

Recursion and F# translations

The INFDEV@HR Team

Hogeschool Rotterdam
Rotterdam, Netherlands

Recursion and
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translations

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Lecture topics

- Recursion (let-rec)
- F# translations of lambda programs so far

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Idea

- The lambda calculus has no `while` loops
- This means that we need to emulate them with recursion

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Idea

- This is a bit of an issue
- A function is just a lambda term, which does not have a name
- If the function does not have a name, how do we call it from its own body?

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Idea

- We can define a recursive function as a function with an extra parameter
- Calling the extra parameter will result in calling the function itself

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For example, the factorial function becomes

```
(λf n→if (n = 0) then 1 else ((f (n - 1)) ×  
n))
```


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- We now need an external operator that handles recursive functions properly
- This must ensure that a recursive function gets itself as a parameter, in an endless chain
- This combinator is known as `fixpoint` operator

$$(\lambda f \rightarrow ((\lambda x \rightarrow (f \ (x \ x))) \ (\lambda x \rightarrow (f \ (x \ x)))))$$

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```
((fix (λf n→if (n = 0) then 1 else (f (n - 1)
))) 2)
```

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```
((fix (λf n→if (n = 0) then 1 else (f (n - 1)) 2)) 2)
```

```
((fix (λf n→if (n = 0) then 1 else (f (n - 1)))) 2)
```

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((fix ( $\lambda f\ n \rightarrow$ if (n = 0) then 1 else (f (n - 1)))) 2)
```

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```
((fix ( $\lambda f\ n \rightarrow$ if (n = 0) then 1 else (f (n - 1)))) 2)
```

```
(( $\lambda n \rightarrow$ if (n = 0) then 1 else (... (n - 1)))  
2)
```

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```
((λn→if (n = 0) then 1 else (... (n - 1))) 2)
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```
((λn→if (n = 0) then 1 else (... (n - 1))) 2)
```

```
((λn→if (n = 0) then 1 else (... (n - 1))) 2)
```

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```


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```

```
if (2 = 0) then 1 else (... (2 - 1))
```

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if (2 = 0) then 1 else (... (2 - 1))
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if (2 = 0) then 1 else (... (2 - 1))
```

```
if (2 = 0) then 1 else (... (2 - 1))
```

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```

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```

```
if FALSE then 1 else (... (2 - 1))
```

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if FALSE then 1 else (... (2 - 1))
```

```
if FALSE then 1 else (... (2 - 1))
```

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```

```
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```

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```

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```
(... (2 - 1))
```

```
((fix ( $\lambda f\ n \rightarrow \text{if } (n = 0) \text{ then } 1 \text{ else } (f\ (n - 1))$ )) (2  
- 1))
```

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```
((fix ( $\lambda f\ n \rightarrow$  if (n = 0) then 1 else (f (n - 1)))) (2  
- 1))
```

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```
((fix ( $\lambda f\ n \rightarrow$ if (n = 0) then 1 else (f (n - 1)))) (2  
- 1))
```

```
(( $\lambda n \rightarrow$ if (n = 0) then 1 else (... (n - 1)))  
(2 - 1))
```

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- 1))
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((λn→if (n = 0) then 1 else (... (n - 1))) (2  
- 1))
```

```
((λn→if (n = 0) then 1 else (... (n - 1)))  
(2 - 1))
```

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```
((λn→if (n = 0) then 1 else (... (n - 1)))  
  (2 - 1))
```


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```
((λn→if (n = 0) then 1 else (... (n - 1)))  
  (2 - 1))
```

```
((λn→if (n = 0) then 1 else (... (n - 1)))  
  1)
```

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```
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```

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```

```
((λn→if (n = 0) then 1 else (... (n - 1))) 1)
```

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```

```
if (1 = 0) then 1 else (... (1 - 1))
```

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if (1 = 0) then 1 else (... (1 - 1))
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```
if FALSE then 1 else (... (1 - 1))
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if FALSE then 1 else (... (1 - 1))
```

```
if FALSE then 1 else (... (1 - 1))
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```

