

Research Achievements of SC Structure
And
Strength Evaluation of US-APWR SC Structure
Based on 1/10th Scale Test Results

Non Proprietary Version

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Revision History

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Abstract

The purpose of this technical report is to present the research achievements for SC structure and the strength evaluation of SC structure of the US-APWR standard plant.

This report describes:

- Research achievements for SC structure
- Strength evaluation of US-APWR SC structure the evaluation results are as follows;
Comparison of the typical dimensions
Comparison of sectional property
Comparison of ultimate strength of SC module
Safety margin against the design forces applied on SC modules which comprise the US-APWR CIS
- Conclusion

Table of Contents

List of Tables	ii
List of Figures	ii
1.0 INTRODUCTION	1
2.0 RESEARCH ACHIEVEMENTS FOR SC STRUCTURE	2
2.1 Outline of SC Structure and Research History	2
2.2 Overview of Research Achievements for SC Structure	4
3.0 STRENGTH EVALUATION OF US-APWR SC MODULES	14
3.1 Methodology of the Evaluations	14
3.2 Evaluation Results	15
3.2.1 Comparison of Typical Dimensions	15
3.2.2 Comparison of Sectional Properties	21
3.2.3 Comparison of Ultimate Strength of SC Wall Members	24
3.2.4 Safety Margin Against the Design Applied Forces of US-APWR CIS	26
4.0 CONCLUSION	31
APPENDIX REPORTS OF RESEARCH ACHIEVEMENTS	

List of Tables

Table 2-1	Research History of SC Structure	3
Table 3-1	Comparison of Dimensions	16
Table 3-2	Comparison of Sectional Properties	22
Table 3-3	Material Properties of SC Modules	24
Table 3-4	Comparison of SC Wall Member Strengths	25
Table 3-5	Margin for Design Force of the US-APWR (1)	29
Table 3-6	Estimated Ultimate Capacity of Modules in the US-APWR CIS	30
Table 3-7	Margin for Design Force of the US-APWR (2)	30

List of Figures (1/2)

Figure 2-1	Outline of SC Module	2
Figure 2-2	Load Relative Rotation Angle Relationship	4
Figure 2-3	Specimen (BS70T10)	5
Figure 2-4	Relation of Load and Deformation (BS70T10)	5
Figure 2-5	Finite Element Model	6
Figure 2-6	Relation of Load and Rotation Angle	6
Figure 2-7	Experimental Equipment and Displacement Measuring Point	7
Figure 2-8	Result of Axial Deformation	7
Figure 2-9	Relation of Shear Force and Shear Strain	8
Figure 2-10	Cracking Propagation (CA)	9
Figure 2-11	Relation of b/t and Buckling Strain	9
Figure 2-12	Loading Method	10
Figure 2-13	Relation of Load and Displacement	10
Figure 2-14	A Sample of SC Design Recommendation	11
Figure 2-15	Loading System of Pure Shear Force	12

List of Figures (2/2)

Figure 2-16	Specimens of SC, Half SC and RC	13
Figure 2-17	Cracking of SC, Half SC and RC	13
Figure 3-1	Comparison of Dimensions	16
Figure 3-2	Plan of SC Modules for US-APWR CIS	17
Figure 3-3	Section of SC Modules for US-APWR CIS	18
Figure 3-4	SC Module Plan of 1/10 th Scale Model	19
Figure 3-5	SC Module Section of 1/10 th Scale Model	20
Figure 3-6	Comparison of Sectional Properties	22
Figure 3-7	Overview Plan of US-APWR	23
Figure 3-8	Overview Plan of 1/10 th Scale Model	23
Figure 3-9	Overview of SC Modules Wall Member	25
Figure 3-10	Comparison of SC Wall Member Strengths	25
Figure 3-11	Load-Displacement Curve of 1/10 th Scale Model	27
Figure 3-12	Distribution of Design Shear Force and Bending Moment for the US-APWR	28
Figure 3-13	Margin for Design Forces of the US-APWR	29

1.0 INTRODUCTION

Currently, design codes for steel-concrete (SC) structures are available in Japan as “Technical Code for Seismic Design of Steel Plate Reinforced Concrete Structures (JEAC 4618-2009)”. Similar codes or guidelines specifically applied to SC Structures are not currently available in the United States (US). However, it is known that US design codes or guidelines are under preparation, and will be codified by US standards in the future.

A SC structure is typically constructed of multiple SC Modules. In the case of the US-APWR, the containment internal structure (CIS) is designed as a SC structure utilizing several SC modules. In SC structure research, the CIS was also referred to as the inner concrete structure. Since there are no specific US design codes applicable to SC modules, the SC modules are conservatively designed utilizing criteria based on ACI-349 requirements for conventional reinforced concrete structures.

The amended response (MHI Letter UAP-HF-09449 dated September 17, 2009) to RAI 322-1999 regarding the SC modules in the CIS discussed in Design Control Document (DCD) Subsection 3.8.3 also addresses the soundness of SC modules under accident and fire events.

This report first introduces the 10 research achievements of SC structures presented in the amended response to RAI 322-1999. In addition, this report confirms that the SC modules have sufficient capacity and safety allowance to applied loads when designed using criteria based on ACI-349, based on the experimental results obtained by the static load tests of a 1/10th scale model of SC structures conducted by MHI in the past.

2.0 RESEARCH ACHIEVEMENTS FOR SC STRUCTURE

2.1 Outline of SC Structure and Research History

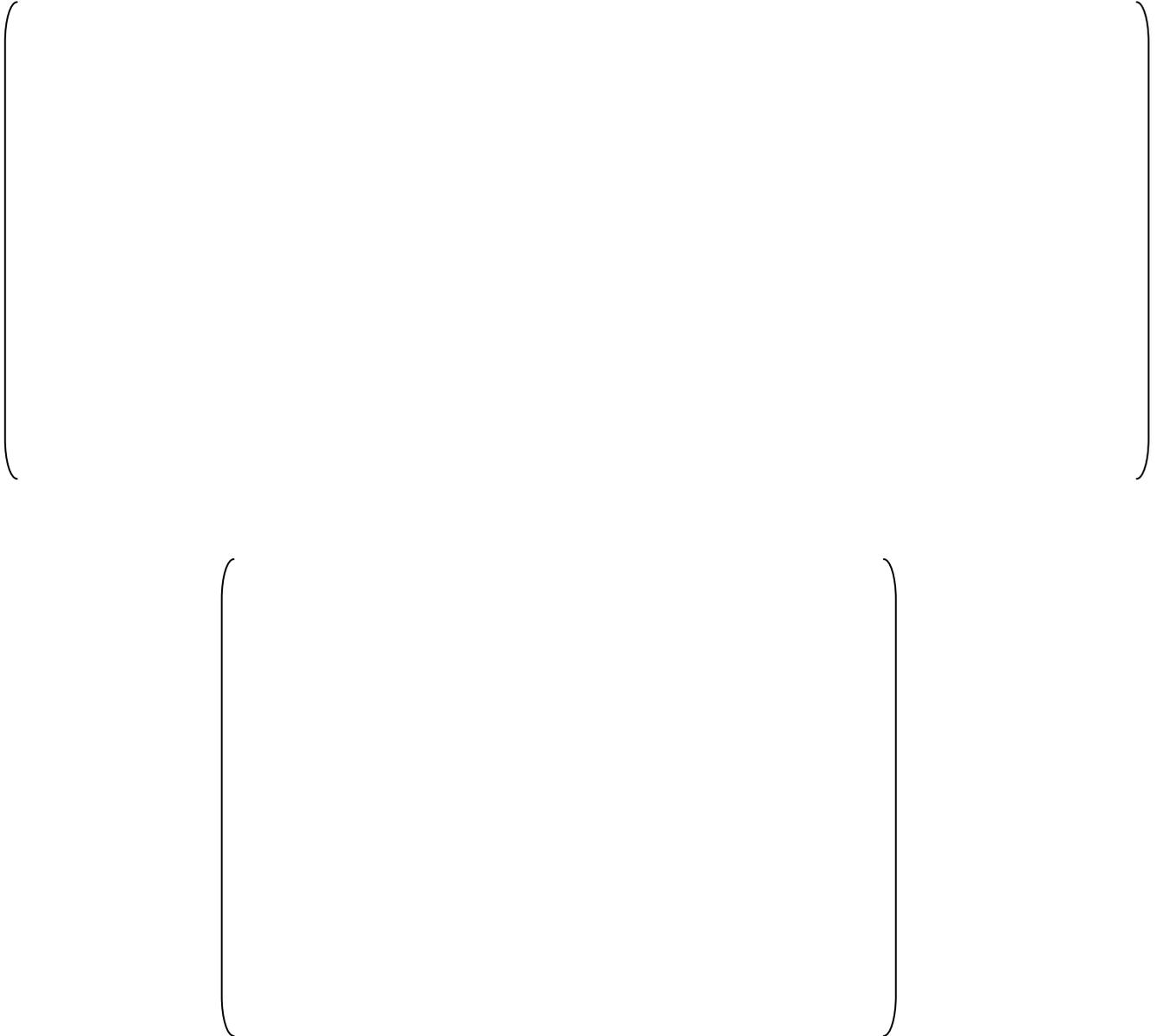


Figure 2-1 Outline of SC Module



Table 2-1 Research History of SC Structure



2.2 Overview of Research Achievements for SC Structure

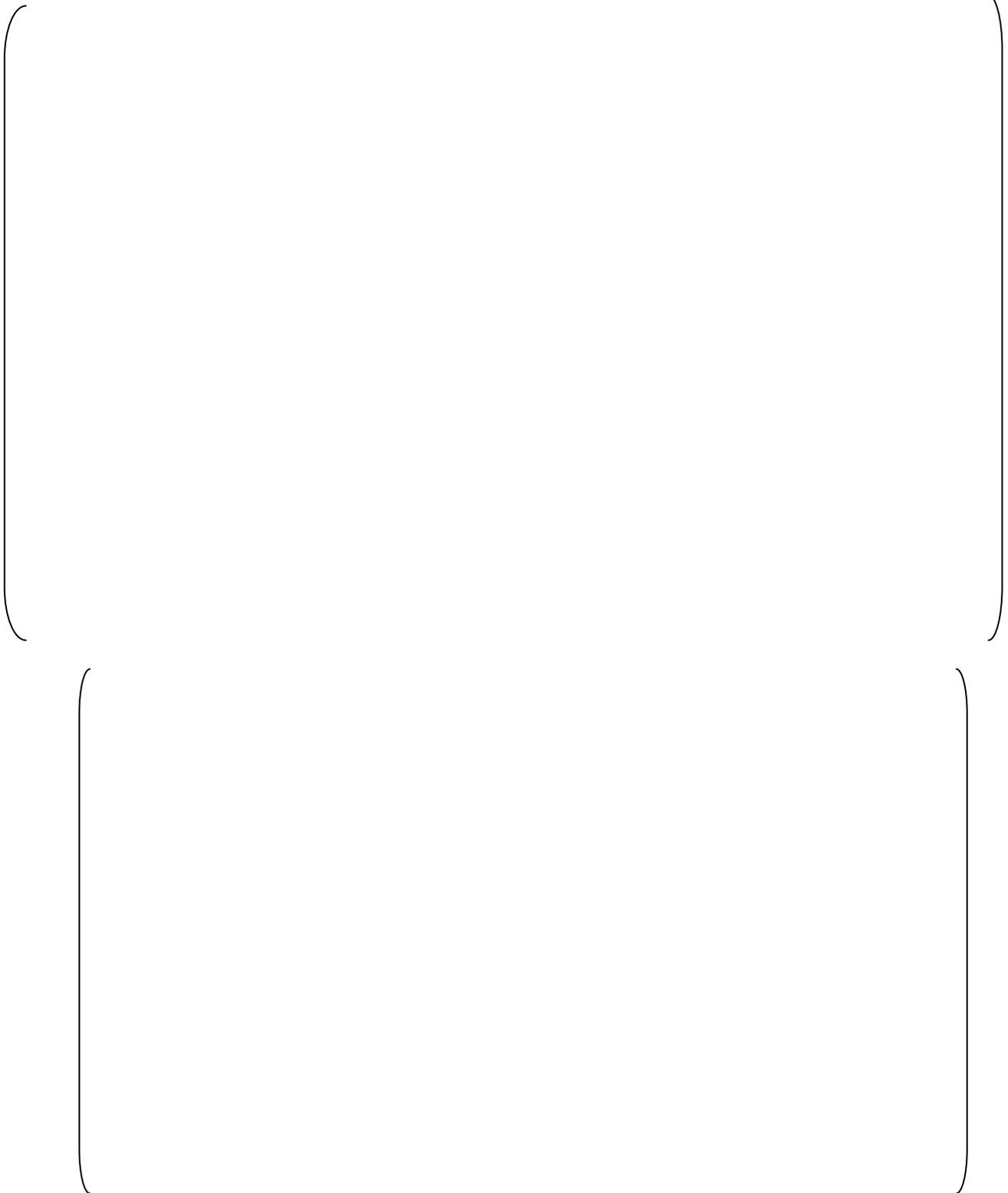


Figure 2-2 Load Relative Rotation Angle Relationship



Figure 2-3 Specimen (BS70T10)

**Figure 2-4 Relation of Load and Deformation
(BS70T10)**



Figure 2-5 Finite Element Model



Figure 2-6 Relationship of Load and Rotation angle



**Figure 2-7 Experimental
Equipment and Displacement
Measuring Point**

Figure 2-8 Result of Axial Deformation

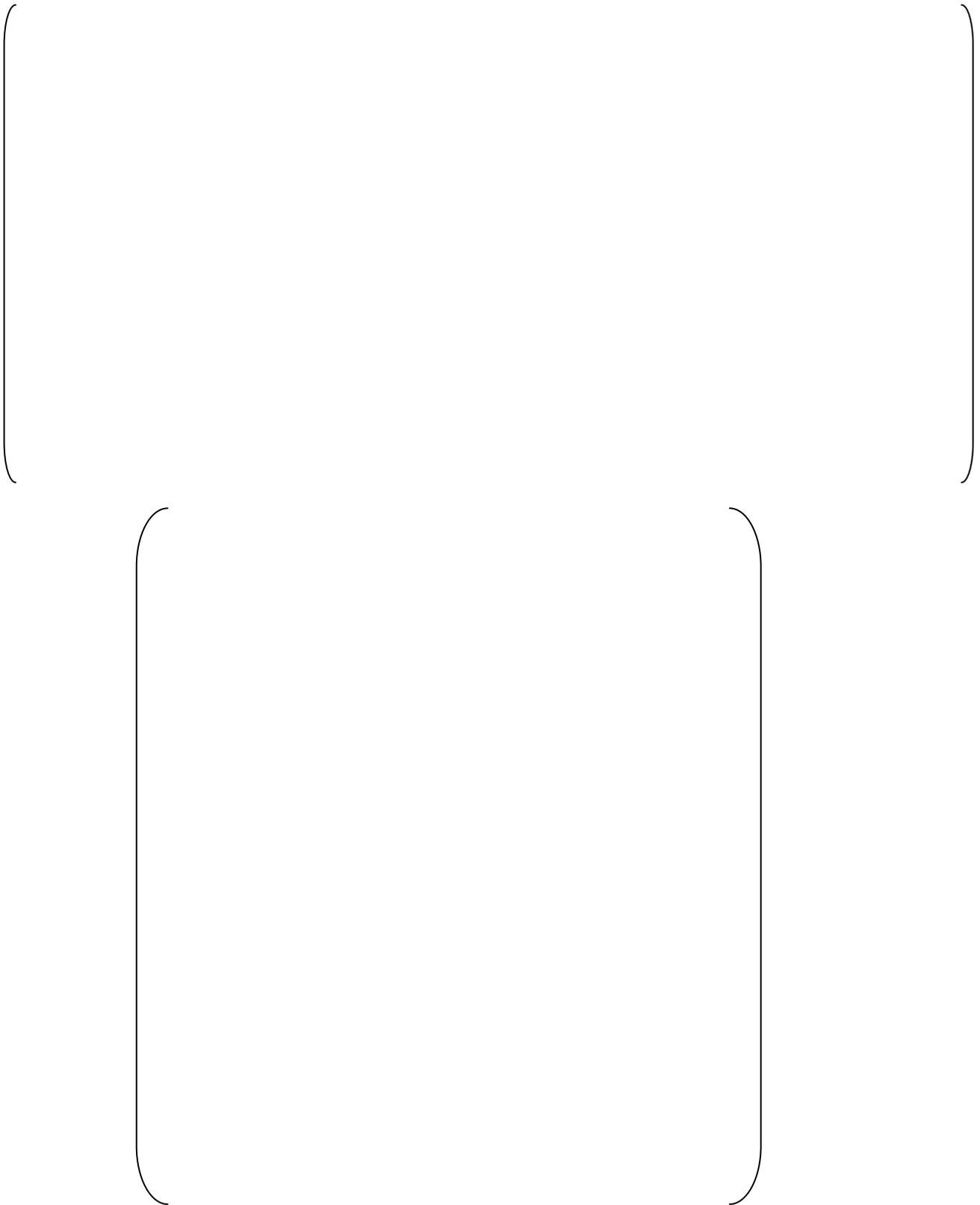


Figure 2-9 Relation of Shear Force and Shear Strain



Figure 2-10 Crack Propagation (CA)



