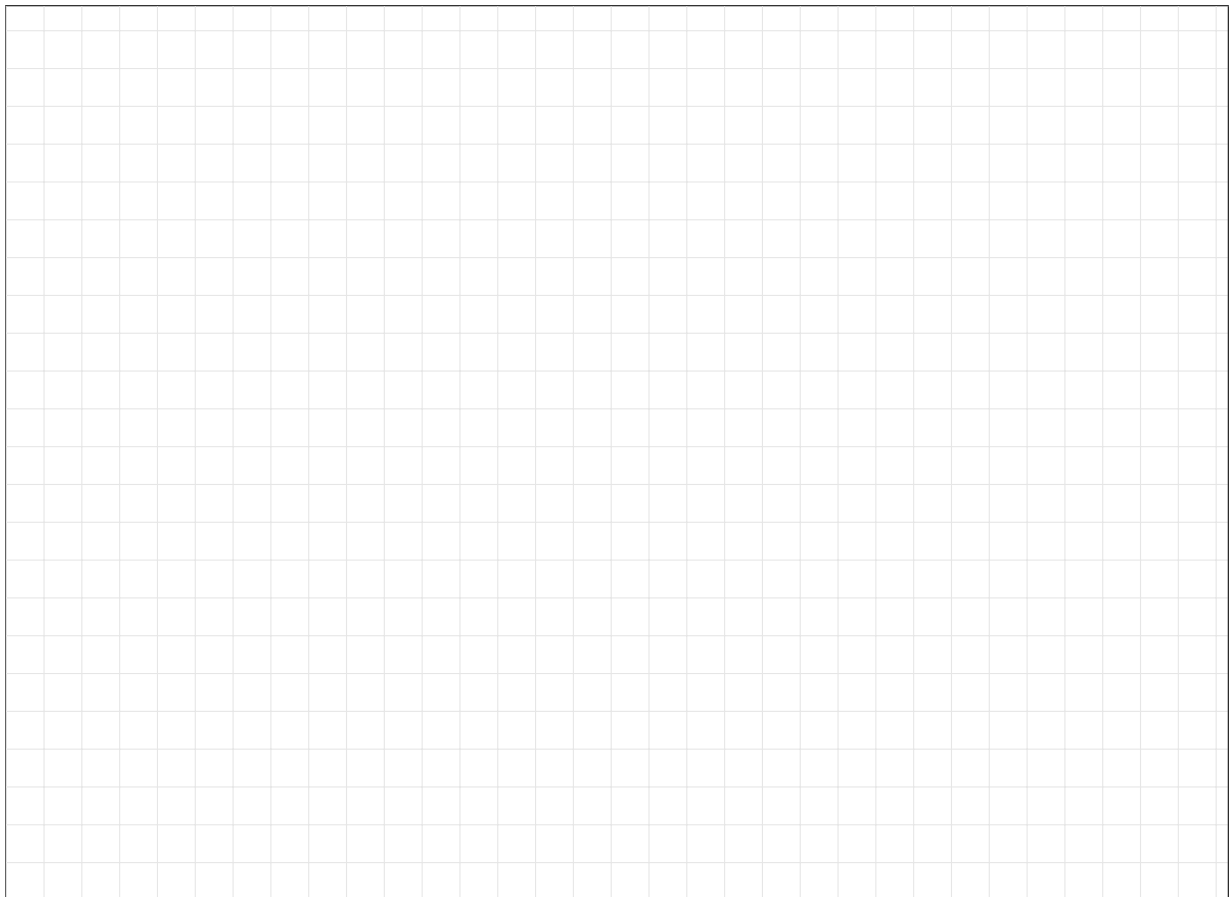


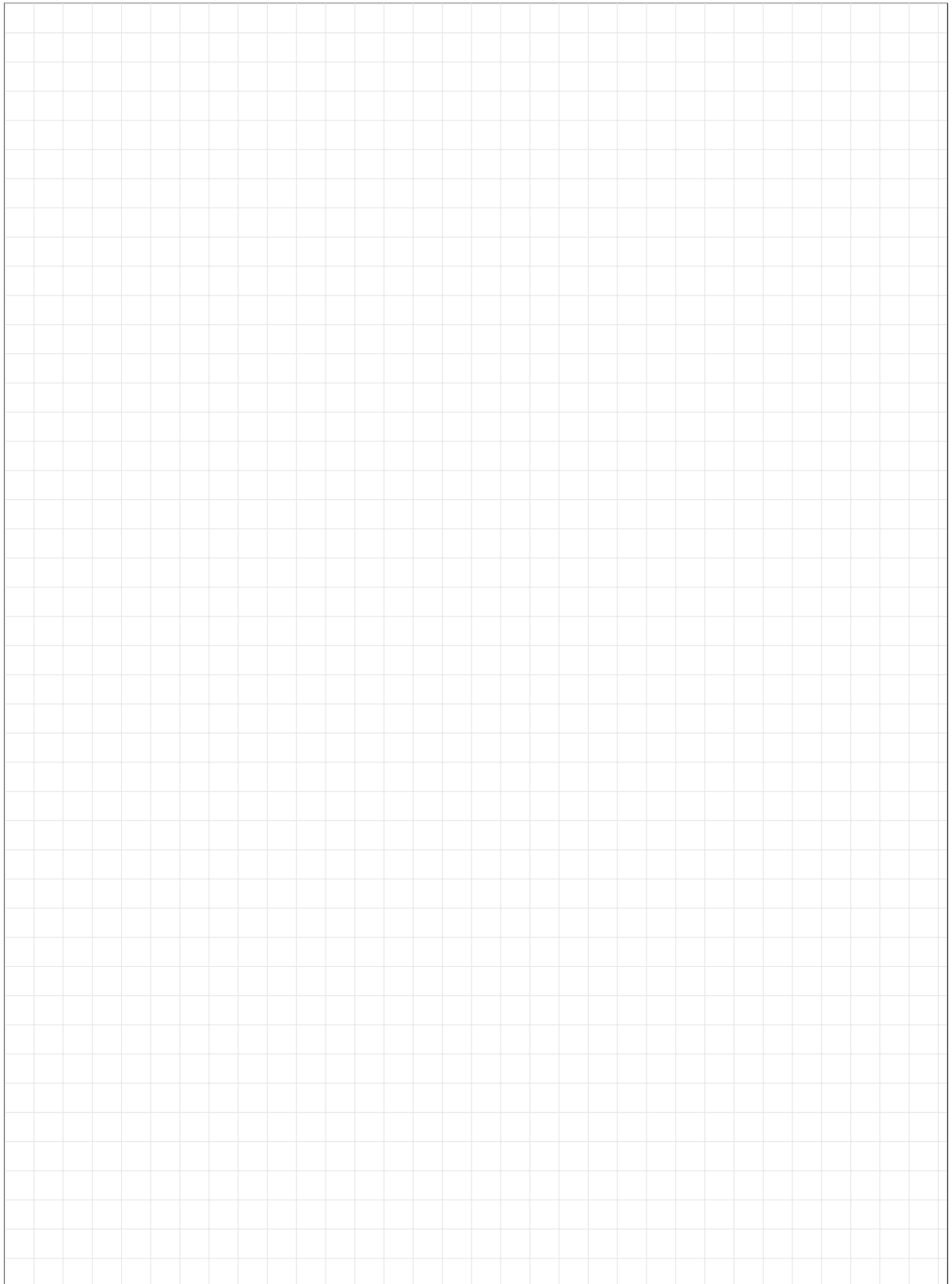
Exercise 1 (Reduction Relation with Closures)

For the evaluation of lambda terms that is closer to evaluation of programs in functional programming languages, one usually replaces textual substitution $t[v/x]$ with a more lazy approach that records the binding $x \mapsto v$ in an environment. These bindings are used whenever we need the value of a variable v .

In this approach abstractions $\lambda x. t$ do not evaluate to themselves, but to a pair $(\lambda x. t)[e]$, where e is the current environment. We call such pairs function *closures*.