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```
(... (1 - 1))
```

```
((fix ( $\lambda f\ n \rightarrow \text{if } (n = 0) \text{ then } 1 \text{ else } (f\ (n - 1))$ ))) (1  
- 1))
```

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- 1))
```


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```
((fix ( $\lambda f n \rightarrow$ if (n = 0) then 1 else (f (n - 1)))) (1  
- 1))
```

```
(( $\lambda n \rightarrow$ if (n = 0) then 1 else (... (n - 1)))  
(1 - 1))
```

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- 1))
```

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((λn→if (n = 0) then 1 else (... (n - 1))) (1  
- 1))
```

```
((λn→if (n = 0) then 1 else (... (n - 1)))  
(1 - 1))
```

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  (1 - 1))
```

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```
((λn→if (n = 0) then 1 else (... (n - 1)))  
  (1 - 1))
```

```
((λn→if (n = 0) then 1 else (... (n - 1)))  
  0)
```

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((λn→if (n = 0) then 1 else (... (n - 1))) 0)
```

```
((λn→if (n = 0) then 1 else (... (n - 1))) 0)
```

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((λn→if (n = 0) then 1 else (... (n - 1))) 0)
```

```
if (0 = 0) then 1 else (... (0 - 1))
```

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if (0 = 0) then 1 else (... (0 - 1))
```

```
if (0 = 0) then 1 else (... (0 - 1))
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if (0 = 0) then 1 else (... (0 - 1))
```

```
if TRUE then 1 else (... (0 - 1))
```

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```

```
if TRUE then 1 else (... (0 - 1))
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if TRUE then 1 else (... (0 - 1))
```

```
1
```

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We can now try our hand at a factorial computation

```
((fix (λf n→if (n = 0) then 1 else ((f (n -  
1)) × n))) 2)
```

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```
((fix (λf n→if (n = 0) then 1 else ((f (n -  
1)) × n))) 2)
```

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```
((fix (λf n→if (n = 0) then 1 else ((f (n -  
1)) × n))) 2)
```

```
((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) 2)
```

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```
((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) 2)
```

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```
((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) 2)
```

```
((λn→if (n = 0) then 1 else ((... (n - 1)) ×  
  n)) 2)
```

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```
((λn→if (n = 0) then 1 else ((... (n - 1)) ×  
n)) 2)
```

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```
((λn→if (n = 0) then 1 else ((... (n - 1)) ×  
n)) 2)
```

```
(λn→ →if (n = 0) then 1 else ((... (n - 1)) × n)  
2)
```


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$$\frac{(\lambda n \rightarrow \text{if } (n = 0) \text{ then } 1 \text{ else } ((\dots (n - 1)) \times n))}{2})$$

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$$(\lambda n \rightarrow \rightarrow \text{if } (n = 0) \text{ then } 1 \text{ else } ((\dots (n - 1)) \times n) \underline{2})$$

```
if (2 = 0) then 1 else ((... (2 - 1)) × 2)
```

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```
if (2 = 0) then 1 else ((... (2 - 1)) × 2)
```

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```
if (2 = 0) then 1 else ((... (2 - 1)) × 2)
```

```
if (2 = 0) then 1 else ((... (2 - 1)) × 2)
```

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```
if (2 = 0) then 1 else ((... (2 - 1)) × 2)
```

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```
if (2 = 0) then 1 else ((... (2 - 1)) × 2)
```

```
if FALSE then 1 else ((... (2 - 1)) × 2)
```

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```
if FALSE then 1 else ((... (2 - 1)) × 2)
```

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```
if FALSE then 1 else ((... (2 - 1)) × 2)
```

```
if FALSE then 1 else ((... (2 - 1)) × 2)
```


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```
if FALSE then 1 else ((... (2 - 1)) × 2)
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```
if FALSE then 1 else ((... (2 - 1)) × 2)
```

```
((... (2 - 1)) × 2)
```

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$$((\dots (2 - 1)) \times 2)$$

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```
((... (2 - 1)) × 2)
```

```
(((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) (2 -  
  1)) × 2)
```