Figure 2-11 Relation of b/t and Buckling Strain



Figure 2-12 Loading Method



Figure 2-13 Relation of Load and Displacement

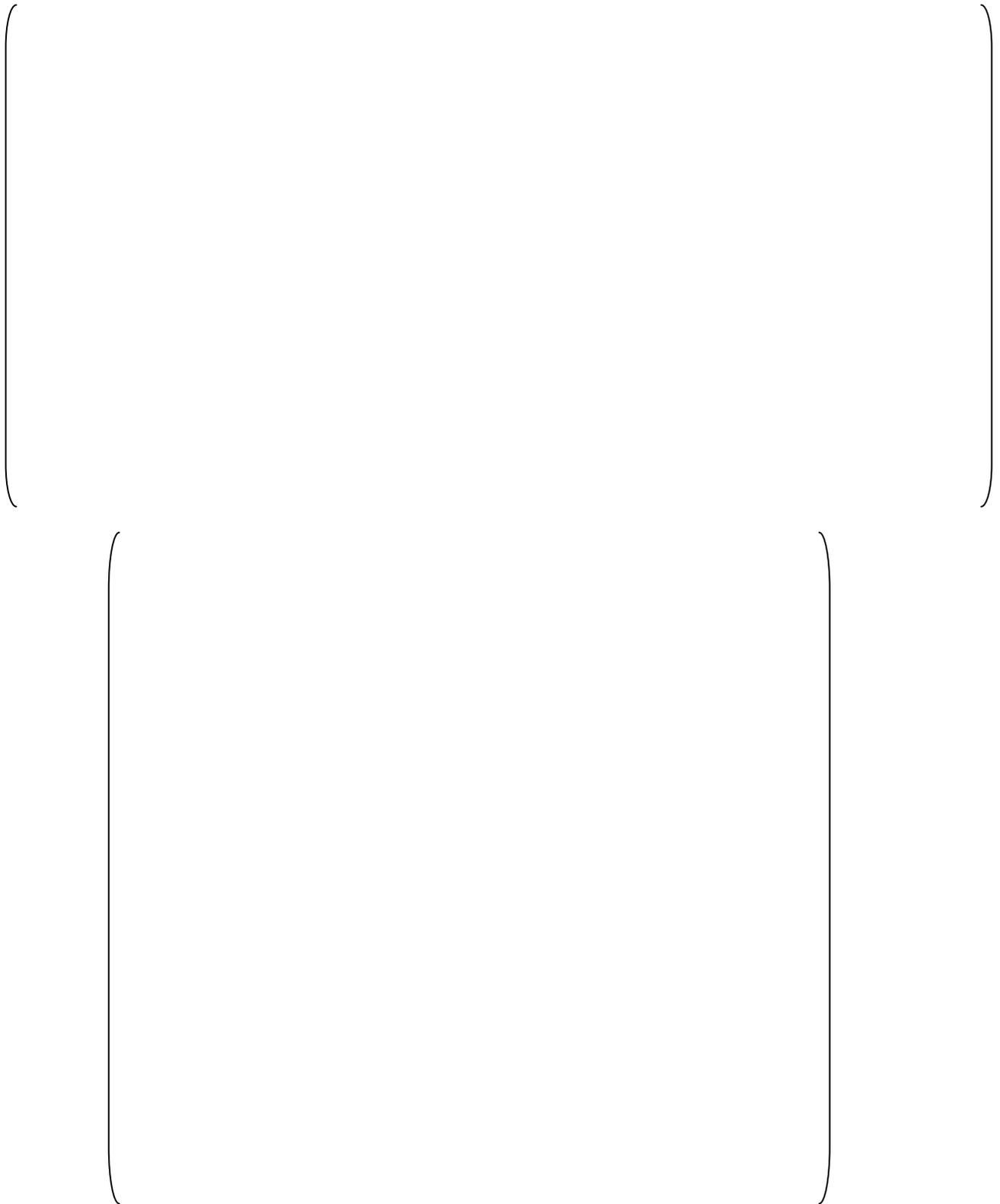


Figure 2-14 A Sample of SC Design Recommendation

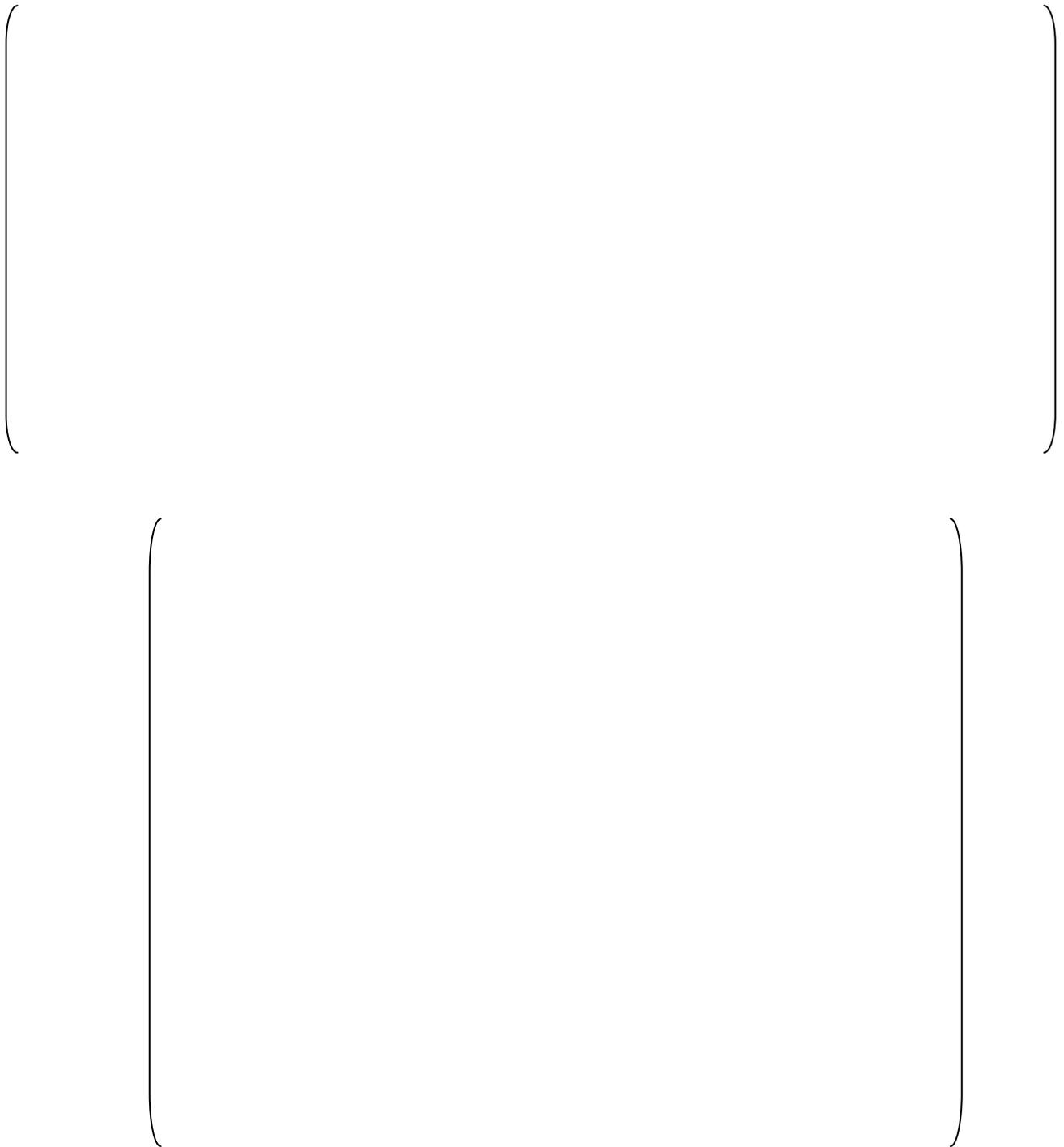


Figure 2-15 Loading System of Pure Shear Force



Figure 2-16 Specimens of SC, Half SC and RC



Figure 2-17 Cracking of SC, Half SC and RC

3.0 STRENGTH EVALUATION OF US-APWR SC MODULES

The SC modules of the US-APWR CIS are confirmed to have sufficient capacity and safety allowance to applied loads when designed using criteria based on ACI-349, based on the experimental results obtained by static loading tests of a 1/10th scale model of SC structures conducted by MHI at the past, as described here.

3.1 Methodology of the Evaluations

To prove the integrity of the SC modules of the US-APWR CIS, the following comparisons between the SC modules of US-APWR CIS and that of the 1/10th scale model have been performed.

(1) Comparison of Typical Dimensions

The typical dimensions of the US-APWR CIS are evaluated by determining these dimensions from plan and section drawings for the SC modules, and comparing with the section dimensions in the 1/10th scale model. Since the SC module dimensions are approximately 10 times that of 1/10th scale model, it is confirmed that the dimensions of the test sections used in the 1/10th scale model are applicable.

(2) Comparison of Sectional Properties

The sectional properties, i.e. sectional area, moment of inertia and section modulus, of the US-APWR SC modules are compared to the sectional properties of the 1/10th scale model converted into real scale. Since the sectional properties of the SC modules are better than or equal to the converted properties from the 1/10th scale model, it is confirmed that the sectional properties of the test sections used in the 1/10th scale model are applicable.

(3) Comparison of Ultimate Strength of Typical SC Wall Members

The ultimate strengths of typical SC wall members used for the US-APWR SC modules are compared to the ultimate strengths of the 1/10th scale model converted into real scale. Since the ultimate strength of the SC modules are equal to or better than the converted ultimate strength from the 1/10th scale model, it is confirmed that the ultimate strength of the test sections used in the 1/10th scale model are applicable.

(4) Safety Margin Against the Applied Design Forces of the US-APWR CIS

The safety margins for the SC modules which comprise the US-APWR CIS are evaluated against the design forces applied to the US-APWR CIS, and ultimate strength capacity of the 1/10th scale model converted into real scale, and are determined to be acceptable. In addition, since the estimated capacity of the US-APWR CIS is greater than the ultimate strength capacity of the 1/10th scale model converted into real scale as evaluated in (2) and (3) above, the safety margin against the applied design forces of the US-APWR CIS is increased further.

3.2 Evaluation Results

3.2.1 Comparison of Typical Dimensions

The typical dimensions of the US-APWR CIS are evaluated as approximately 10 times that of the 1/10th scale model, by comparison of the dimensions on plan and section drawings for the SC modules.

Figure 3-1 and Table 3-1 compare the results of the typical dimensions. Figures 3-2 through 3-5 show the plans and the sections of SC modules used in the comparison between US-APWR and the 1/10th scale model.

- a) The comparison of typical dimensions of plans shows that the dimensions of the US-APWR CIS are nearly equal to the dimensions of the 1/10th scale model increased by a basic scale ratio of 10. The CIS dimensions exceed the dimensions of the 1/10th scale (times 10) except for the dimensions of secondary shield wall and pressurizer wall. It is judged that the strength reduction effect due to the differences of these walls to the overall ultimate strength of US-APWR CIS is insignificant. In this evaluation, the RWSP outer peripheral walls of the actual US-APWR CIS have been excluded to conservatively evaluate the total capacity of the structure.
- b) The comparison of typical thicknesses of the CIS walls shows that the thicknesses of the US-APWR are equal to or exceed the thicknesses of the 1/10th scale model increased by a basic scale ratio of 10, except the thickness of the pressurizer wall. It is judged that the strength reduction effect due to the difference of this wall to the overall ultimate strength of US-APWR CIS is insignificant.
- c) The comparison of typical heights of SC walls shows that the heights of US-APWR are approximately 1.5 times against the heights of 1/10th scale model increased by a basic scale ratio of 10. Therefore, it is judged that the bending moment applied to US-APWR CIS is larger than that to the real scale CIS converted from the 1/10th scale model. In the strength evaluation of US-APWR CIS, applied loads calculated for the US-APWR CIS design have been used.

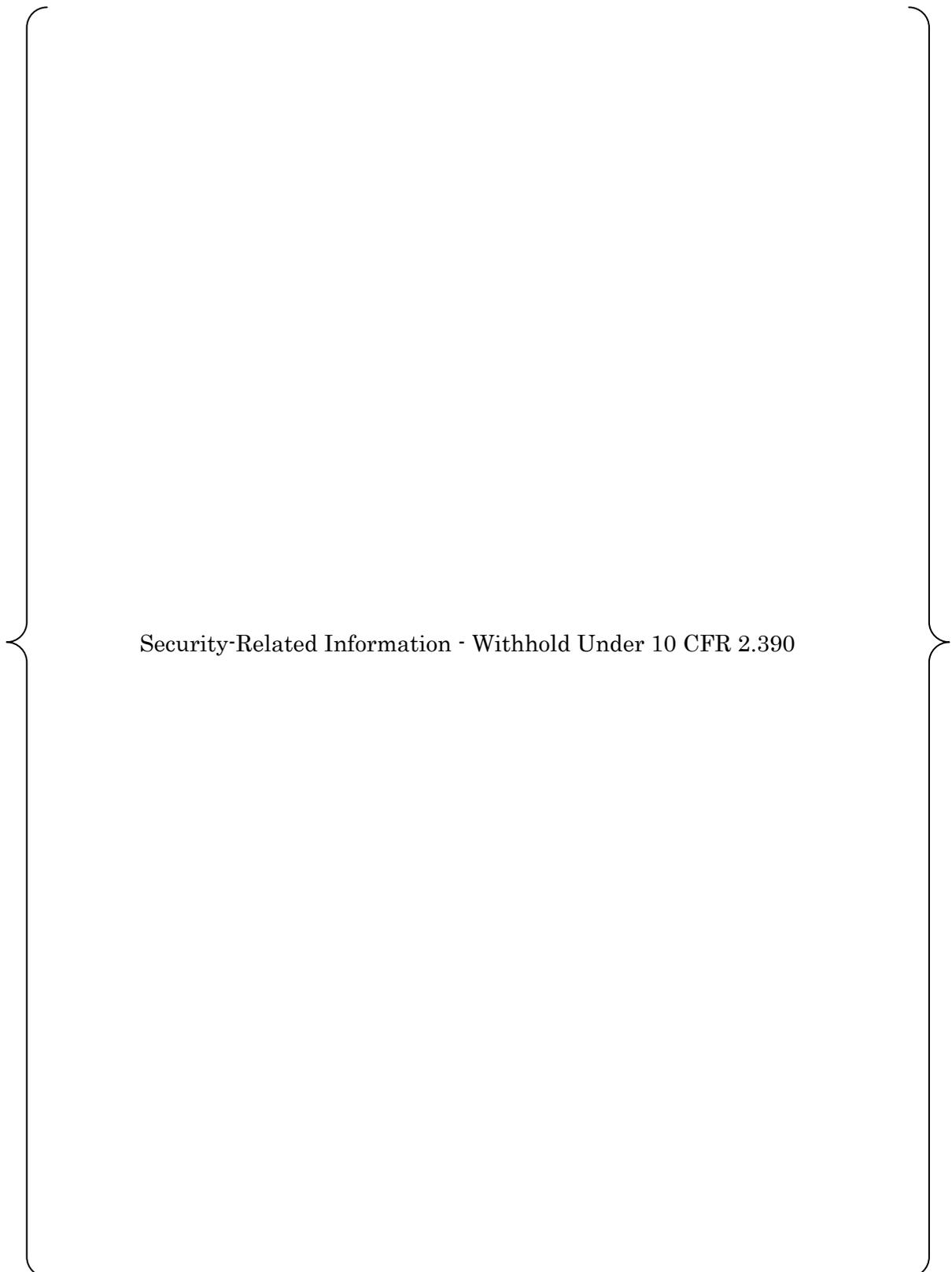
Based on the above evaluations, it is concluded that the results of the 1/10th scale model test can be adopted to evaluate the strength capacity and safety allowance to applied loads of the US-APWR CIS with the basic scale ratio of 10.



