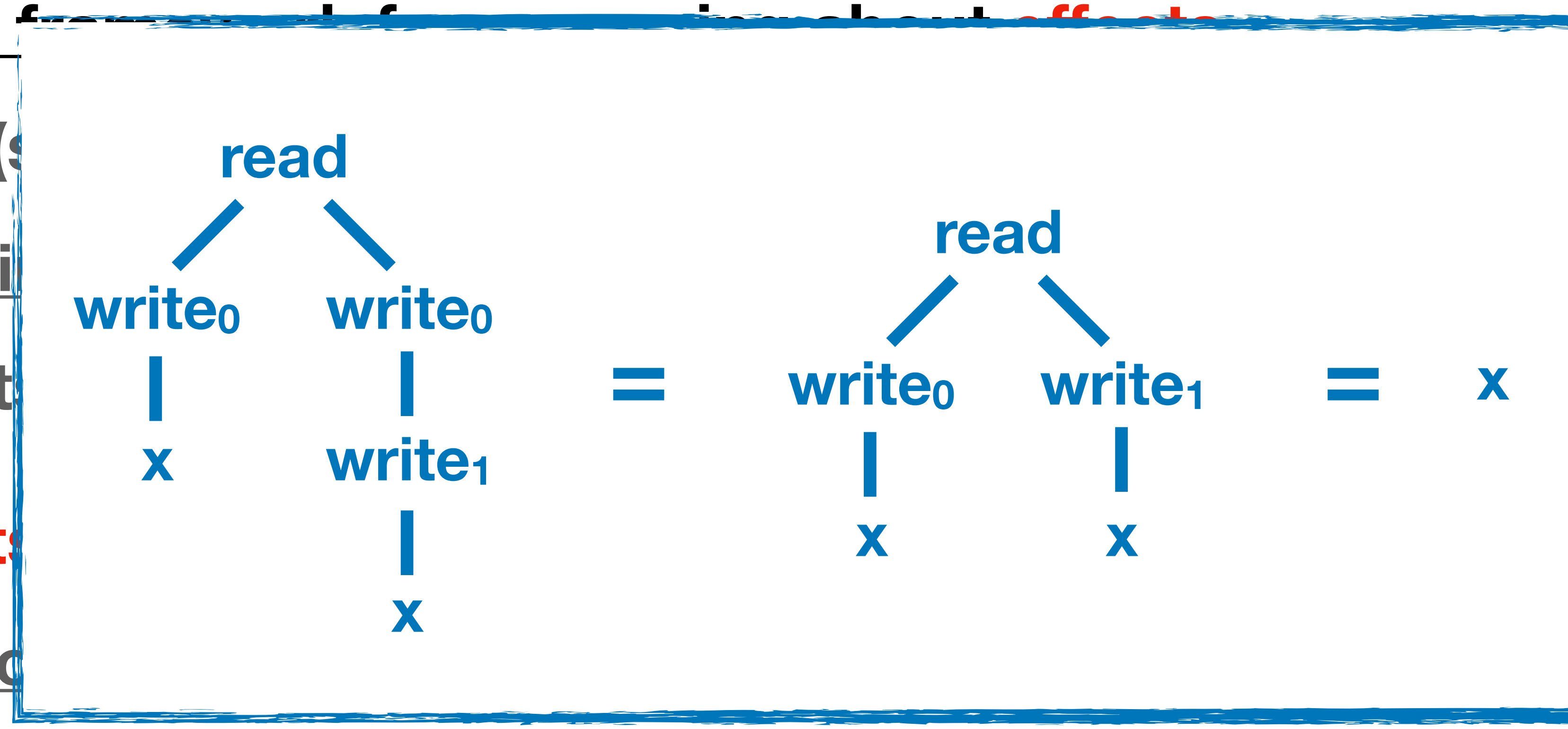

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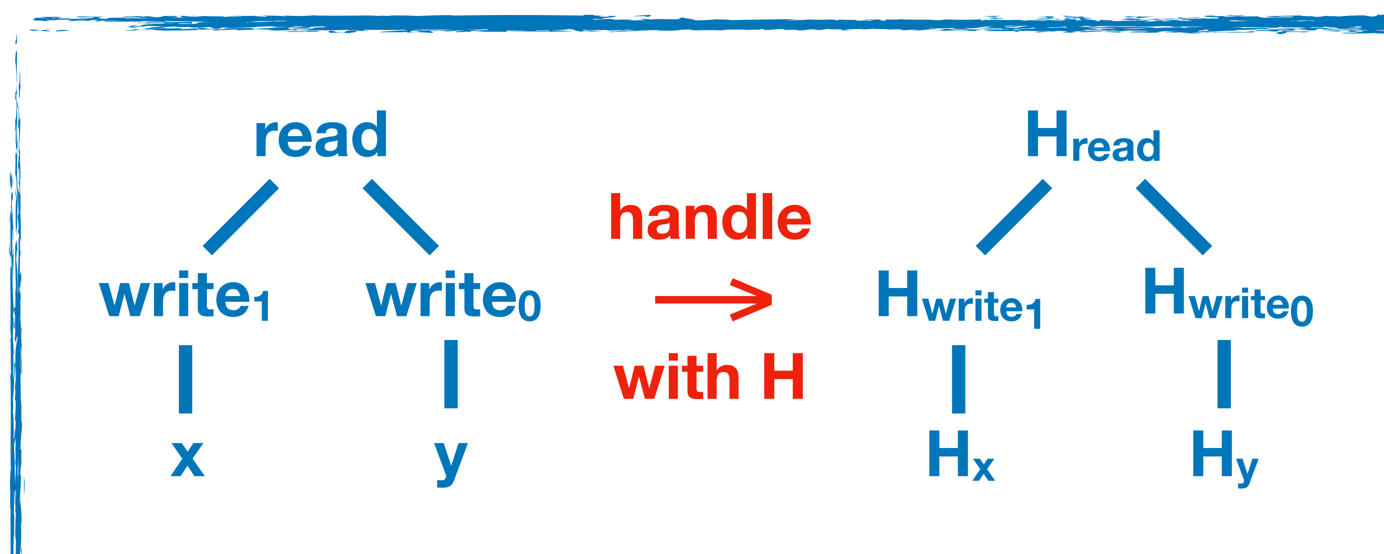

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- **State of the art:** very popular (!) but effect systems too coarse grained (!)
  - concurrency, probability, delimited control, monadic reflection, ...
  - Multicore OCaml, Uber's Pyro tool, Eff, Koka, Frank, ...
  - `M : A ! { read , write, throw }`

The plan: modal logic based c. ref. types

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$$\langle op \rangle(\psi_1, \ldots, \psi_n) = \left\{ \begin{array}{c} op \\ t_1 \quad \cdots \quad t_n \end{array} \;\middle|\; t_1 \in \psi_1 \wedge \cdots \wedge t_n \in \psi_n \right\}$$

$$\mathtt{M : A\ !\ \psi}$$

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```
{{1}} A {Q} = A ! ⋁_{i∈{0,1},q∈Q} <rd>(<wr_i>(ret),<wr_q>(ret))
```

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- **Challenges:**
  - lifting non-linear effect equations (read x x = x)
  - operations with value params. and variable binding
  - effect instances, generativity, and locality (my current focus in LJ)
  - dynamic nature of handlers

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  - commutative monoid structure (an algebraic effect)
  - partitioning, spatial layout, ...

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  - HL + **generative instances** and **locality**
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  - (multi-)**handlers** based concurrency
  - Scala's `promises` and `futures` as a **monotonic state effect**
- **Probabilistic programming**
  - `sample` as an **algebraic effect**; `condition` as a **handler** (cf Pyro)

Temporal view

- **Year 1**
  - modal logic (design, model and proof theory)
  - instances, generativity, locality
  - case studies and applications
- **Year 2**
  - declarative PL design (type-and-effect system)
  - meta-theory (denotational and operational)
  - case studies and applications
- **Year 3**
  - algorithmic PL design (type-and-effect inference)
  - implementation
  - case studies and applications

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  - case studies

- **In parallel**
  - continue collaborations with the F* team
  - continue collaborations on container datatypes
  - forge new collaborations in Oxford (and elsewhere)

Conclusions

- **Software is everywhere!**
- **We had better know what it does!**

- **General and uniform frameworks already exist for values!**
- **But only scattered, effect-specific frameworks for behaviour!**

- **My research will seek to rectify this situation**
  - a uniform and widely applicable approach
  - inspired by algebraic effects and effect handlers
  - both foundational theory and exciting applications