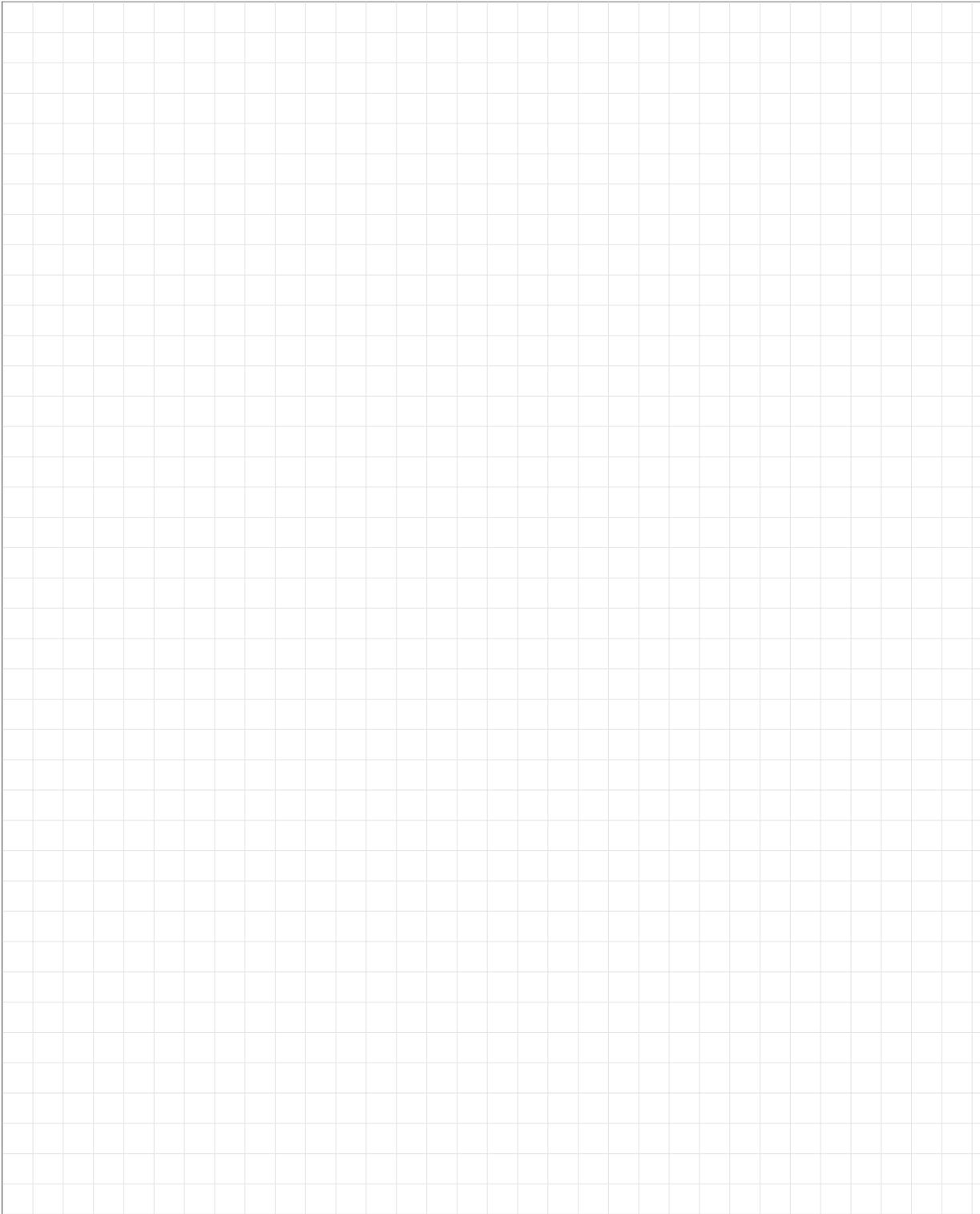
- a) Define a big-step reduction relation for the lambda calculus with function closures and environments.
- b) Add explicit error handling for the case where the binding of a free variable v cannot be found in the environment. Introduce an explicit value **abort** to indicate such an exception in the relation.





Exercise 2 (Better Translation Algorithm)

Give a variant of the translation algorithm that produces shorter terms. More specifically, define a variant of $\lambda^*x. t$ that analyzes more precisely where x actually appears in t .



Homework 3 (Proofs with Small-steps and Big-steps)

Let $\omega := \lambda x. x x$ and

$$t := (\lambda x. (\lambda x y. x) z y) (\omega \omega ((\lambda x y. x) y)).$$

Prove the following:

- a) $t \Rightarrow_n z$
- b) $t \rightarrow_{cbv}^3 t$
- c) $t \not\rightarrow_{cbn}^+ t$

Homework 4 (More Combinators)

Find combinators O and W such that:

$$\begin{aligned} O &\rightarrow^+ O \\ W X Y &\rightarrow^* X Y Y \end{aligned}$$

Homework 5 (Mocking Birds)

Consider a combinatory logic that only provides the basic combinators B and M (the “mocking bird”) where:

$$\begin{aligned} B X Y Z &\rightarrow^* X (Y Z) \\ M X &\rightarrow^* X X \end{aligned}$$

Prove the following properties of this logic:

- a) For every combinator X , there is a combinator Y such that $Y \rightarrow^* X Y$.
- b) For all combinators U and W , there exist combinators X and Y such that $Y \rightarrow^* U X$ and $X \rightarrow^* W Y$.

Homework 6 (Correctness of the Translation Algorithm)

Show that the translation algorithm given in the tutorial is correct. That is, show that it fulfills the following property:

$$(\lambda^* x. X) Y \rightarrow^* X[Y/x]$$