

Chesskell: Modelling a Two-Player Game at the Type-Level

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Why do type systems exist?

Type systems exist because:

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Type systems exist because: we want to avoid errors.

(Cardelli, “Type systems”)

Type Errors

A type system can prevent certain errors from occurring at all:

```
not 5
```

The above will not compile, preventing an error.

Type Errors cont.

You have a website, where you sell books.

Type Errors cont.

You have a website, where you sell books.

For some reason, you use Java to build the server:

```
int noOfPages = -1;
```

This is obviously an error. But it compiles!

Recent developments to Haskell have focused on performing computation at the type level (Schrijvers et al., “Towards open type functions for Haskell”, Eisenberg et al., “Closed type families with overlapping equations”).

Haskell is NOT a dependently typed language; types and values are separated.

Type Erasure

In fact, Haskell programs undergo *type erasure*.

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```
x :: Int  
x = 3
```

Haskell type-level programming involves circumventing type erasure.

Complex Type-Level Computation

There are other attempts at rule enforcement, in Haskell, at the type level.

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Mezzo is an EDSL for musical composition, which can enforce classical harmony rules at the type level (Szamozvancev and Gale, “Well-typed music does not sound wrong (experience report)”).

Complex Type-Level Computation

There are other attempts at rule enforcement, in Haskell, at the type level.

Mezzo is an EDSL for musical composition, which can enforce classical harmony rules at the type level (Szamozvancev and Gale, “Well-typed music does not sound wrong (experience report)”).

BioShake is an EDSL for Bioinformatics workflows, whereby only workflows that are configured correctly will compile (Bedő, “BioShake: a Haskell EDSL for bioinformatics workflows”).

Why create Chesskell?

These capabilities are intended for use; and so must be tested through use.

What issues do we run into when implementing a complex rule set at the type level?

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What issues do we run into when implementing a complex rule set at the type level?

Is Haskell's type system mature enough for Chess?

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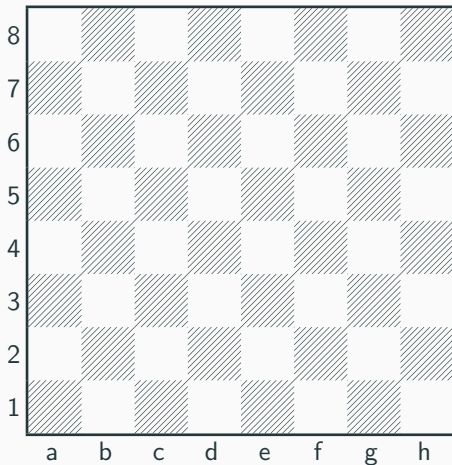
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- It's been widely studied in the field of Computer Science (Gusev, "Using Chess Programming in Computer Education.", Block et al., "Using reinforcement learning in chess engines");
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Why Chess?

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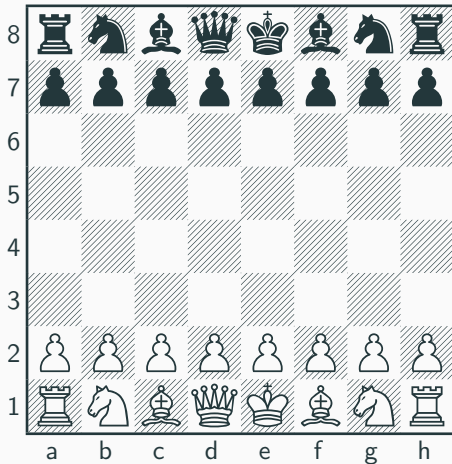
A note on Chess

A Chess game takes place on a board.



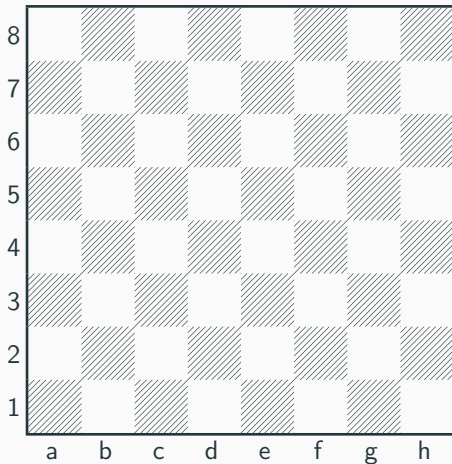
A note on Chess cont.

There are two *Teams*; Black and White.



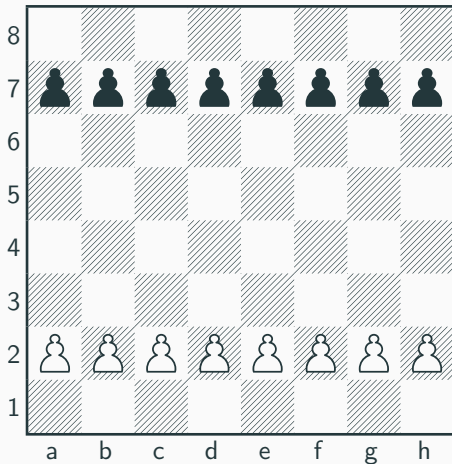