Figure 3-1 Comparison of Dimensions

Table 3-1 Comparison of Dimensions





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Figure 3-2 Plan of SC Modules for US-APWR CIS

(SRI)

Security-Related Information - Withhold Under 10 CFR 2.390

Figure 3-3 Section of SC Modules for US-APWR CIS

(SRI)

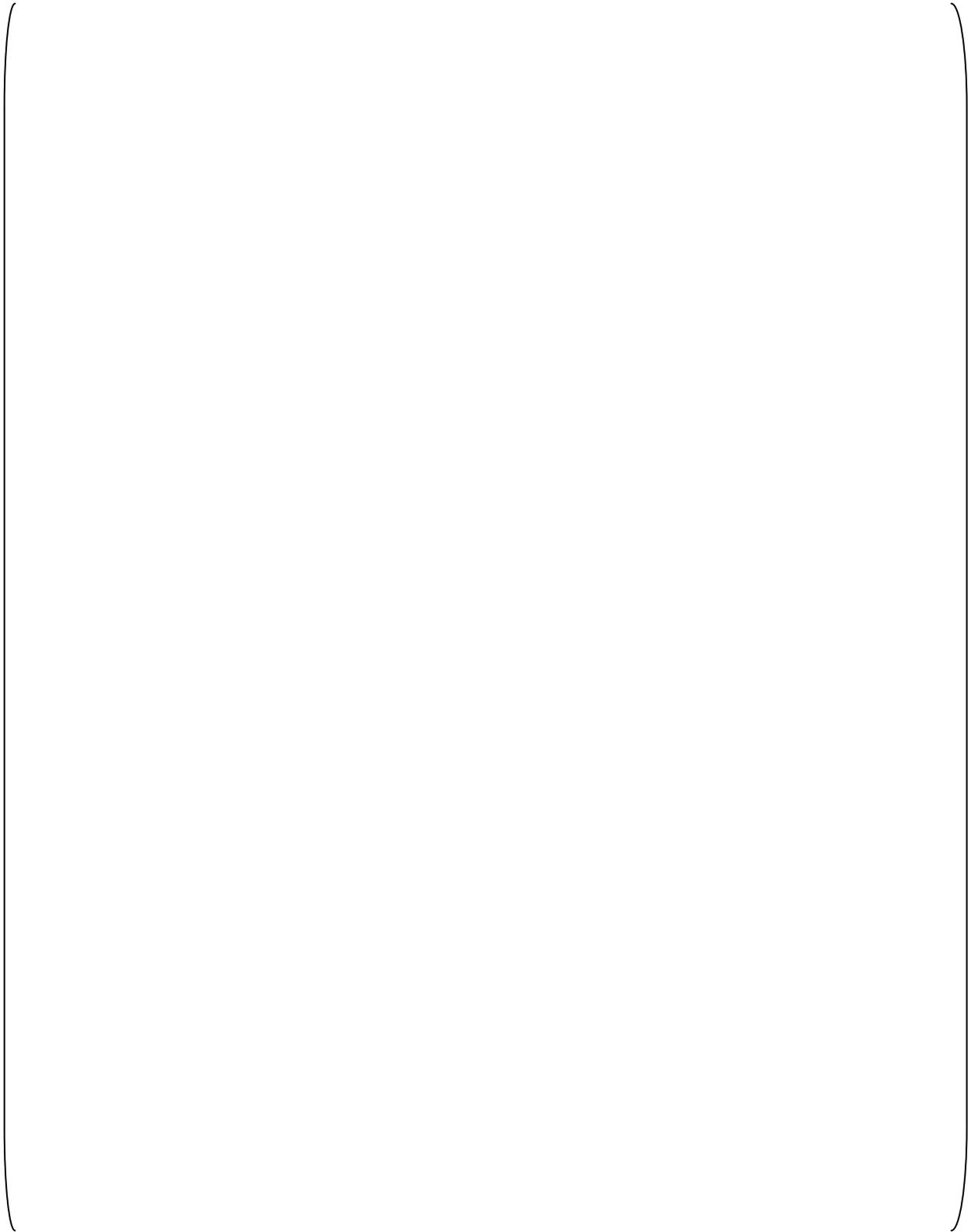


Figure 3-4 SC Module Plan of 1/10th Scale Model



Figure 3-5 SC Module Section of 1/10th Scale Model

3.2.2 Comparison of Sectional Properties

The sectional properties, i.e. sectional area, moment of inertia and section modulus, of the US-APWR CIS are evaluated as greater than or equal to the properties of the 1/10th scale model converted to real scale, by comparing these properties for SC modules.

(1) Basis of the Evaluation

- a) In the calculation of the sectional properties of the SC module, only the concrete sectional area has been taken into account except for the steel sectional area.
- b) The sectional properties of the overall CIS are calculated based on the results of the calculation of the sectional properties for each SC module wall members.
- c) The sectional properties of the 1/10th scale model are converted into real scale using a basic scale ratio of 10, for comparison with the properties of the US-APWR CIS. Sectional area, moment of inertia and section modulus are calculated as 100 times, 10,000 times and 1,000 times of original values of the 1/10th scale model, respectively.

(2) Results

Figure 3-6 and Table 3-2 show the results of the evaluation using the above basis. Figures 3-7 and 3-8 show the overview plans of US-APWR and 1/10th scale model used in this evaluation.

It is verified that the sectional properties of US-APWR are greater than or equal to those of the 1/10th scale model converted into real scale, because the ratio (a/b) of sectional properties exceeds 1.0 as shown in Figure 3-6.



Figure 3-6 Comparison of Sectional Properties

Table 3-2 Comparison of Sectional Properties

A large, empty, vertically-oriented bracketed area, consisting of two long, thin, curved lines on the left and right sides, with their ends pointing towards the center. This area is positioned below the caption for Table 3-2.



Figure 3-7 Overview Plan of US-APWR



Figure 3-8 Overview Plan of 1/10th Scale Model

3.2.3 Comparison of Ultimate Strength of SC Wall Members

The ultimate strengths of typical SC wall members used for the US-APWR SC modules are compared to the ultimate strengths of the 1/10th scale model converted into real scale, and determined to be equal to or better than the converted ultimate strength from the 1/10th scale model.

(1) Calculation methodology

The ultimate strengths for SC module wall members are calculated using JEAC 4618-2009, "Technical Code for Seismic Design of Steel Plate Reinforced Concrete Structures".

Table 3-3 shows the material properties of the SC modules. The yield strength of steel and the compression strength of concrete are the values obtained by test of the 1/10th scale model, and the values specified in the design specification for the US-APWR.

Figure 3-9 shows the structural overviews of SC module wall members for US-APWR and the 1/10th scale model. The ultimate strengths of the 1/10th scale model are converted into real scale based on the basic scale ratio of 10, for comparison with those of the US-APWR.

(2) Calculation results

Figure 3-10 and Table 3-4 show the comparison of the ultimate strengths of SC module wall members for the US-APWR and the 1/10th scale model.

It is verified that the ultimate strengths of the SC module wall member for US-APWR are greater than those of the 1/10th scale model converted into real scale, because the ratios (a/b) of strengths exceed 1.0 as shown in Figure 3-10.

Table 3-3 Material Properties of SC Modules





Figure 3-9 Overview of SC Modules Wall Member



Figure 3-10 Comparison of SC Wall Member Strengths

Table 3-4 Comparison of SC Wall Member Strengths

3.2.4 Safety Margin Against the Design Applied Forces of US-APWR CIS

The safety margins for the design forces applied to the US-APWR CIS are evaluated as acceptable against the ultimate strength capacity of the 1/10th scale model converted into real scale. In addition, the actual safety margins of the estimated capacity of the US-APWR CIS, considering the evaluation in 3.2.2 and 3.2.3 above, is evaluated to provide even greater margin.

(1) Evaluation Methodology

Figure 3-11 shows the load-displacement curve obtained by the static loading test of the 1/10th scale model. The maximum force is 11.49MN, and the failure mode is shear failure. The loading points of the test are at 2 levels. The maximum forces are distributed with 8.29MN on the upper point whose height is 1490mm from the base, and 3.20MN on the lower point at a height of 730mm from the base. The ultimate shear force and bending moment are calculated by the maximum force.

Figure 3-12 shows the distributions of shear force and bending moment calculated for as governing cases in SC modules of the US-APWR. The maximum design shear force and bending moment are produced by these distributions.

The ultimate shear force and bending moment of the 1/10th scale model are converted into real scale based on the basic scale ratio of 10, for the comparison with sections of the US-APWR CIS. The safety margins of the ultimate capacities of the 1/10th scale model converted into real scale for the design forces of the US-APWR CIS are evaluated by comparison. In addition, actual ultimate shear and bending moment capacities of the SC modules in the US-APWR CIS are estimated based on the evaluation of sectional properties listed in Table 3-2 and ultimate strengths of SC wall members listed in Table 3-4. For these estimated capacities, the safety margins have been evaluated.

(2) Results of the Evaluations

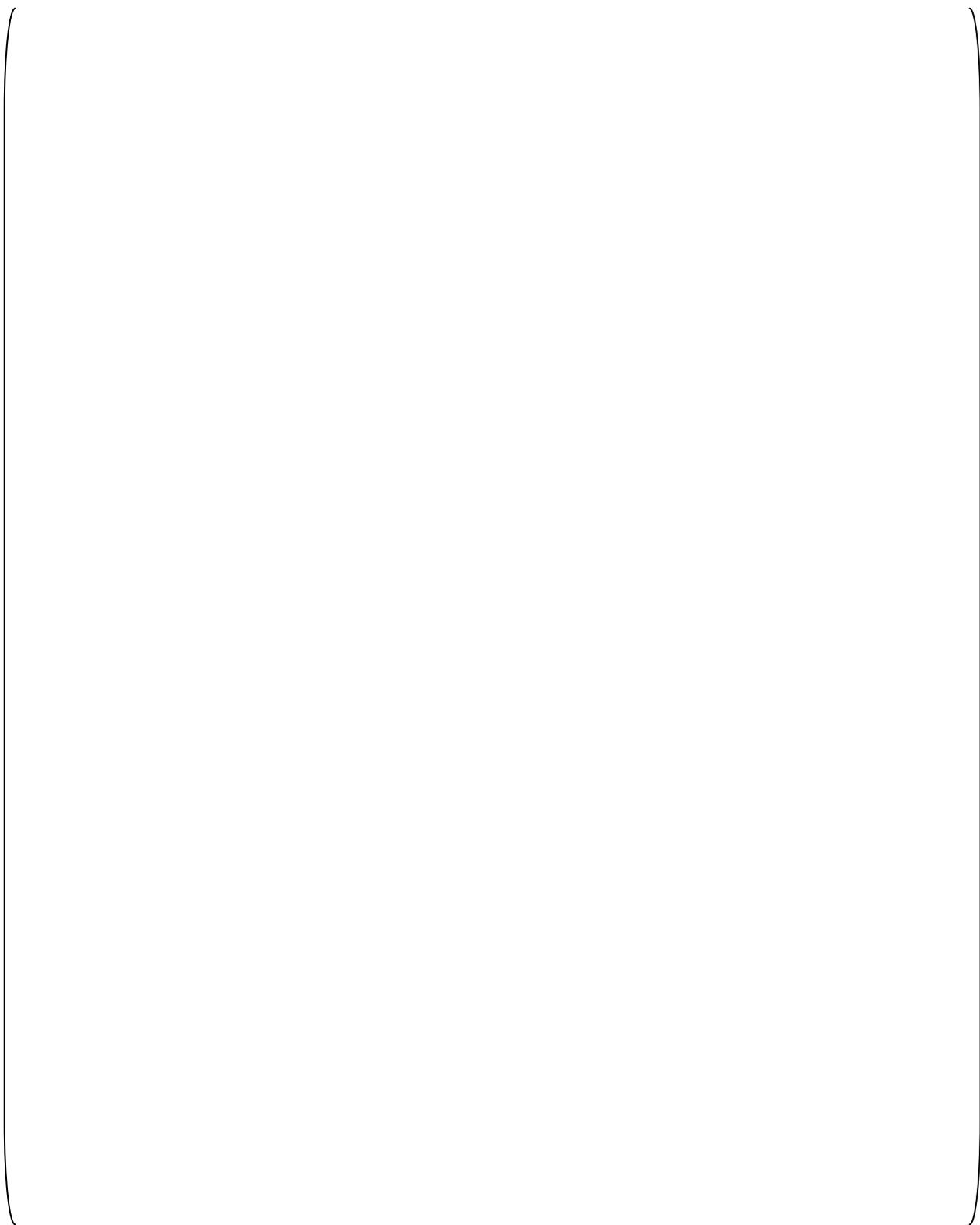
Figure 3-13, Table 3-5 and Table 3-7 show the safety margins against the maximum design forces of the US-APWR CIS. Table 3-6 shows the results of the calculated estimated ultimate capacities of SC modules for the US-APWR CIS.

Results of the evaluations are as follows:

- It is verified that based on the 1/10th scale model test to the maximum design shear force, the margin is 5.2 for the ultimate strength capacity of SC modules in the US-APWR CIS, and 3.3 for the maximum design bending moment.
- It is verified that for the estimated ultimate strength capacities of SC modules in the US-APWR CIS, the margin is 8.9 for the maximum design shear force and 6.2 for the maximum design bending moment.
- The margin for bending moment is less than that for the shear force. Therefore it is judged that the margin for bending moment exceeds 6.2, because the 1/10th scale model failed by shear force and not by bending moment.



Figure 3-11 Load-Displacement Curve of 1/10th Scale Model



**Figure 3-12 Distribution of Design Shear Force and Bending Moment
for the US-APWR**



Figure 3-13 Margin for Design Forces of the US-APWR

Table 3-5 Margin for Design Force of the US-APWR (1)

Table 3-6 Estimated Ultimate Capacity of SC Modules in the US-APWR CIS

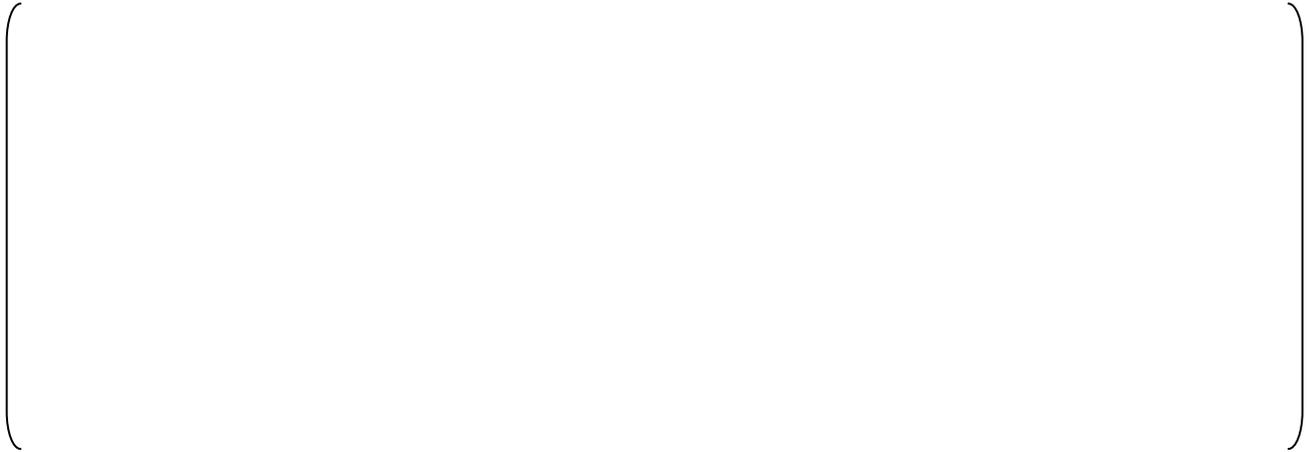
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Table 3-7 Margin for Design Force of the US-APWR (2)