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((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) (2 -  
  1)) × 2)
```

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```
(((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) (2 -  
  1)) × 2)
```

```
(((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (2 - 1)) × 2)
```

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```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (2 - 1)) × 2)
```

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```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (2 - 1)) × 2)
```

```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (2 - 1)) × 2)
```


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```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (2 - 1)) × 2)
```

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```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (2 - 1)) × 2)
```

```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) 1) × 2)
```

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```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) 1) × 2)
```

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```
((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) 1) × 2)
```

```
((λn→ →if (n = 0) then 1 else ((... (n - 1)) × n)  
  1) × 2)
```

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$$((\lambda n \rightarrow \text{if } (n = 0) \text{ then } 1 \text{ else } ((\dots (n - 1)) \times n) \\ \underline{1}) \times 2)$$

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```
((λn→ if (n = 0) then 1 else ((... (n - 1)) × n)  
  1) × 2)
```

```
(if (1 = 0) then 1 else ((... (1 - 1)) × 1)  
  × 2)
```

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```
(if (1 = 0) then 1 else ((... (1 - 1)) × 1) × 2)
```

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```
(if (1 = 0) then 1 else ((... (1 - 1)) × 1) ×  
2)
```

```
(if (1 = 0) then 1 else ((... (1 - 1)) × 1) ×  
2)
```


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```
(if (1 = 0) then 1 else ((... (1 - 1)) × 1) ×  
2)
```

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```
(if (1 = 0) then 1 else ((... (1 - 1)) × 1) ×  
2)
```

```
(if FALSE then 1 else ((... (1 - 1)) × 1) ×  
2)
```

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```
(if FALSE then 1 else (... (1 - 1)) × 1) ×  
2)
```

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```
(if FALSE then 1 else ((... (1 - 1)) × 1) ×  
  2)
```

```
(if FALSE then 1 else ((... (1 - 1)) × 1) × 2)
```

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```
(if FALSE then 1 else ((... (1 - 1)) × 1) × 2)
```

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```
(if FALSE then 1 else ((... (1 - 1)) × 1) × 2)
```

```
( ((... (1 - 1)) × 1) × 2)
```

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$$(((\dots (1 - 1)) \times 1) \times 2)$$

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```
((... (1 - 1)) × 1) × 2)
```

```
((((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) (1 -  
  1)) × 1) × 2)
```


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```
((((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) (1 -  
  1)) × 1) × 2)
```

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```
((((fix λf→ n→  
  if (n = 0) then 1 else ((f (n - 1)) × n)) (1 -  
  1)) × 1) × 2)
```

```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (1 - 1)) × 1) × 2)
```

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```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
× n)) (1 - 1)) × 1) × 2)
```

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```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
× n)) (1 - 1)) × 1) × 2)
```

```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
× n)) (1 - 1)) × 1) × 2)
```

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```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) (1 - 1)) × 1) × 2)
```

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```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
× n)) (1 - 1)) × 1) × 2)
```

```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
× n)) 0) × 1) × 2)
```

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```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
× n)) 0) × 1) × 2)
```

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```
((((λn→if (n = 0) then 1 else ((... (n - 1))  
  × n)) 0) × 1) × 2)
```

```
((((λn→ →  
  if (n = 0) then 1 else ((... (n - 1)) × n) 0) ×  
  1) × 2)
```


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$$\begin{array}{l} (((\lambda n \rightarrow \rightarrow \\ \quad \underline{\text{if } (n = 0) \text{ then } 1 \text{ else } ((\dots (n - 1)) \times n) \ 0}) \times} \\ \quad 1) \times 2) \end{array}$$

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$$\frac{(((\lambda n \rightarrow \rightarrow$$
$$\text{if } (n = 0) \text{ then } 1 \text{ else } ((\dots (n - 1)) \times n) \ 0) \times$$
$$1) \times 2)$$
$$((\text{if } (0 = 0) \text{ then } 1 \text{ else } ((\dots (0 - 1)) \times$$
$$0) \times 1) \times 2)$$