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Each Team has 16 *Pieces*; 8 Pawns, 2 Rooks, 2 Bishops, 2 Knights, a Queen, and a King.



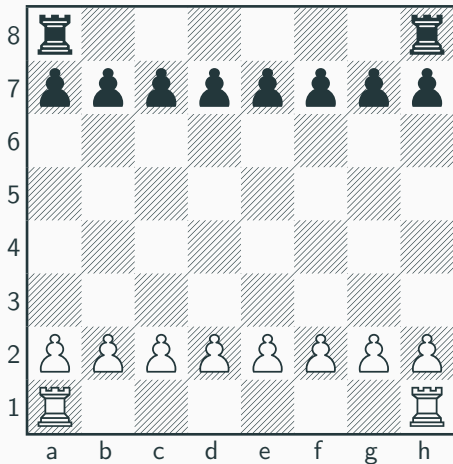
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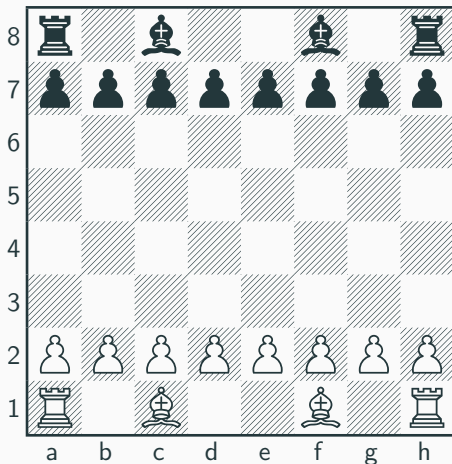
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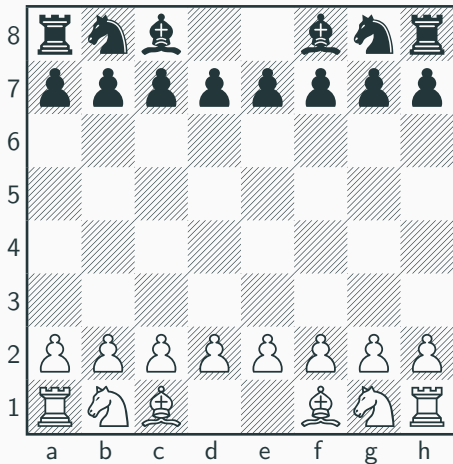
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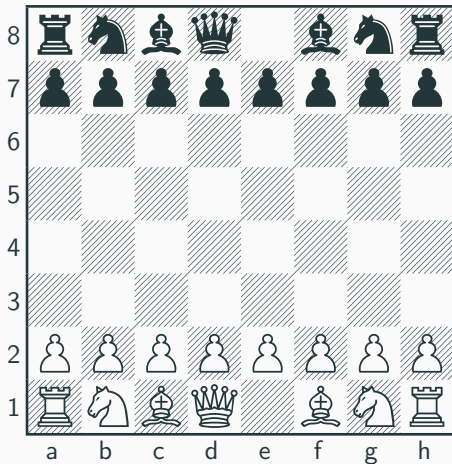
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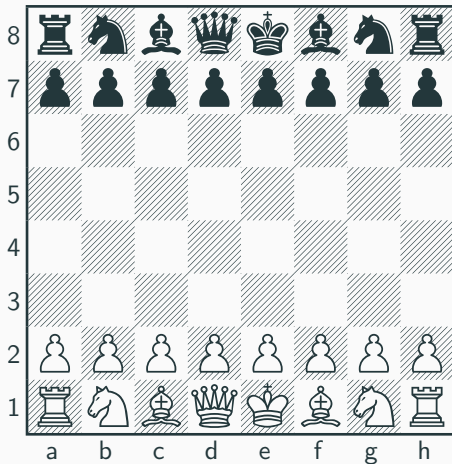
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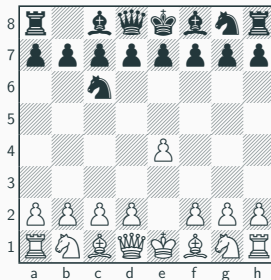
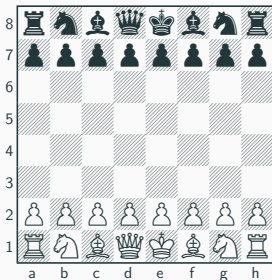
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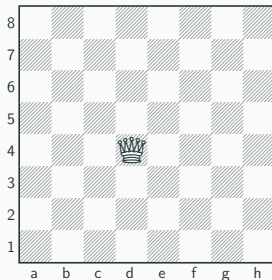
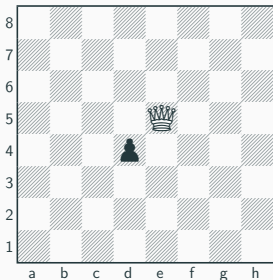
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Each piece has different movement rules, allowing them to move around the 8x8 board.



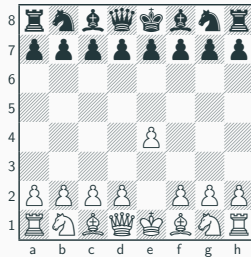
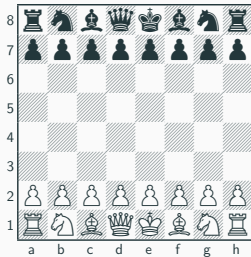
A note on Chess cont.

Pieces can remove other pieces from the board via *capture*; which almost always involves moving to the other piece's square.



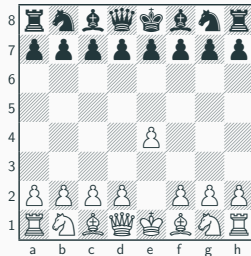
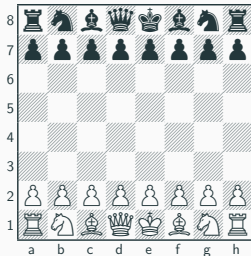
A Short Example

Below is a valid move by a White Pawn:



A Short Example

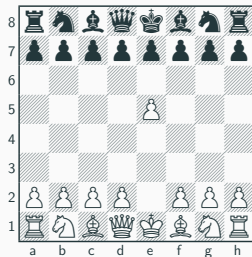
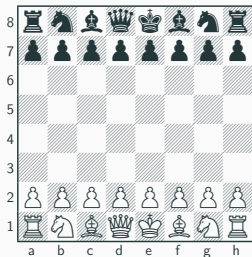
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```
chess
  pawn e2 to e4
end
```