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4.0 CONCLUSION

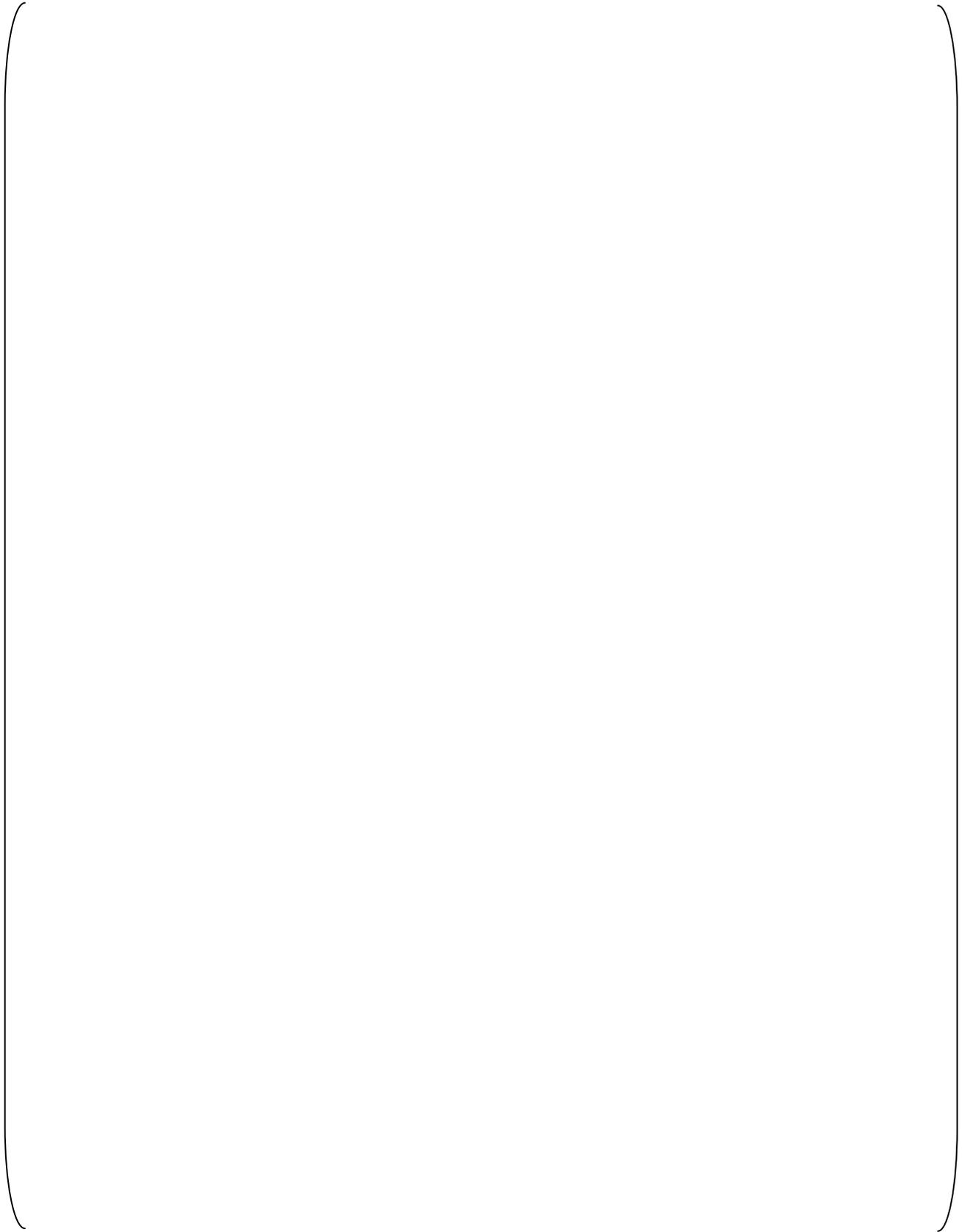
This report has first introduced the 10 research achievements for SC modules addressed in the amended response to RAI 322-1999. In addition, this report has shown that the SC modules of the US-APWR CIS, when designed using criteria based on ACI-349, has enough strength capacity and safety allowance to applied loads, based on the experimental results obtained by static loading test of the 1/10th scale model of SC modules.

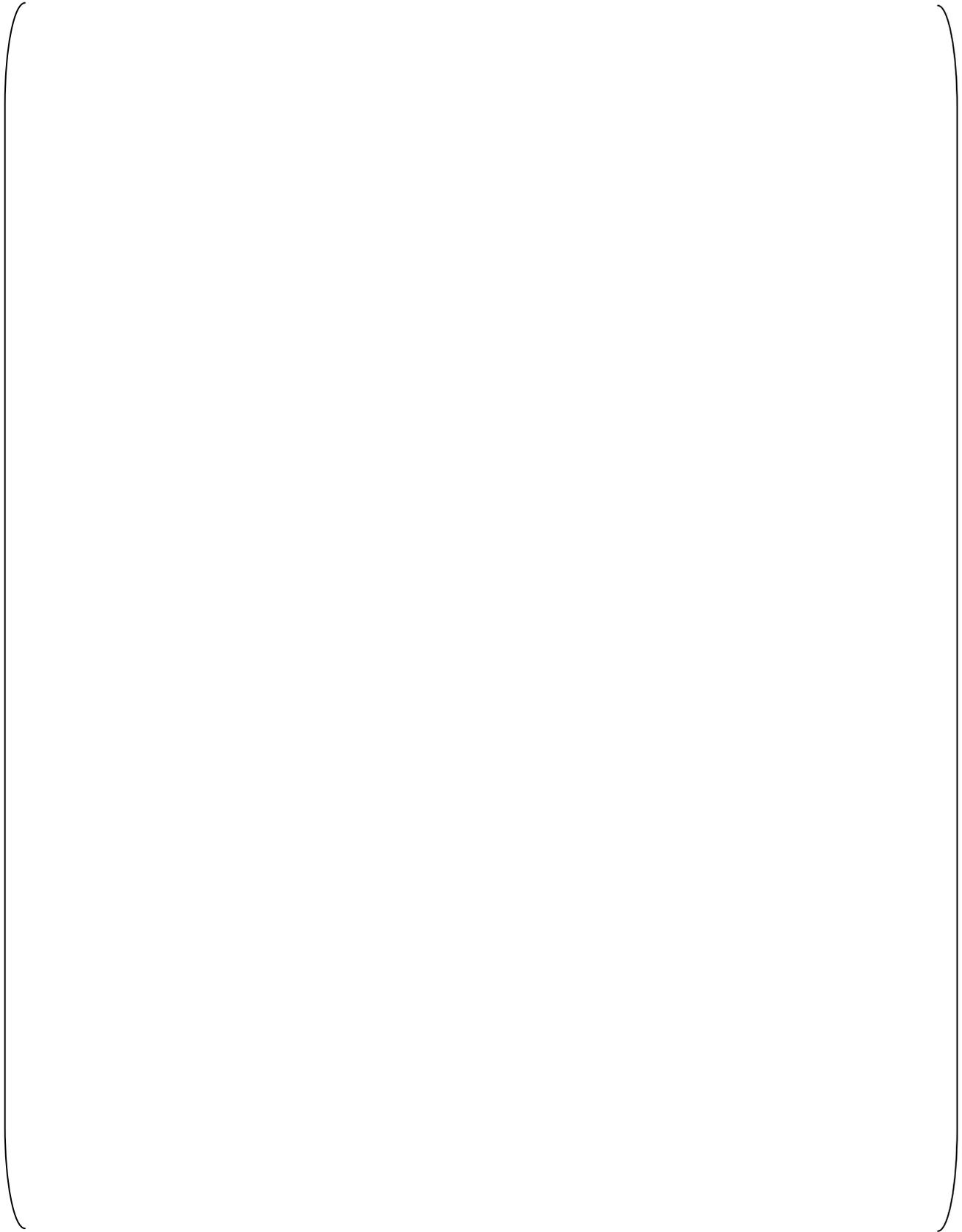
The following conclusions summarize the evaluation results of US-APWR SC modules:

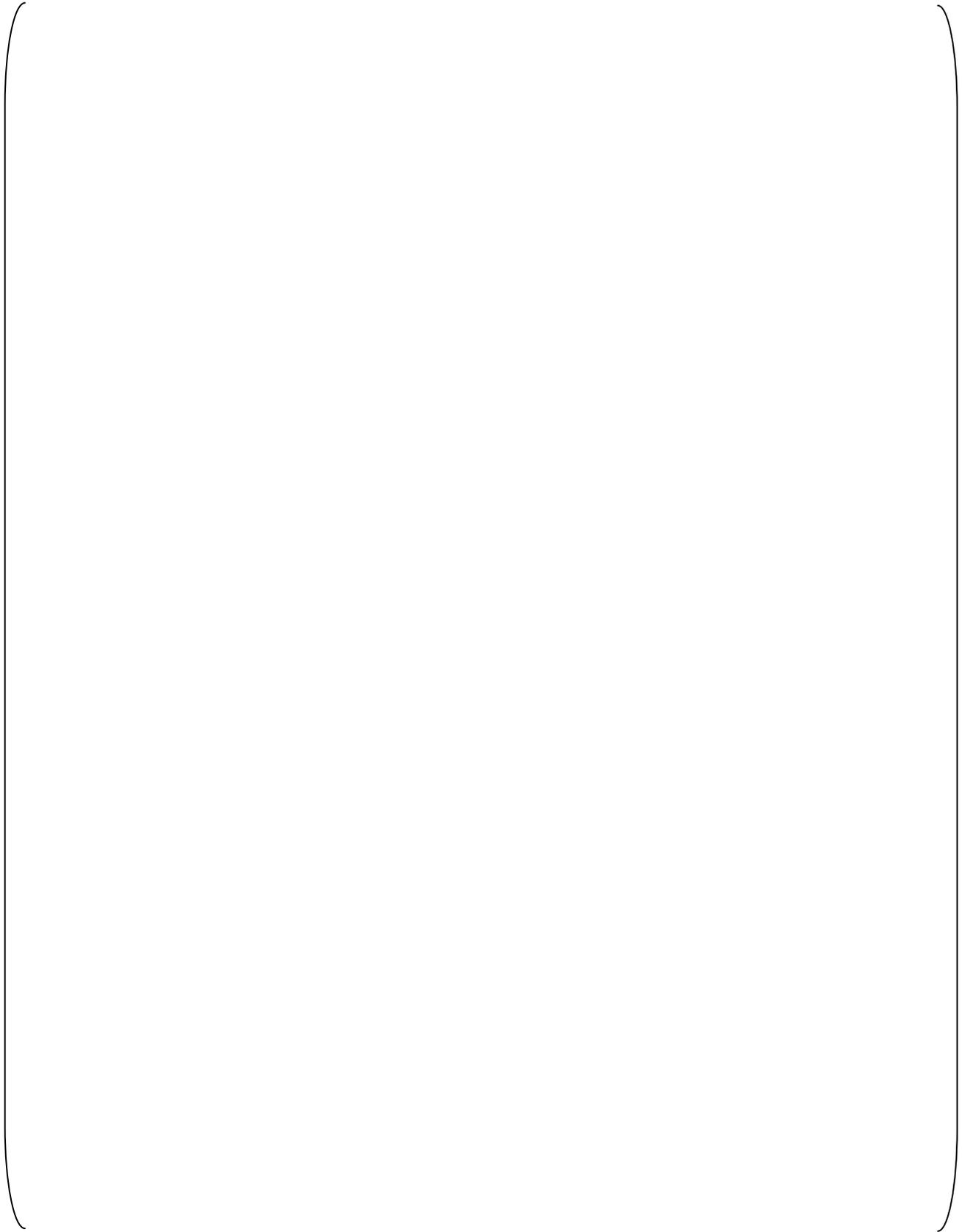
- a) The strength evaluation of the SC modules in the US-APWR CIS is conservative based on the 1/10th scale model test results using the basic scaling ratio of 10.
- b) The sectional properties of the US-APWR are greater than or equal to that of the 1/10th scale model converted into real scale.
- c) The ultimate strengths of the US-APWR wall members are greater than that of the 1/10th scale model converted into real scale.
- d) The safety margins of the SC modules in the US-APWR CIS are 8.9 for maximum design shear force and 6.2 for the maximum design bending moment.

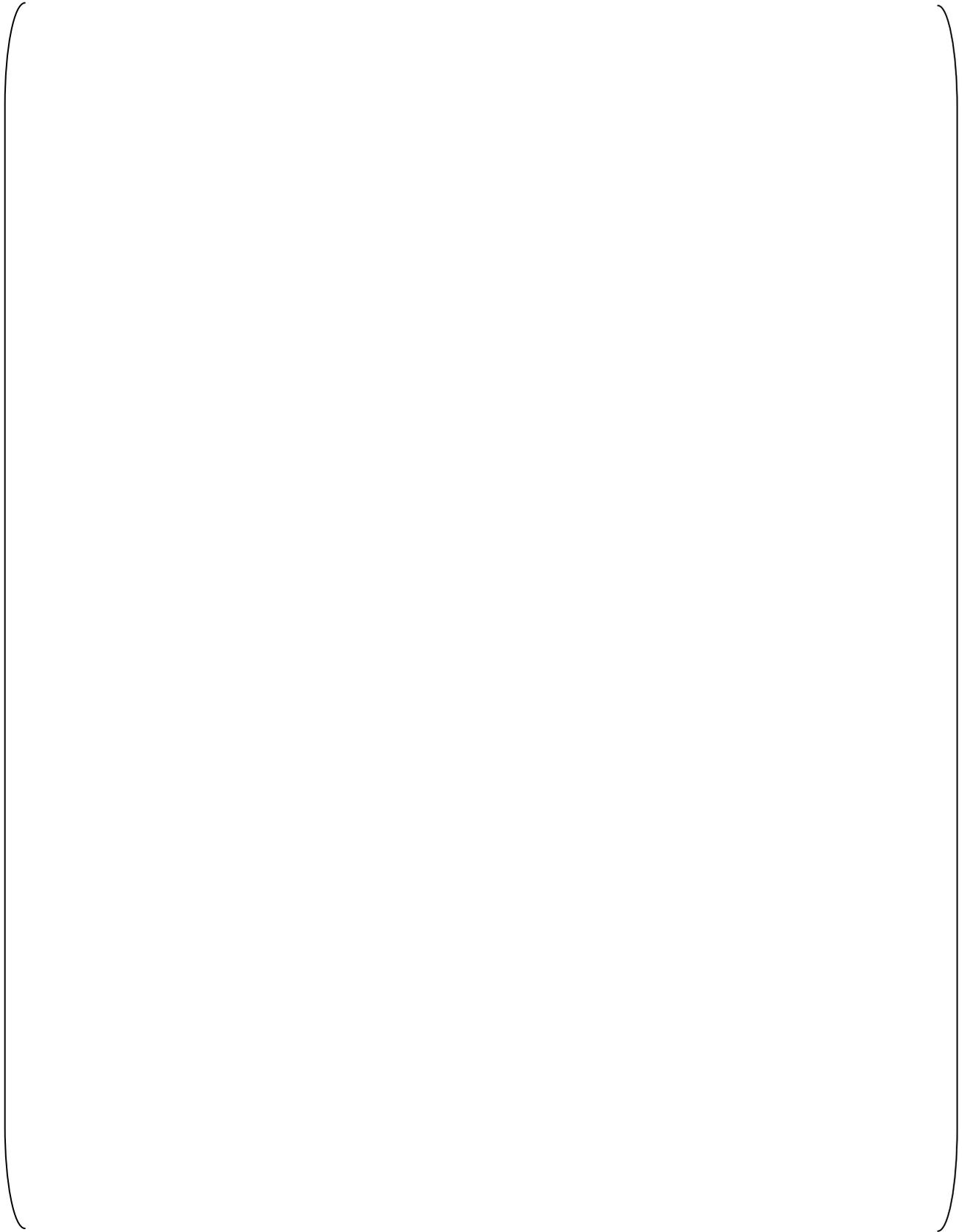
Based on the evaluations mentioned above, it is confirmed that the SC modules in the US-APWR CIS have sufficient safety margins to the design forces.