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```
((if (0 = 0) then 1 else ((... (0 - 1)) × 0)
  × 1) × 2)
```

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```
((if (0 = 0) then 1 else ((... (0 - 1)) × 0) × 1) × 2)
```

```
((if (0 = 0) then 1 else ((... (0 - 1)) × 0) × 1) × 2)
```

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```
((if (0 = 0) then 1 else ((... (0 - 1)) × 0) ×  
1) × 2)
```

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```
((if (0 = 0) then 1 else ((... (0 - 1)) × 0) ×  
1) × 2)
```

```
((if TRUE then 1 else ((... (0 - 1)) × 0) ×  
1) × 2)
```

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```
((if TRUE then 1 else (... (0 - 1)) × 0) ×  
 1) × 2)
```

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```
((if TRUE then 1 else ((... (0 - 1)) × 0) ×  
1) × 2)
```

```
((if TRUE then 1 else ((... (0 - 1)) × 0) × 1) ×  
2)
```


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```
((if TRUE then 1 else ((... (0 - 1)) × 0) × 1) ×  
  2)
```

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```
((if TRUE then 1 else ((... (0 - 1)) × 0) × 1) ×  
 2)
```

```
((1 × 1) × 2)
```

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$$((1 \times 1) \times 2)$$

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$$((1 \times 1) \times 2)$$
$$((\underline{1 \times 1}) \times 2)$$

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$$((\underline{1 \times 1}) \times 2)$$

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$$((1 \times 1) \times 2)$$
$$(1 \times 2)$$

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$$(1 \times 2)$$

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(1×2)

(1×2)

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(1 × 2)

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(1 × 2)

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Overview

- Each and every one of the constructs we have seen so far has a direct translation in F#^a
- All constructs have exactly the same behaviour as in the lambda calculus, but with a slightly less mathematical syntax for ASCII keyboards
- A few operators are menemonically friendlier or just plain more readable, but the essence remains exactly the same
- F# is indentation-sensitive, like Python: pay a lot of attention to how terms are indented!

^aHaskell is a bit different, so we leave it for later

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Integers, booleans, floats, strings have the usual meaning, both in the lambda calculus, F#, and the languages you are used to:

```
((2 + 3) - 4)
```

```
(true && false)
```

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- Conditionals behave just like in the lambda calculus
- This means that they return the evaluation of either of the two branches
- This differs from imperative languages, where we just jump into either of the two branches

```
if (true && false) then  
    0  
else  
    1
```

Functions look very similar, with `fun` instead of λ

```
(fun x f -> (f x))
```

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Functions look very similar, with `fun` instead of λ

```
(fun x f -> (f x))
```

Just like function application

```
((fun x f -> (f x)) 3) (fun x -> (3 + x))
```


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We can give names to functions, and code becomes much prettier as a result

```
let apply =  
    fun x f -> (f x)  
((apply 3) (fun x -> (3 + x)))
```

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We can also give names to recursive functions by using `let rec` instead of `let`, and code becomes much more readable than with `fix`

```
let rec fact =  
    fun n ->  
        if (n = 0) then  
            1  
        else  
            ((fact (n - 1)) * n)  
  
(fact 2)
```

We can define tuples by just putting a comma between the values, with or without nesting for more than two values is done for us

```
(1, true)
```

Pairs

- Nested tuples are the same as in the lambda calculus, and of course they also work in F#
- They are, in essence, pairs of pairs, such as: $(1, (2, (3, 4)))$ or $(((1, 2), 3), 4)$, which are not the same
- Non-nested tuples are a slight extension for practical ease of work in F#
- They are, in essence, tuples with as many elements as we want, such as: $(1, 2, 3, 4)$
- All the examples in this slide are valid in F#, but are not identical objects

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- Functions such as π_1 and π_2 , which both extract one item of a pair, also exist in F#
- They are called, respectively, `fst` and `snd`

```
(fst (1, true))
```

```
(snd (1, true))
```

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- Of course F#, just like the lambda calculus, imposes no limitation on composition
- Why not build a tuple of functions, then? Why not indeed!