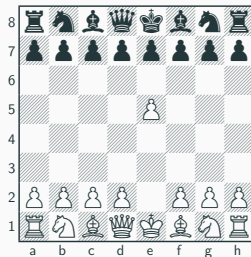
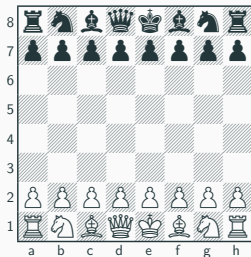
A Short Example cont.

Below is an *invalid* move by a White Pawn:



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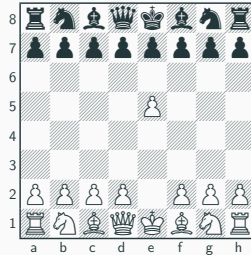
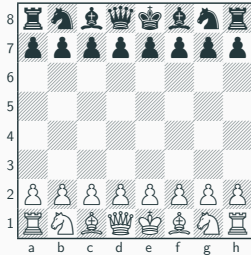
Below is an *invalid* move by a White Pawn:



```
chess
    pawn e2 to e5
end
```

A Short Example cont.

Below is an *invalid* move by a White Pawn:



```
-- Fails to compile with type error:  
--      * There is no valid move from E2 to E5.  
--      The Pawn at E2 can move to: E3, E4  
chess  
    pawn e2 to e5  
end
```

A Little Terminology

In Haskell, values have *types*, and types have *kinds*.

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```
data Book = Fiction | NonFiction
```

With the extension, this creates the values `Fiction` and `NonFiction` of type `Book`, and also the *types* `'Fiction` and `'NonFiction` of kind `Book`.

A Little Terminology cont.

In Haskell, you compute on values with *functions*.

```
factorial :: Int -> Int
factorial 0 = 1
factorial x = x * factorial (x - 1)
```

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factorial :: Int -> Int
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But you have to use *type families* to compute on types (Schrijvers et al., “Towards open type functions for Haskell”, Eisenberg et al., “Closed type families with overlapping equations”).

```
type family Factorial (x :: Nat) :: Nat where
  Factorial 0 = 1
  Factorial x = Mult x (Factorial (x - 1))

type family Mult (x :: Nat) (y :: Nat) :: Nat where
  Mult 0 y = 0
  Mult 1 y = y
  Mult x y = y + (Mult (x - 1) y)
```

Problems with Type Families?

Lots of idiomatic Haskell code relies on functions being *first-class*; partial application, mapping, etc.

```
x = map (+ 2) [1,2,3]
```


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```
x = map (+ 2) [1,2,3]
```

But type families can't be partially applied!

```
-- Type error: type family (+) was expecting 2
-- arguments, got 1
type X = Map (+ 2) '[1,2,3]
```

Introducing First Class Families

Thanks to Li-yao Xia, we have First Class Families!

It relies on a data type `Exp`, and a type family `Eval`, to create a type-level interpreter:

```
type Exp a = a -> *  
type family Eval (e :: Exp a) :: a
```

Making a First Class Family

```
type family And (x :: Bool) (y :: Bool) :: Bool where
  And True  True  = True
  And True  False = False
  And False True  = False
  And False False = False
```

becomes:

```
data And :: Bool -> Bool -> Exp Bool
type instance Eval (And True  True)  = True
type instance Eval (And True  False) = False
type instance Eval (And False True)  = False
type instance Eval (And False False) = False
```

Creating the Types for Chess

Using promotion (as we explain earlier), we define appropriate types for use with type families in Chess. We give some examples below, in both regular and GADT (Peyton Jones et al., “Simple unification-based type inference for GADTs”) syntax:

```
data Team = Black | White
```

```
data PieceInfo where
```

```
    Info :: Nat -> Position -> PieceInfo
```

```
data Piece where
```

```
    MkPiece :: Team -> PieceName -> PieceInfo -> Piece
```