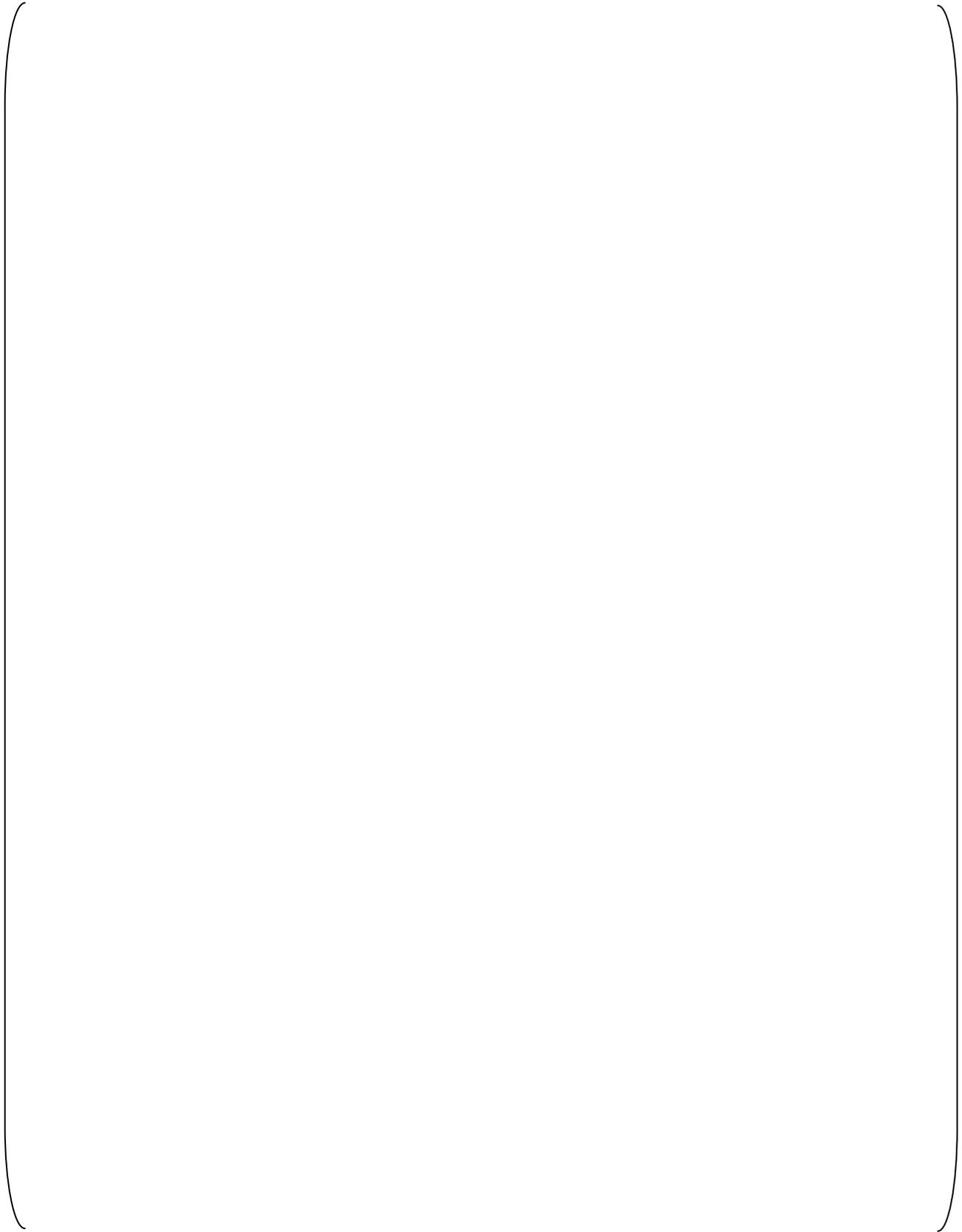
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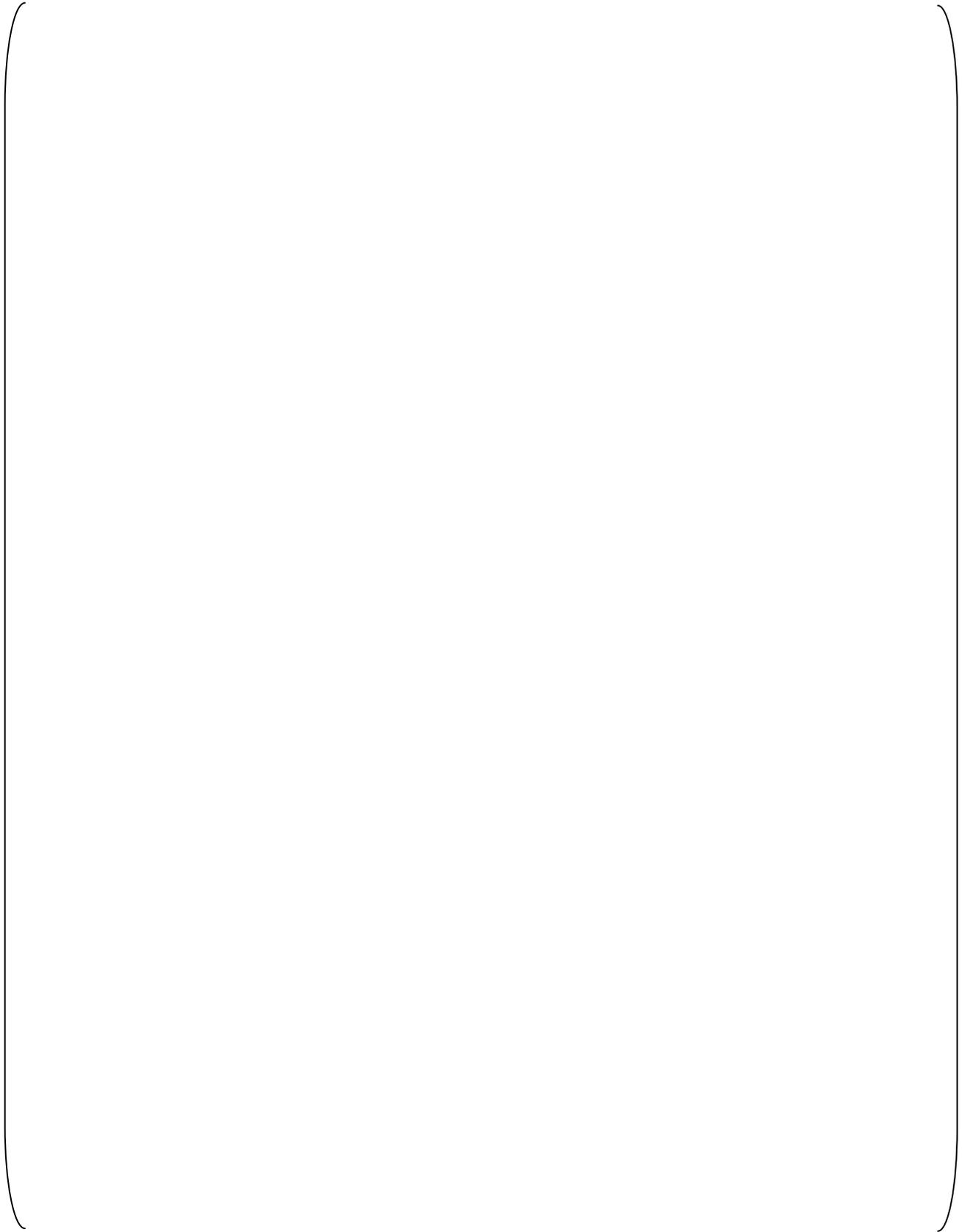