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- Of course F#, just like the lambda calculus, imposes no limitation on composition
- Why not build a tuple of functions, then? Why not indeed!

```
((fun x -> (1 + x)), (fun x -> (2 * x)))
```

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- Of course F#, just like the lambda calculus, imposes no limitation on composition
- Why not build a tuple of functions, then? Why not indeed!

```
((fun x -> (1 + x)), (fun x -> (2 * x)))
```

Could we also build a tuple of tuples of numbers and functions returning tuples of functions?

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- Of course F#, just like the lambda calculus, imposes no limitation on composition
- Why not build a tuple of functions, then? Why not indeed!

```
((fun x -> (1 + x)), (fun x -> (2 * x)))
```

Could we also build a tuple of tuples of numbers and functions returning tuples of functions?

Yes, but we are not going to do it :)

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- F# also offers built-in discriminated unions
- Functions such as `inl` and `inr`, which both embed one item into the union, also exist in F#
- They are called, respectively, `Choice10f2` and `Choice20f2`

```
(Choice10f2 1)
```

```
(Choice20f2 true)
```

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We can, of course, perform matches on discriminated unions

```
match (Choice10f2 1) with
| Choice10f2 x ->
    (Choice10f2 x)
| Choice20f2 y ->
    (Choice20f2 y)
```

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We can, of course, perform matches on discriminated unions

```
match (Choice10f2 1) with
| Choice10f2 x ->
    (Choice10f2 x)
| Choice20f2 y ->
    (Choice20f2 y)
```

```
let i =
    match (Choice10f2 1) with
    | Choice10f2 x ->
        x
    | Choice20f2 y ->
        0

(i * 2)
```

Discriminated unions, and their corresponding matches, can be nested as deep as we need

```
match (Choice10f2 (Choice20f2 true)) with
| Choice10f2 x ->
    match x with
    | Choice10f2 x ->
        (Choice10f2 x)
    | Choice20f2 y ->
        (Choice20f2 y)

| Choice20f2 y ->
    (Choice20f2 y)
```

Structural equality

- Composable data types make it possible for F# to build a series of useful functions automatically
- These functions allow automatic comparison of data structures with the same shape (for example, tuples with tuples or lists with lists)
- Comparison can work with values made up of primitive expressions, tuples, unions, lists, records, and any composition of them
- With the only exclusion of functions: functions, or composite values containing functions, may not be compared

Interoperability

- One of the practical strengths of F# is its ability to fully interoperate with the .Net framework
- Any feature or library available, even if written in other languages like C#, can be used from inside F#
- Moreover, any F# library can be used from other languages like C#
- This means that applications could be the internal logic in F#, and the UI and database store in C#

Interoperability

- For example, we can call functions such as `System.Console.WriteLine`, `System.Console.ReadLine`, `System.Int32.Parse`, etc.
- This gives a whole other dimension of usefulness to F#
- Ranging from games to web applications, the language knows no intrinsic limitation
- This also comes with full IDE, autocompletion, and debugger support in Visual Studio and a few other IDE's
- Scala is to some extent comparable

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Interoperability

A short F# demo might be in order

Forbidden features

- F# is a hybrid language
- It also contains OO features, mutability (variables), interfaces, classes, inheritance, etc.
- You may only use these features in the assignments if there is no alternative to access a library you need
- Mutability may only be used in the main program, which then calls regular functions that only use the lambda calculus derived core
- Failure to comply will result in an automatic insufficient grade

About types

- A major difference between F# and the lambda calculus is that F# is, in fact, a statically typed language
- Even though the language does not require type declarations like Java or C#, the compiler will still ensure that the types make sense
- This means that we will get compiler errors because we mix types
- Code like `fst 1` will not compile, for example, because `1` is not a pair and therefore `fst` cannot be applied to it
- We will cover the type system of F# in the next lecture

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Ways to exercise

- We have added a ton of F# homework, with solutions
- It is all on GitHub
- It is not mandatory, but it is a good idea to do it until you feel more sure
- You may discuss it during one of the two practicums

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Recap

- The lambda calculus can be translated, term to term, into F#
- F# is therefore just a practical lambda calculus with a series of handy extensions and slightly more readable

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The best of luck, and thanks for the attention!