The Board type

To avoid repeated length checks, we use *length-indexed vectors* with a type-level implementation of Peano natural numbers:

```
data Vec (n :: Nat) (a :: Type) where
  VEnd    :: Vec Z a
  (:->)   :: a -> Vec n a -> Vec (S n) a
```

Since a Chess board is always an 8x8 grid, we use vectors of vectors:

```
type Eight = (S (S (S (S (S (S (S (S Z))))))))
type Row   = Vec Eight (Maybe Piece)
type Board = Vec Eight Row
```

The BoardDecorator type

In the codebase, we use a wrapper data structure to hold helpful information along with the Board for rule checking:

```
data BoardDecorator where
  Dec :: Board
        -> Team
        -> Position
        -> (Position, Position)
        -> Nat
        -> BoardDecorator
```

Representing Movement

Movement is expressed as a single First Class Family:

```
data Move :: Position -> Position -> BoardDecorator  
    -> Exp BoardDecorator
```

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```

Thanks to First Class Families, we can extend this with rule-checking naturally; using a type-level version of the function composition operator, (.):

```
PostMoveCheck2 . PostMoveCheck1 . Move fromPos toPos  
    . PreMoveCheck2 . PreMoveCheck1
```


Interacting with Type-Level model at the value level

The core idea is wrapping the BoardDecorator type in a Proxy, so that it can be passed around within a value by functions:

```
data Proxy a = Proxy

edslMove :: SPosition from
         -> SPosition to
         -> Proxy (b :: BoardDecorator)
         -> Proxy (Eval (Move from to b))
edslMove (x :: SPosition from) (y :: SPosition to) (z
  :: Proxy (b :: BoardDecorator))
  = Proxy @(Eval (Move from to b))
```

But this would still look similar to Haskell syntax; we need a new approach.

Ideally, the EDSL should look like existing chess notation:

```
1. e4 e5 2. Nf3 Nc6 3. Bb5 a6
```

Can achieve using Continuation Passing Style, inspired by Dima Szamozvancev's Flat Builders work (Szamozvancev, "Well-typed music does not sound wrong").

Making continuations for Chess

The core continuations are `chess`, the piece continuations, and `to`:

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```
type Spec t = forall m. (t -> m) -> m

chess :: Spec (Proxy StartDec)
chess cont = cont (Proxy @StartDec)
```

Making continuations for Chess

The core continuations are chess, the piece continuations, and to:

```
data MoveArgs where
  MA :: BoardDecorator
      -> Position
      -> PieceName
      -> Position
      -> MoveArgs

pawn :: Proxy (b :: BoardDecorator)
      -> SPosition fromPos
      -> Spec (Proxy (MA b fromPos 'Pawn))
pawn (dec :: Proxy b) (from :: SPosition fromPos) cont
  = cont (Proxy @(MA b fromPos Pawn))
```

Making continuations for Chess

The core continuations are chess, the piece continuations, and to:

```
to :: Proxy (MA (b :: BoardDecorator) (fromPos ::  
    Position) (n :: PieceName))  
    -> SPosition toPos  
    -> Spec (Proxy (Eval (MoveWithStateCheck n fromPos  
        toPos b)))  
to (args :: Proxy (MA (b :: BoardDecorator) (fromPos  
    :: Position) (n :: PieceName))) (to' :: SPosition  
    toPos) cont  
    = cont (Proxy @(Eval (MoveWithStateCheck n  
        fromPos toPos b)))
```

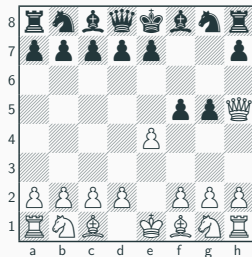
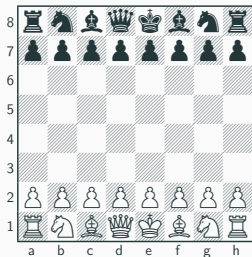
Using the Chess continuations

All of the above continuations can be chained together (along with `end` which ends the continuation stream) like so:

```
game = chess pawn a1 to a2 end
```

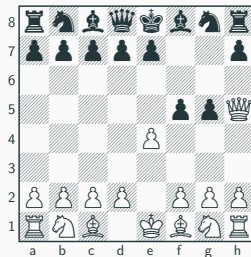
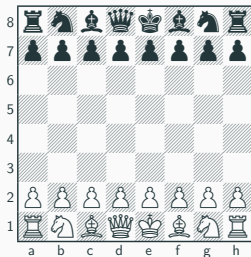
A Longer Example

Below is a short game, ending in checkmate by White:



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```
game = chess
    pawn e2 to e4
    pawn f7 to f5
    queen d1 to f3
    pawn g7 to g5
    queen f3 to h5
end
```

A Longer Example

What about a piece trying to move after Checkmate, when the game ends?

```
game = chess
  pawn e2 to e4
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  pawn g7 to g5
  queen f3 to h5
  pawn g5 to g4
end
```

A Longer Example

What about a piece trying to move after Checkmate, when the game ends?

```
-- Below results in the following type error:  
-- * The Black King is in check after a Black  
  move. This is not allowed.  
-- * When checking the inferred type  
--      game :: Data.Proxy.Proxy (TypeError ...)  
game = chess  
  pawn e2 to e4  
  pawn f7 to f5  
  queen d1 to f3  
  pawn g7 to g5  
  queen f3 to h5  
  pawn g5 to g4  
end
```

A Longer Example cont.

What about if the White Queen tries to move through another piece, mid-game?

```
game = chess
  pawn e2 to e4
  pawn f7 to f5
  queen d1 to d3  -- Invalid move
  pawn g7 to g5
  queen f3 to h5
end
```

A Longer Example cont.

What about if the White Queen tries to move through another piece, mid-game?

```
-- Below results in the following type error:
-- * There is no valid move from D1 to D3.
-- The Queen at D1 can move to: E2, F3, G4, H5,
...
-- * When checking the inferred type
-- game :: Data.Proxy.Proxy (...)
game = chess
  pawn e2 to e4
  pawn f7 to f5
  queen d1 to d3  -- Invalid move
  pawn g7 to g5
  queen f3 to h5
end
```

A Longer Short Example

We also developed a shorthand syntax!

The below game:

```
game = chess
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  pawn f7 to f5
  queen d1 to f3
  pawn g7 to g5
  queen f3 to h5
end
```

becomes:

```
game = chess
  p e4 p f5
  q f3 p g5
  q h5
end
```

Combination of:

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- Unit testing with assertions, based on whether a code snippet compiles or fails to compile;
- EDSL testing with famous Chess games, written out in Chesskell notation.

Compile-time and memory issues

Compile-time and memory issues came up time and again throughout development; putting a hard limit on the length of Chesskell games.

With some games, GHC will run out of memory ($>25\text{GB}$) and crash.

Through testing, it seems the upper limit is **12 moves maximum**; while all 6-move games tested have compiled, most 8- and 10-move games do as well.

Further Work

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- More domains could be modelled at the type level, not just Chess;
- A session-typed version of Chesskell;
- Further optimisations to try and increase the move limit;
- An automated tool to transform from Algebraic Notation into Chesskell notation.

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- Interesting findings on compile-time and memory usage issues.

Conclusions

We have created:

- A full type-level model of Chess, which enforces all rules in the FIDE 2018 Laws of Chess;
- An EDSL for describing Chess games and creating custom chess boards, which uses the type-level model for rule-checking;
- Interesting findings on compile-time and memory usage issues.

Furthermore, Chesskell is unique and has never been done before. Though there is room for further work and improvement, Chesskell is a success!

References



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Brent A Yorgey et al. “Giving Haskell a promotion”. In: *Proceedings of the 8th ACM SIGPLAN workshop on Types in language design and implementation*. 2012, pp. 53–66.

Demo

Q&A