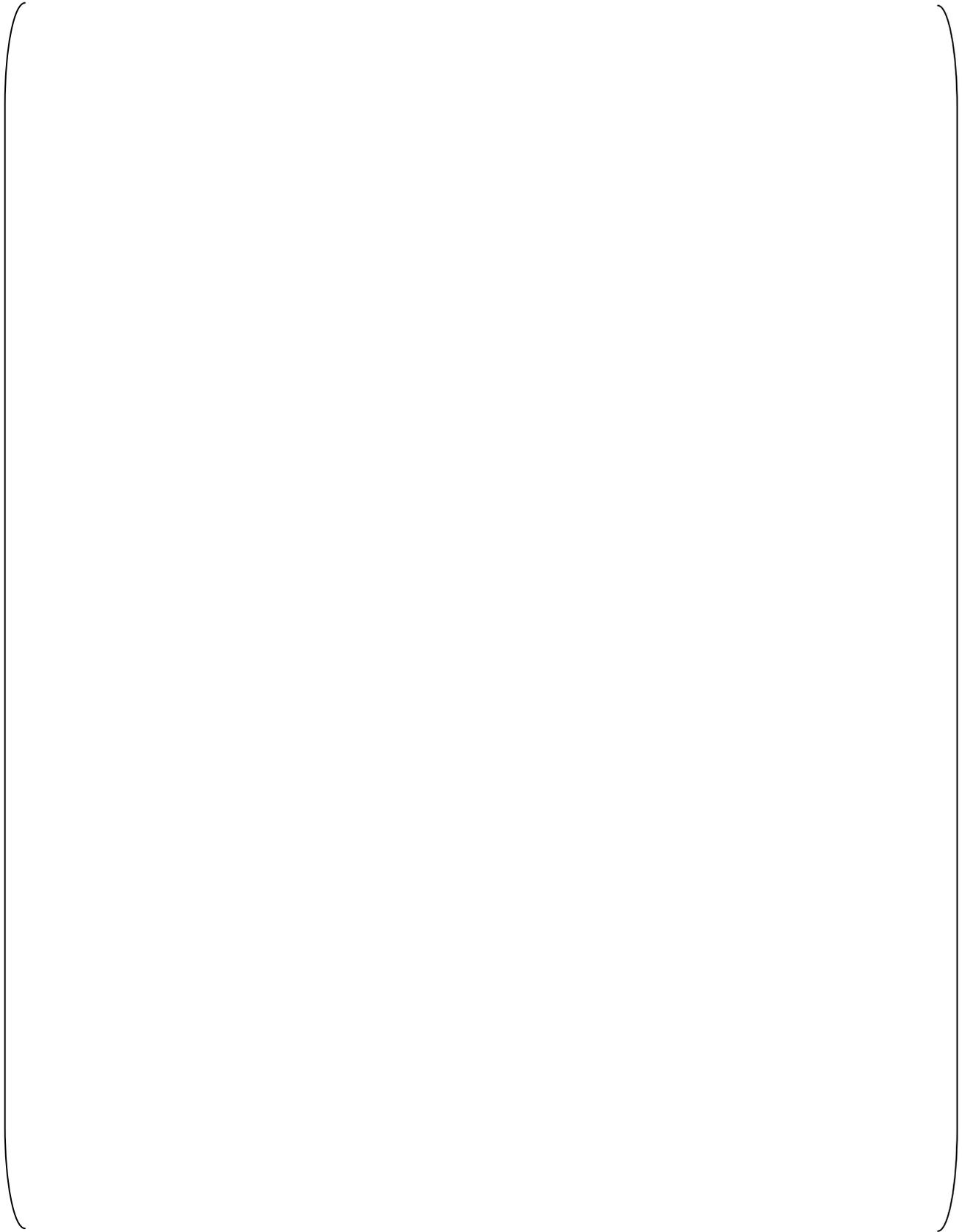


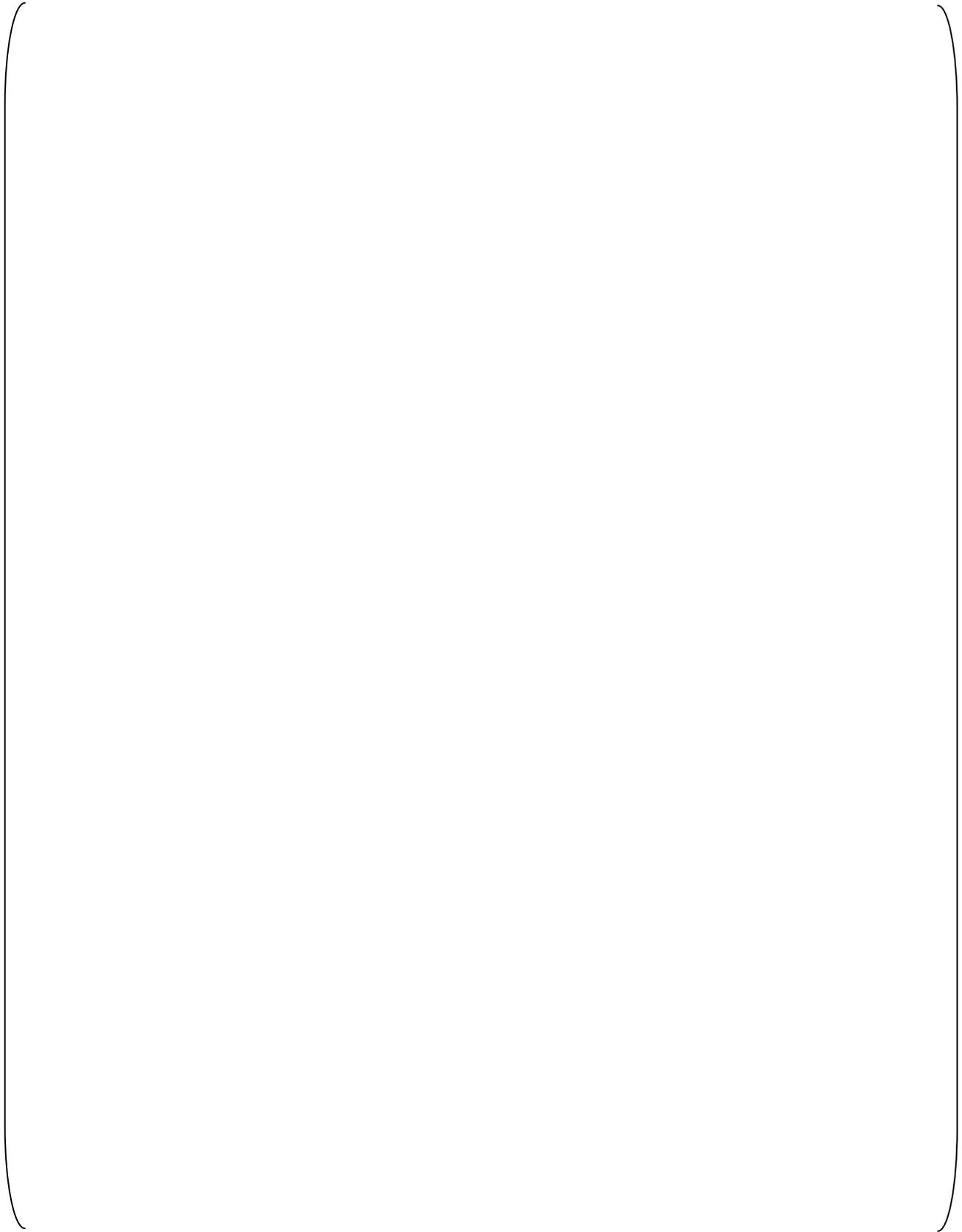


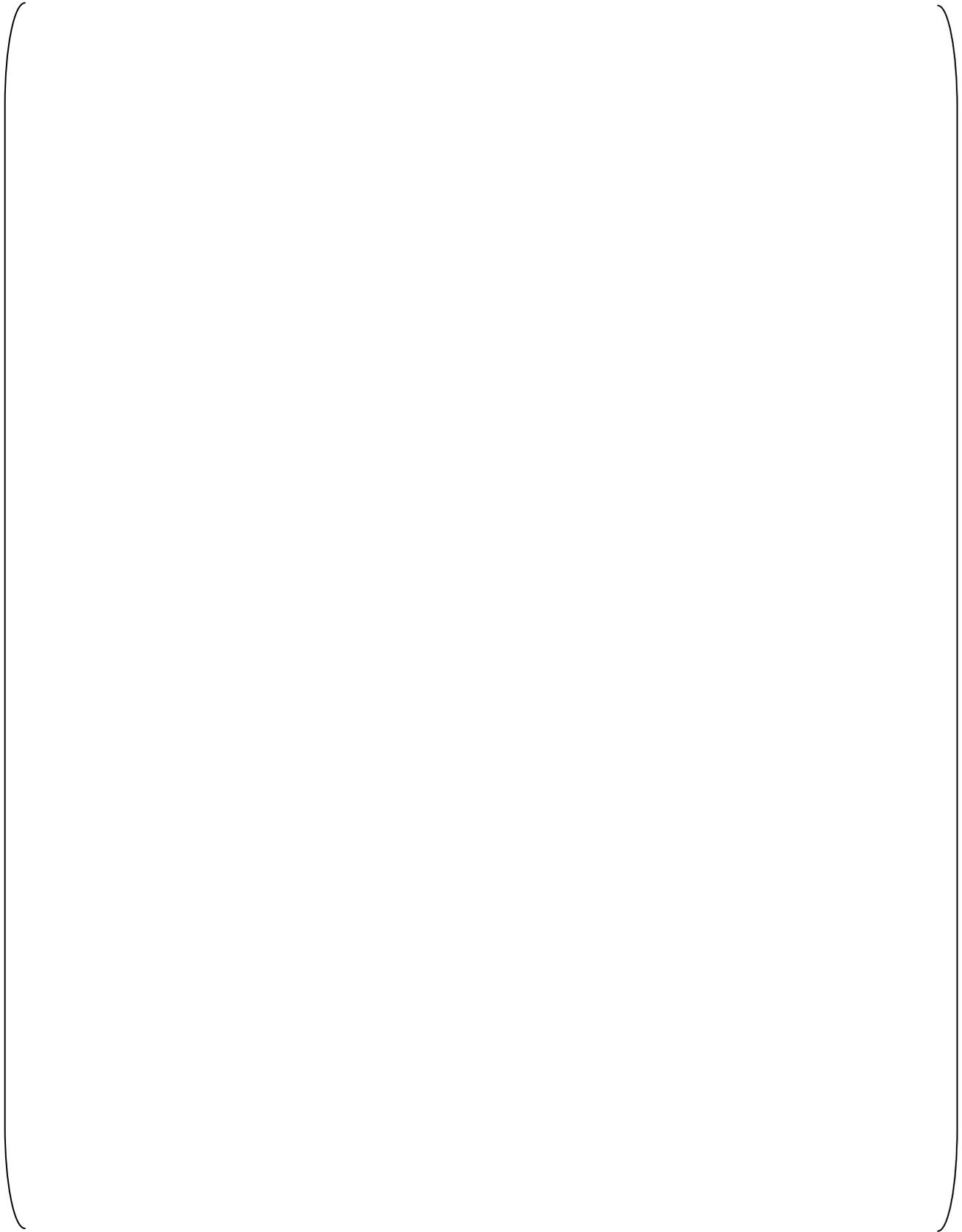


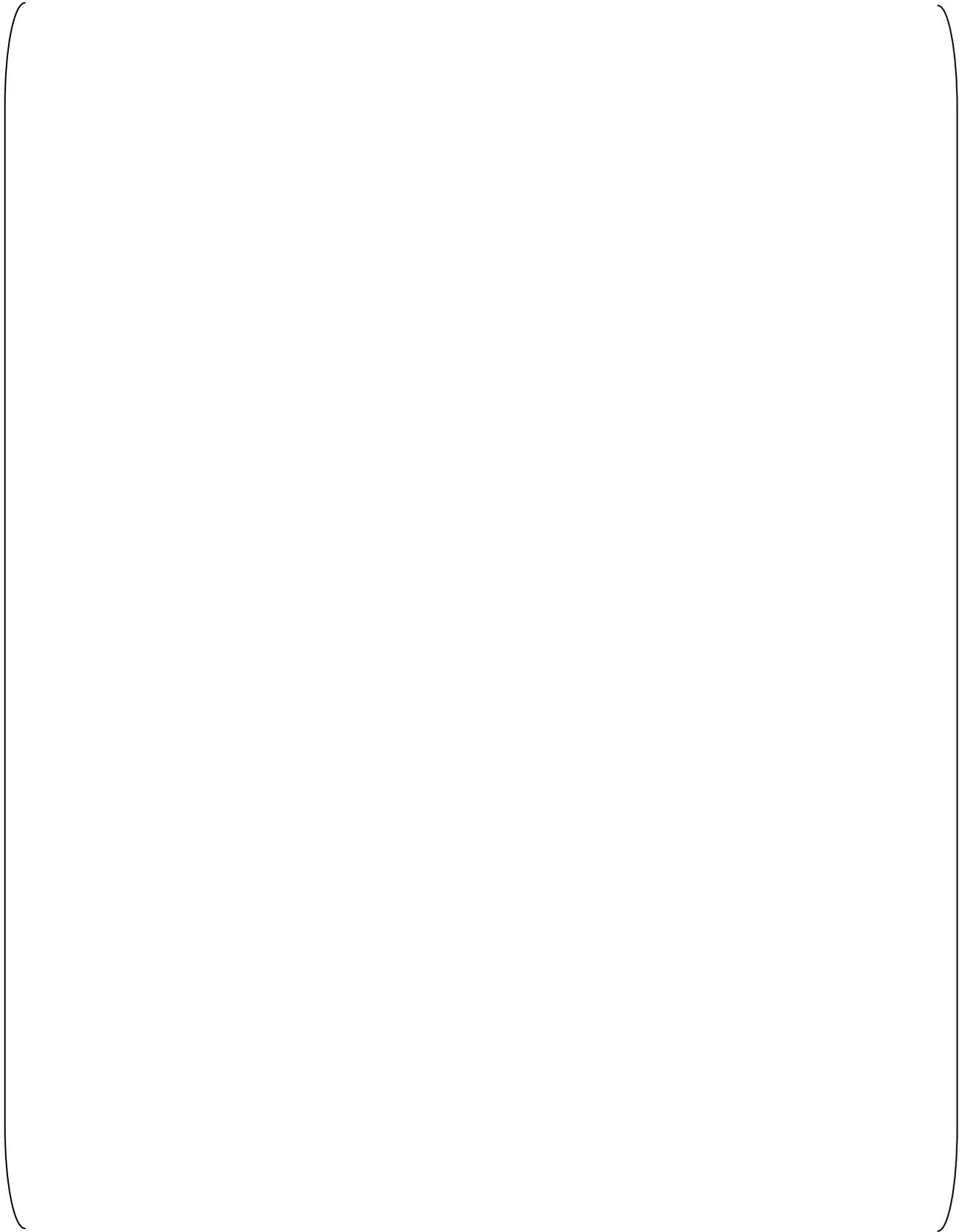


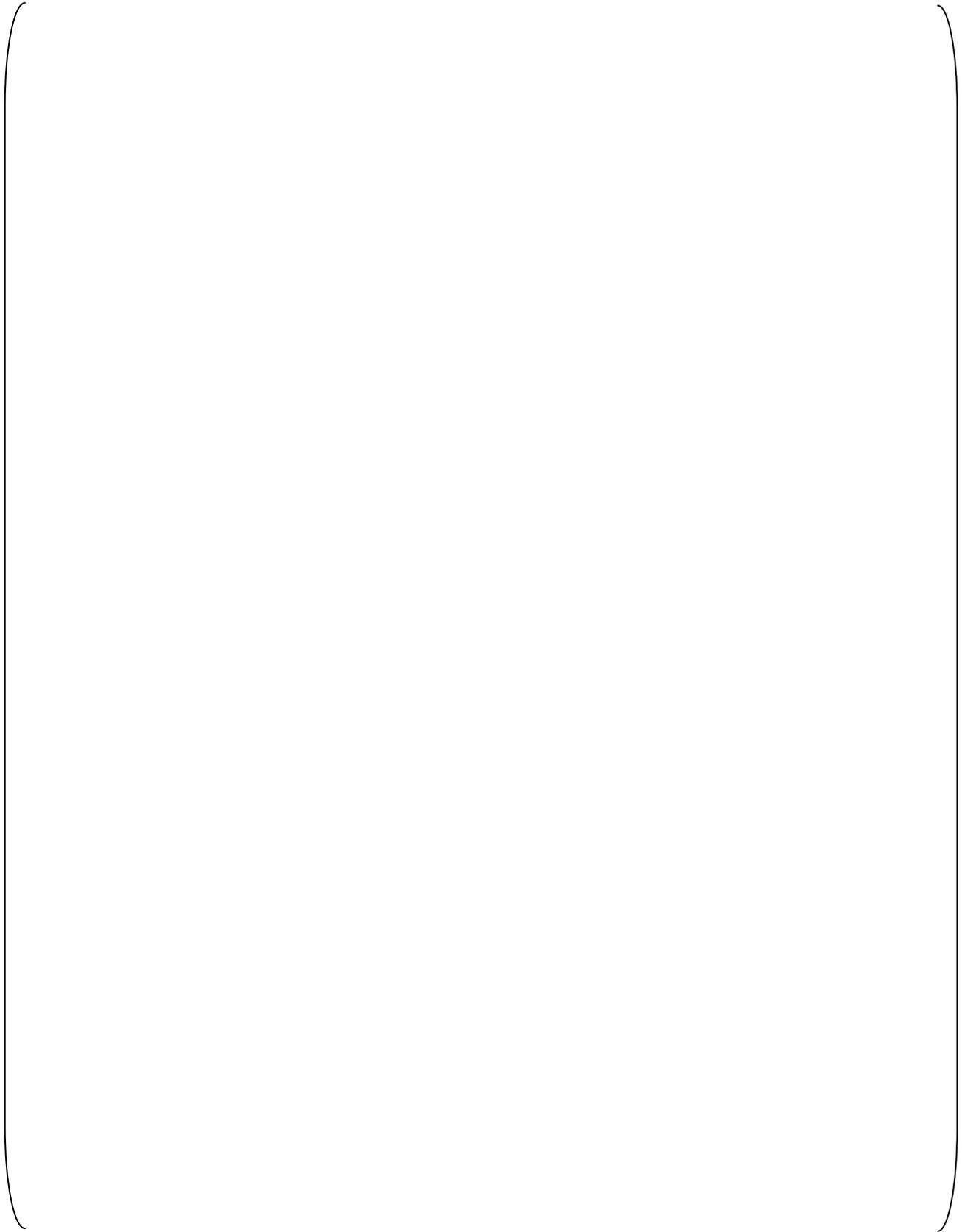


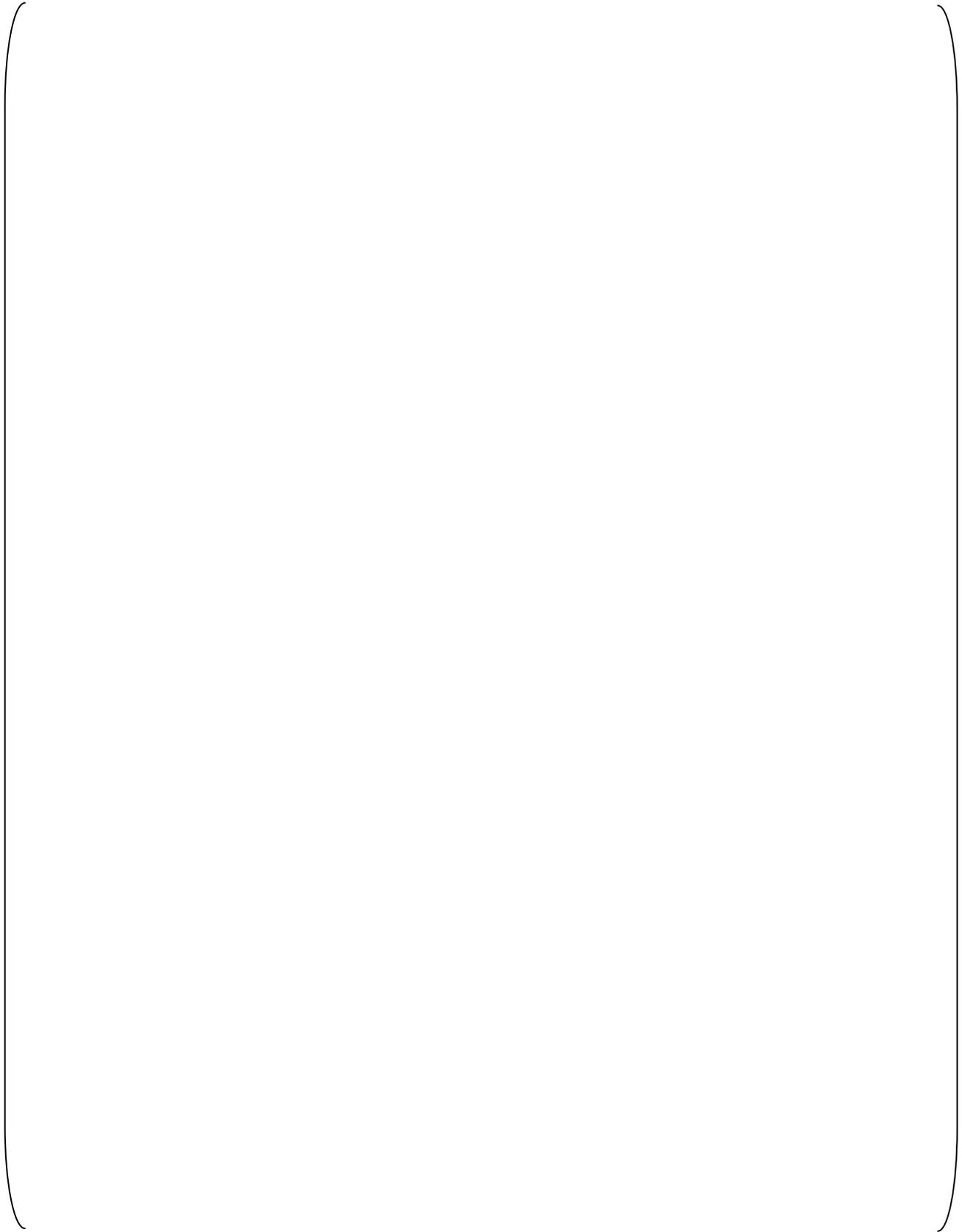


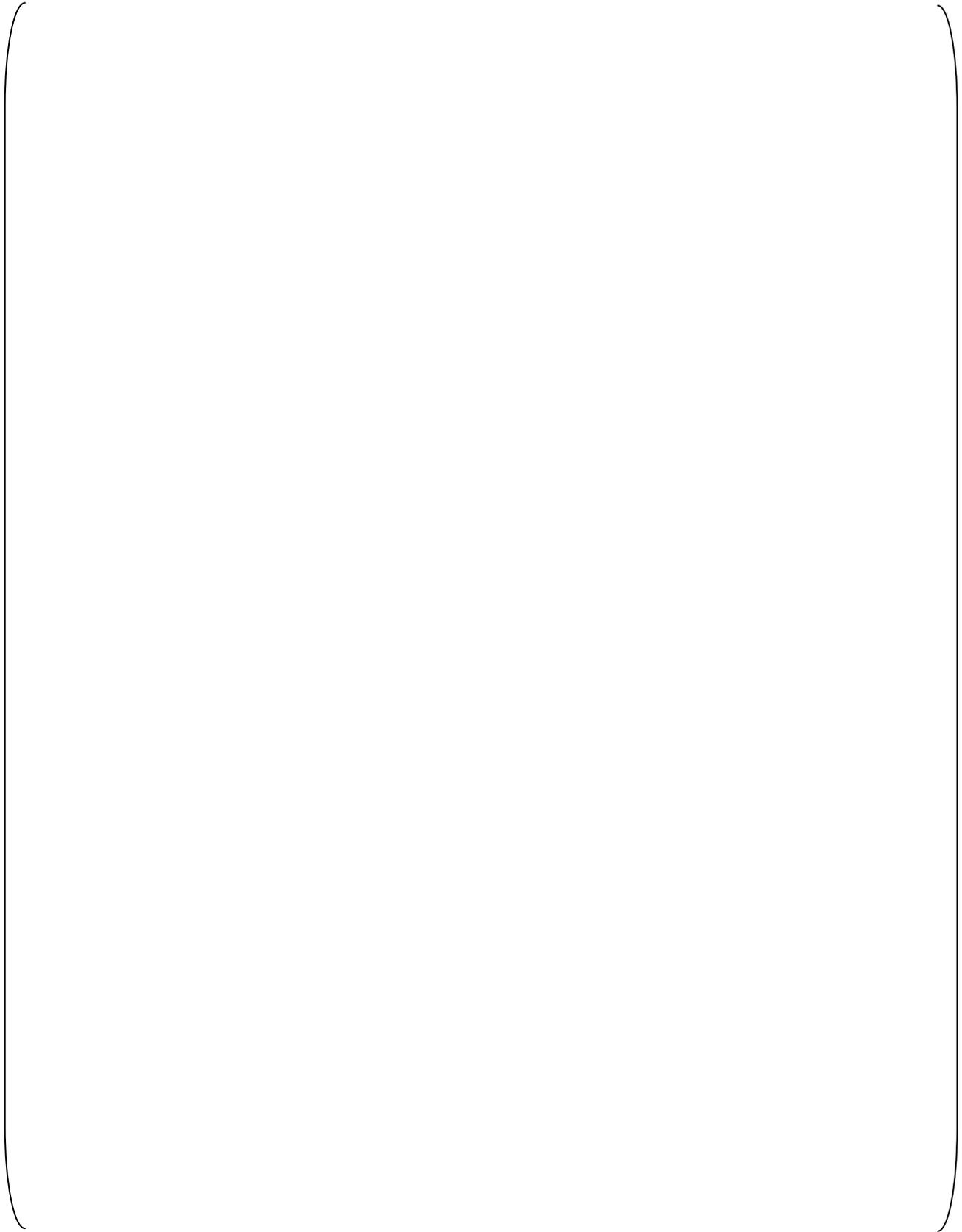


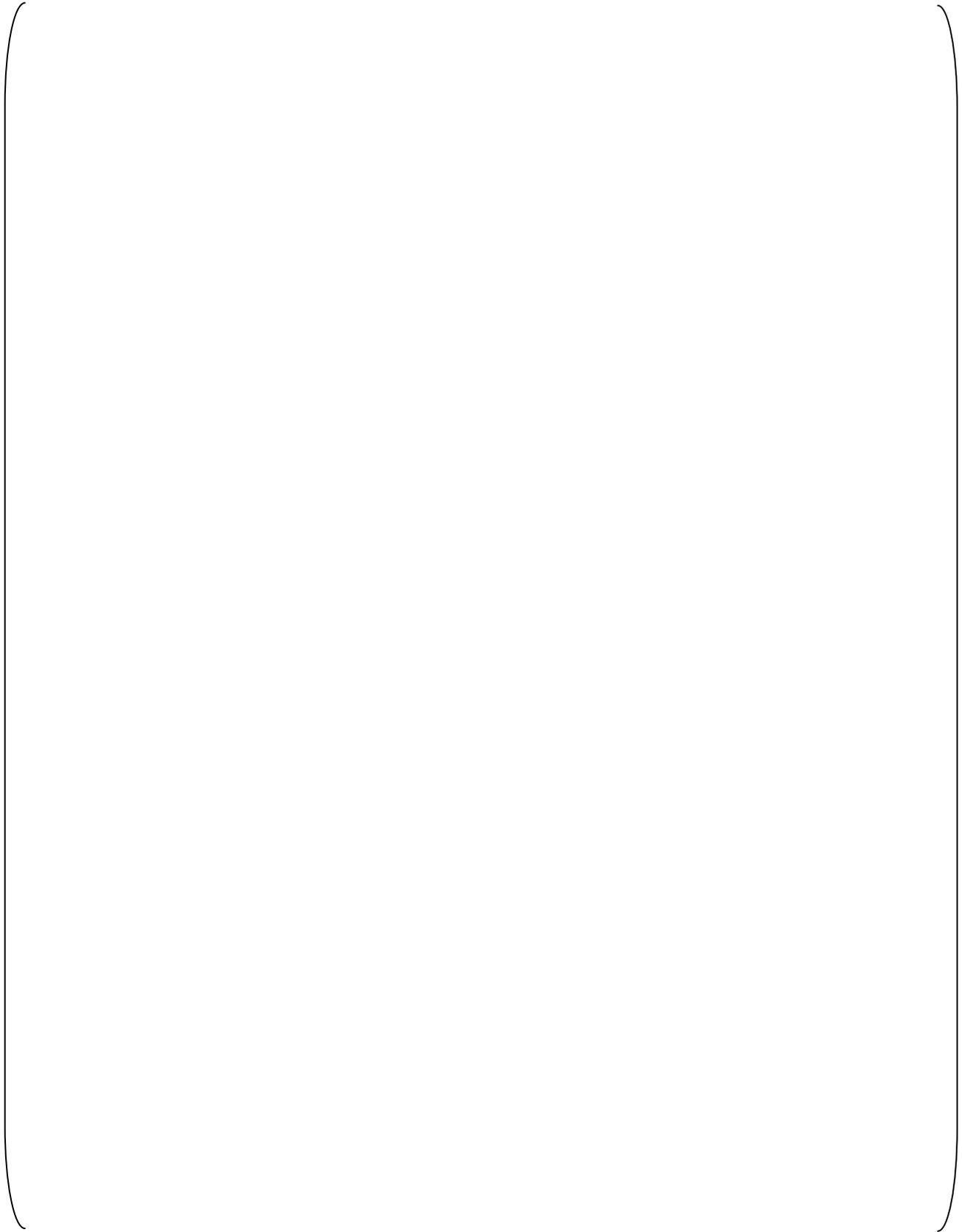


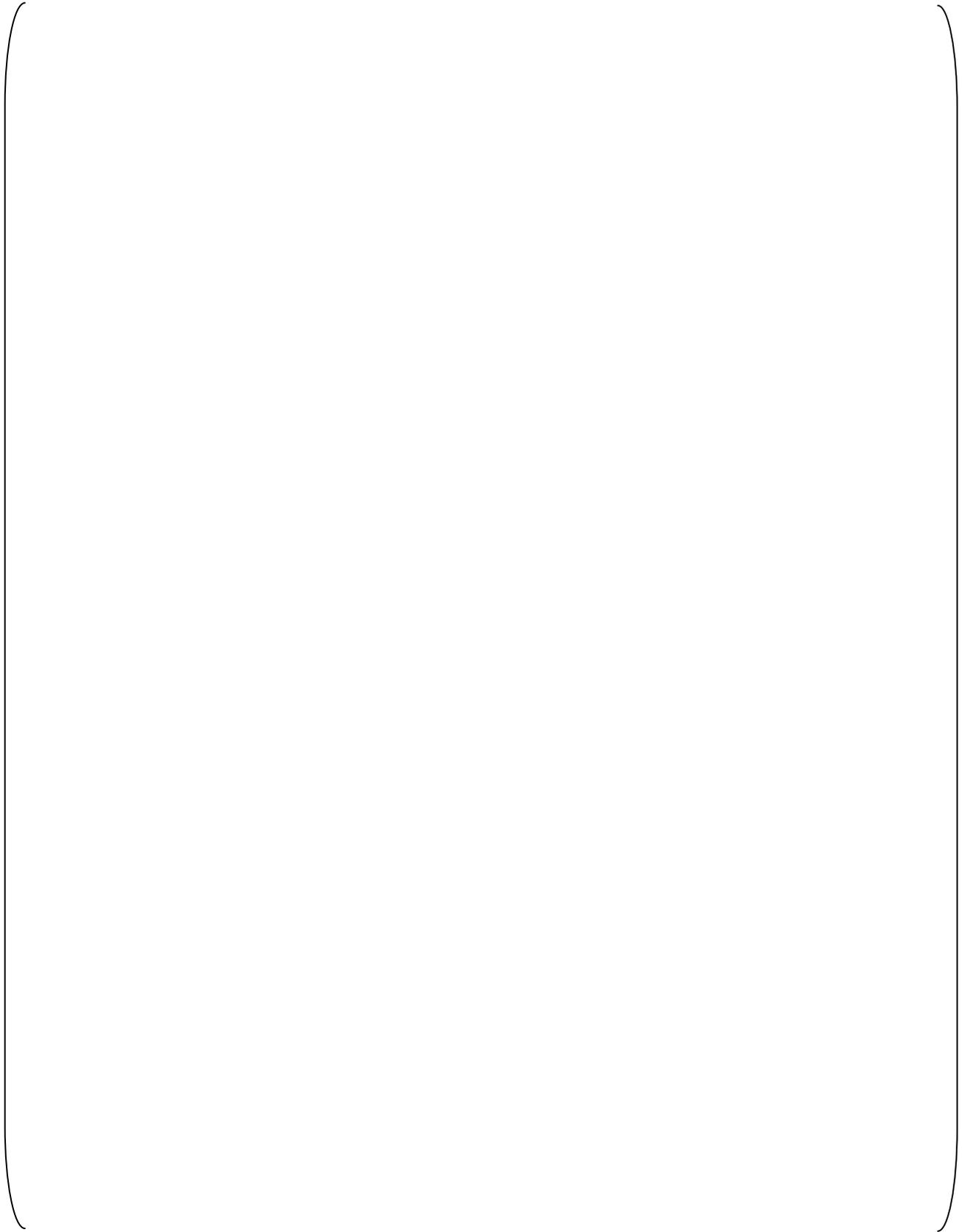


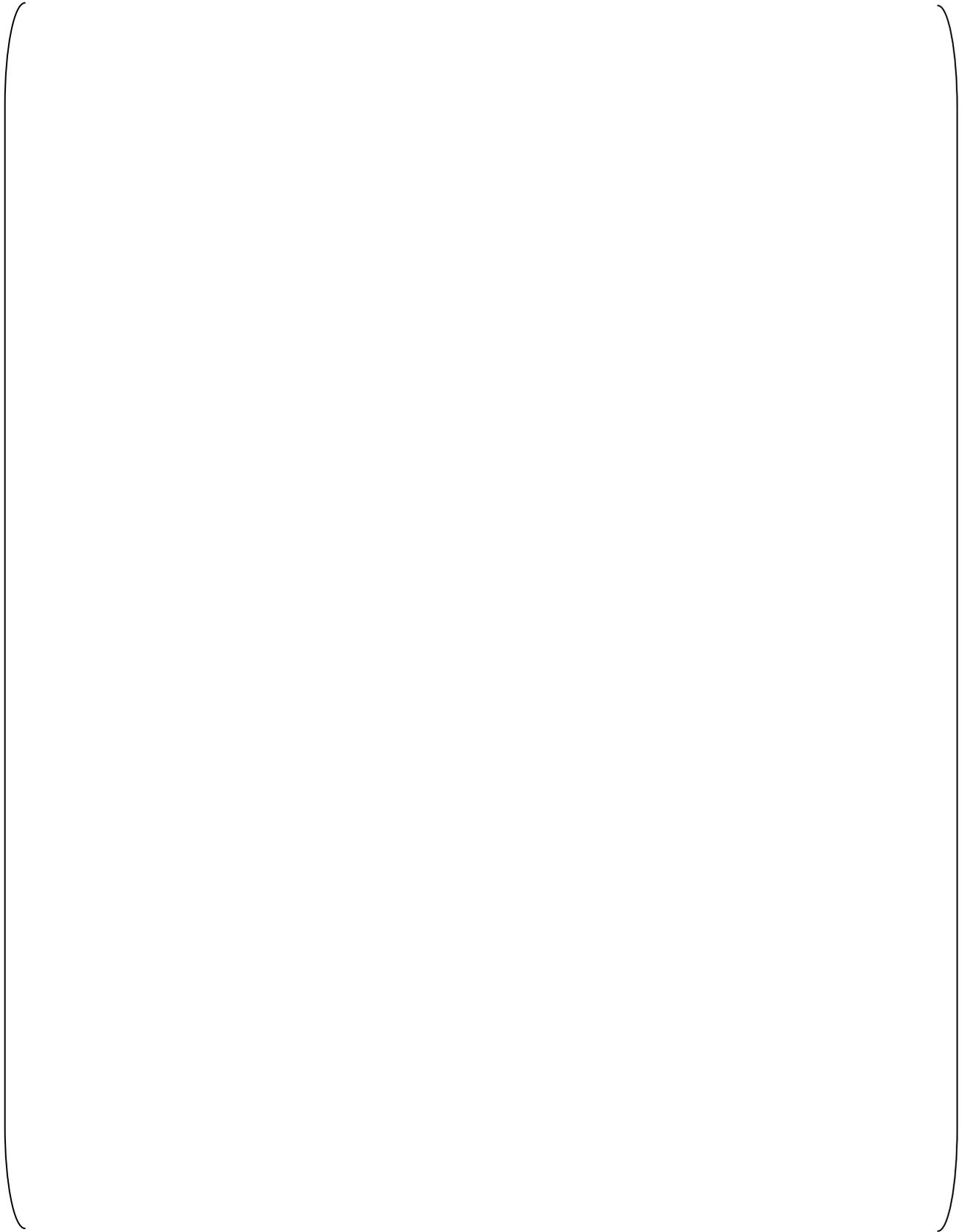


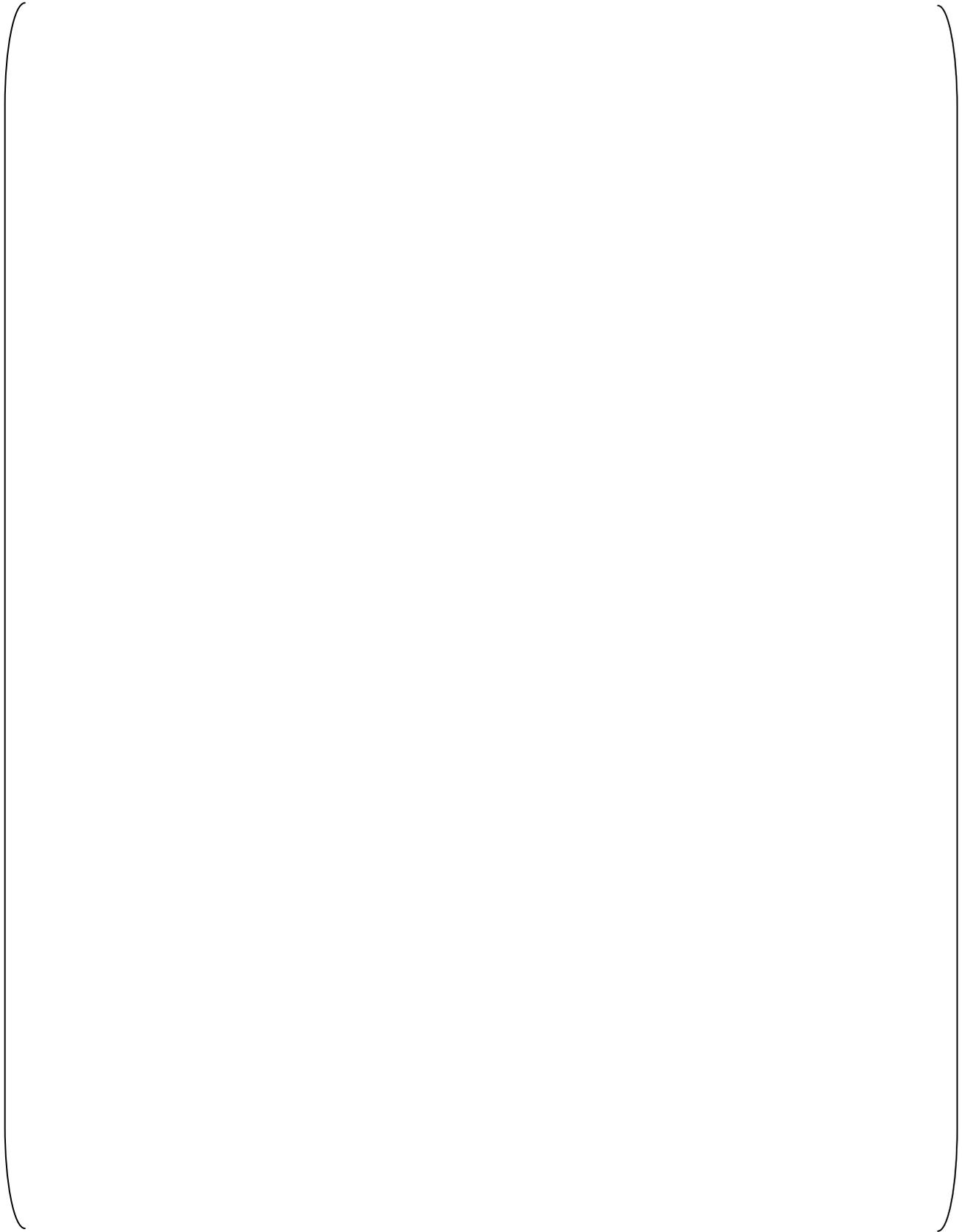


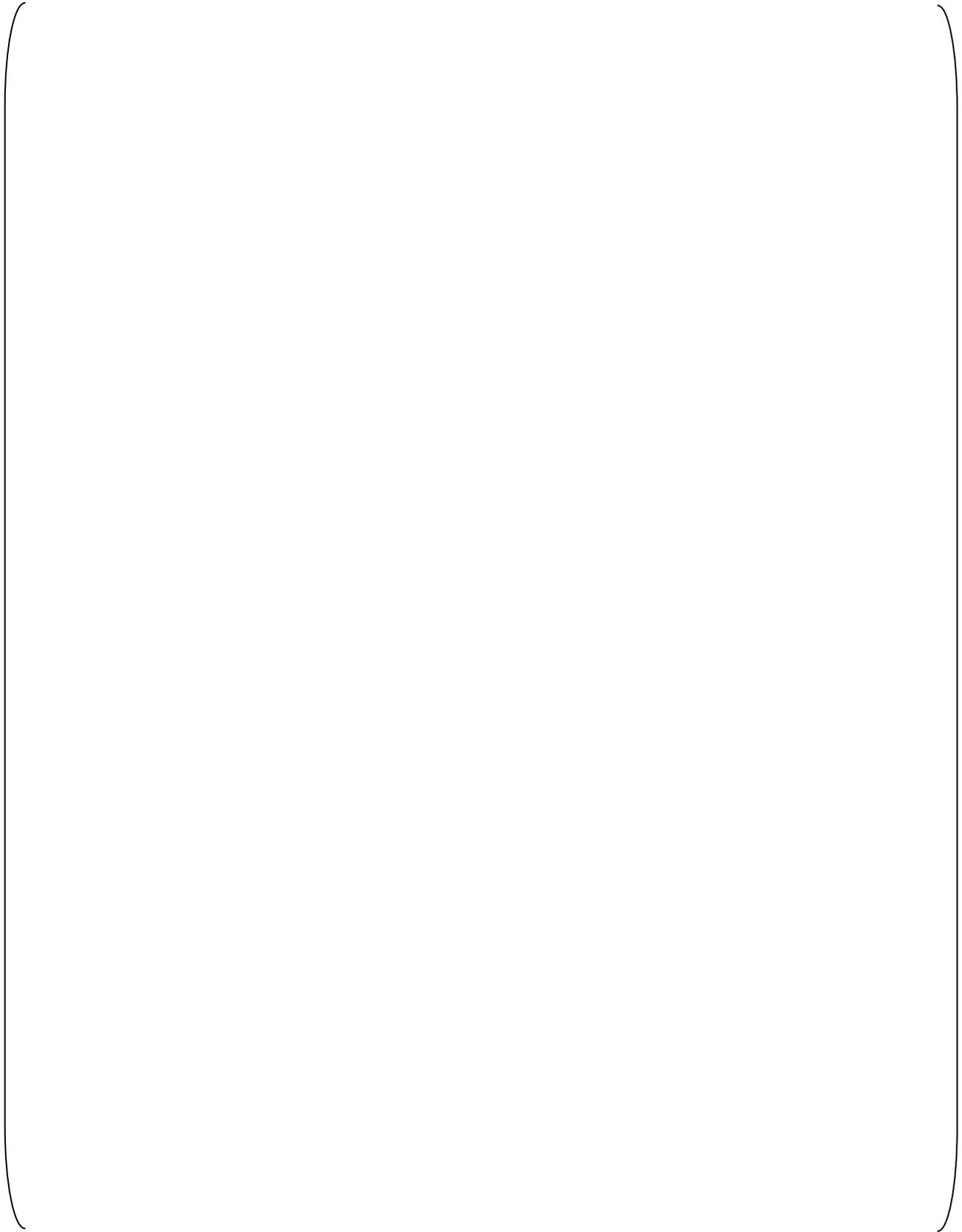


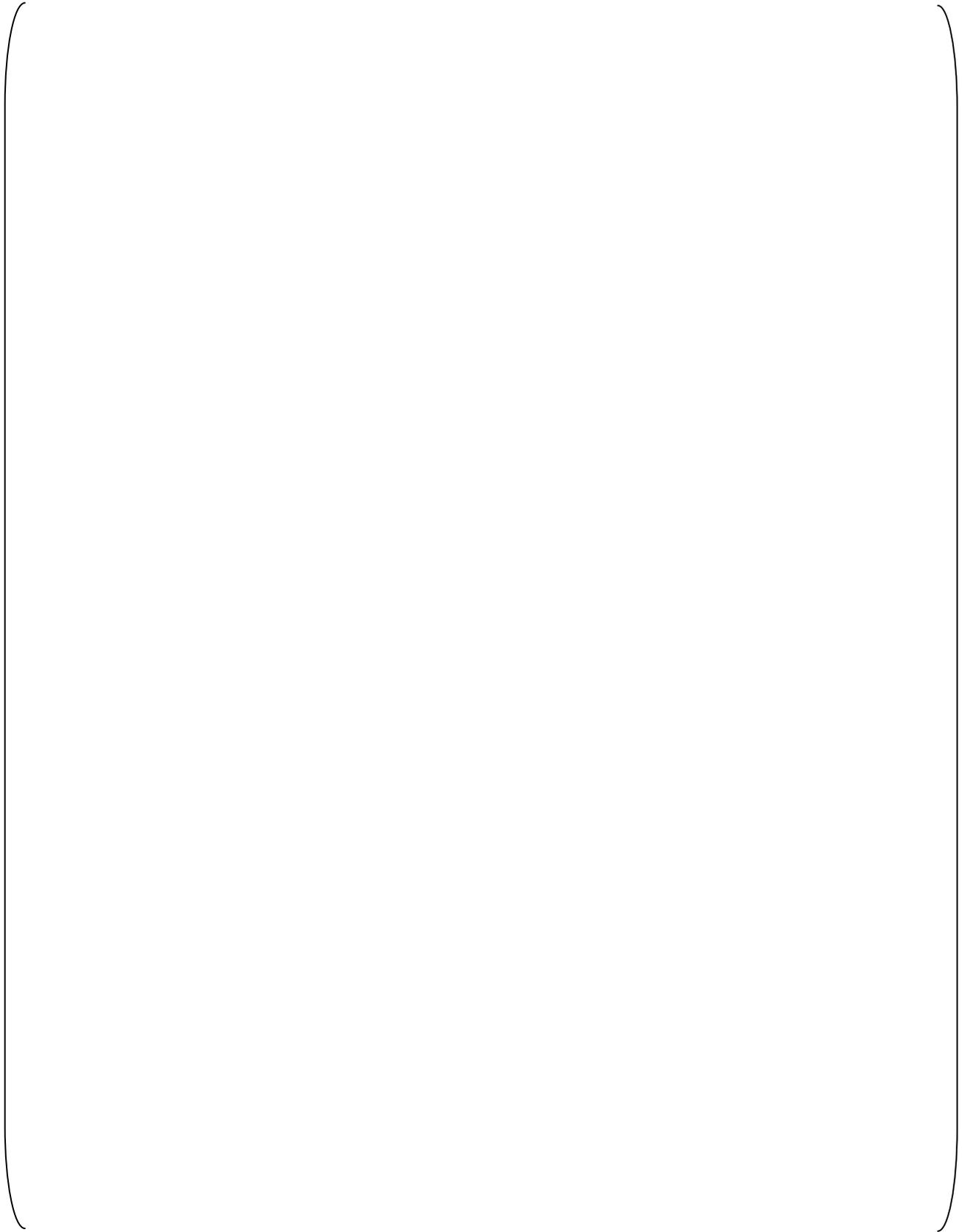


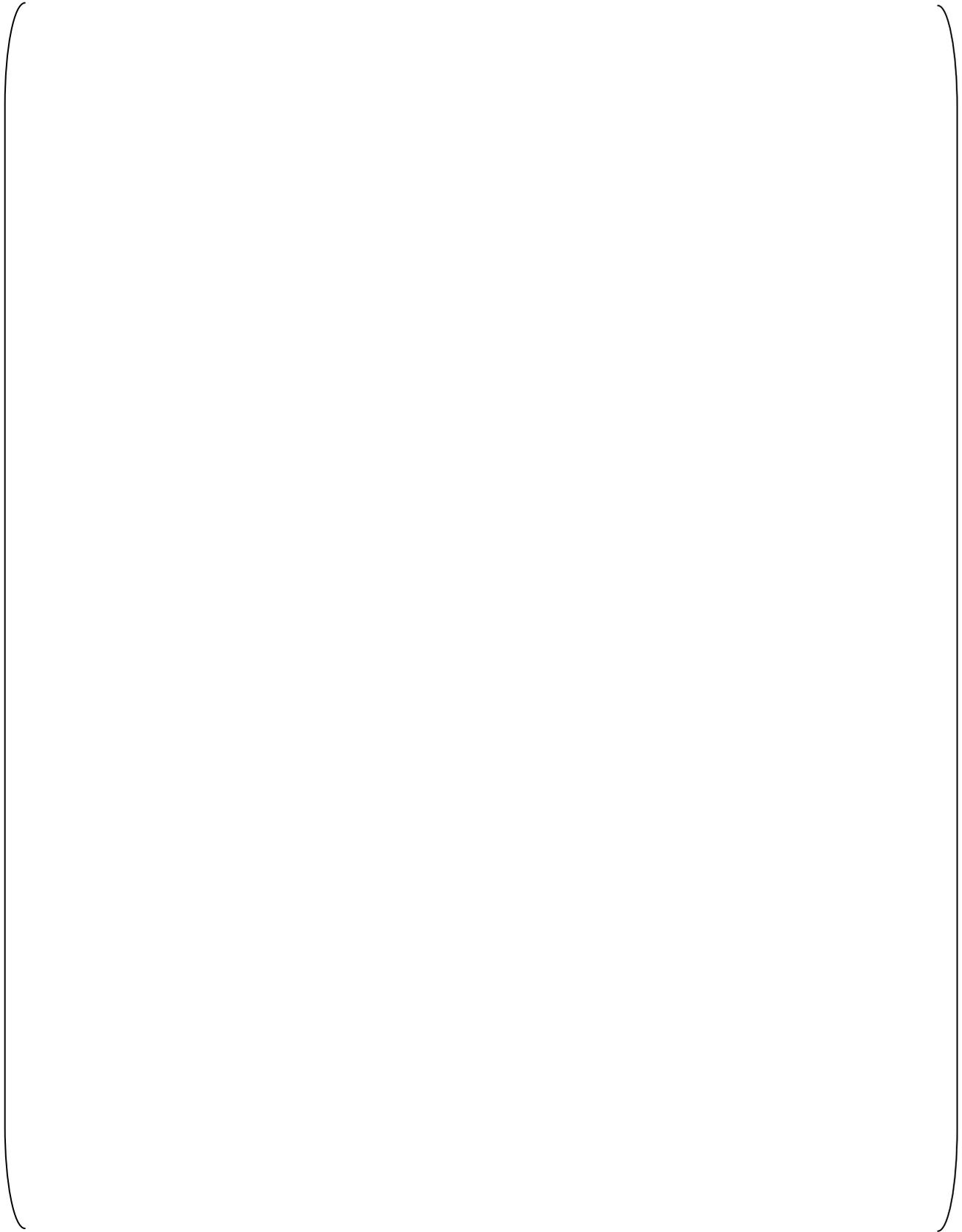


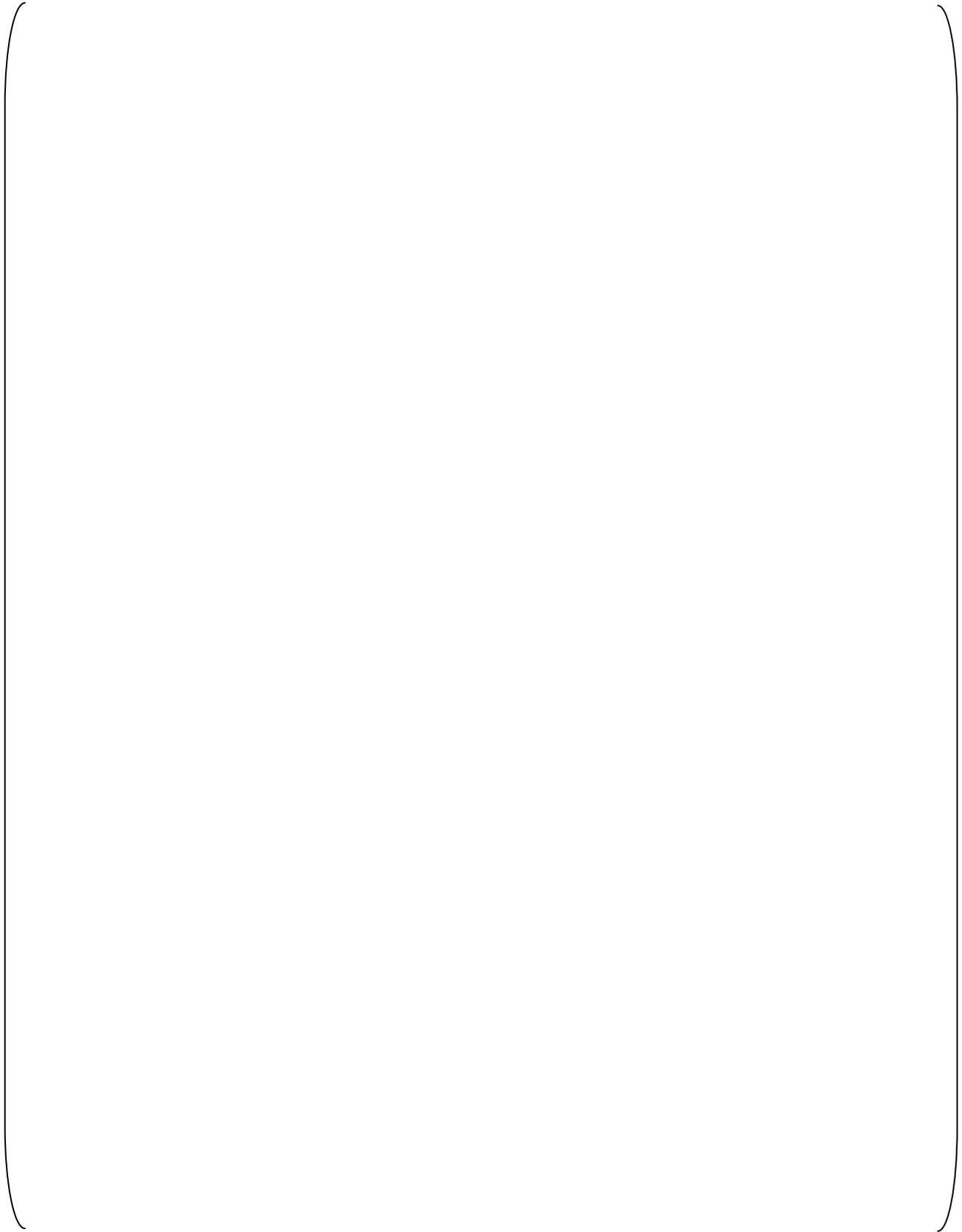


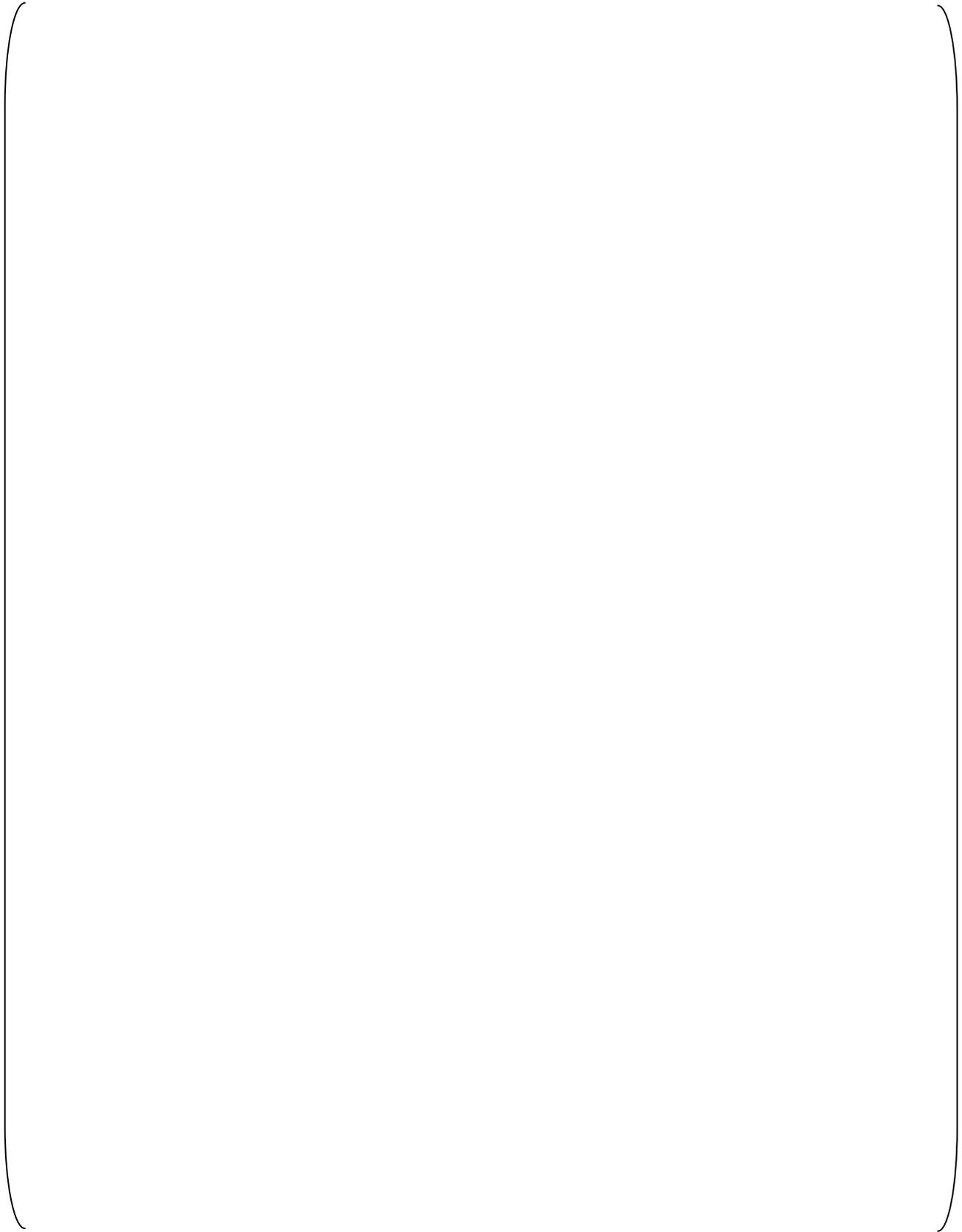


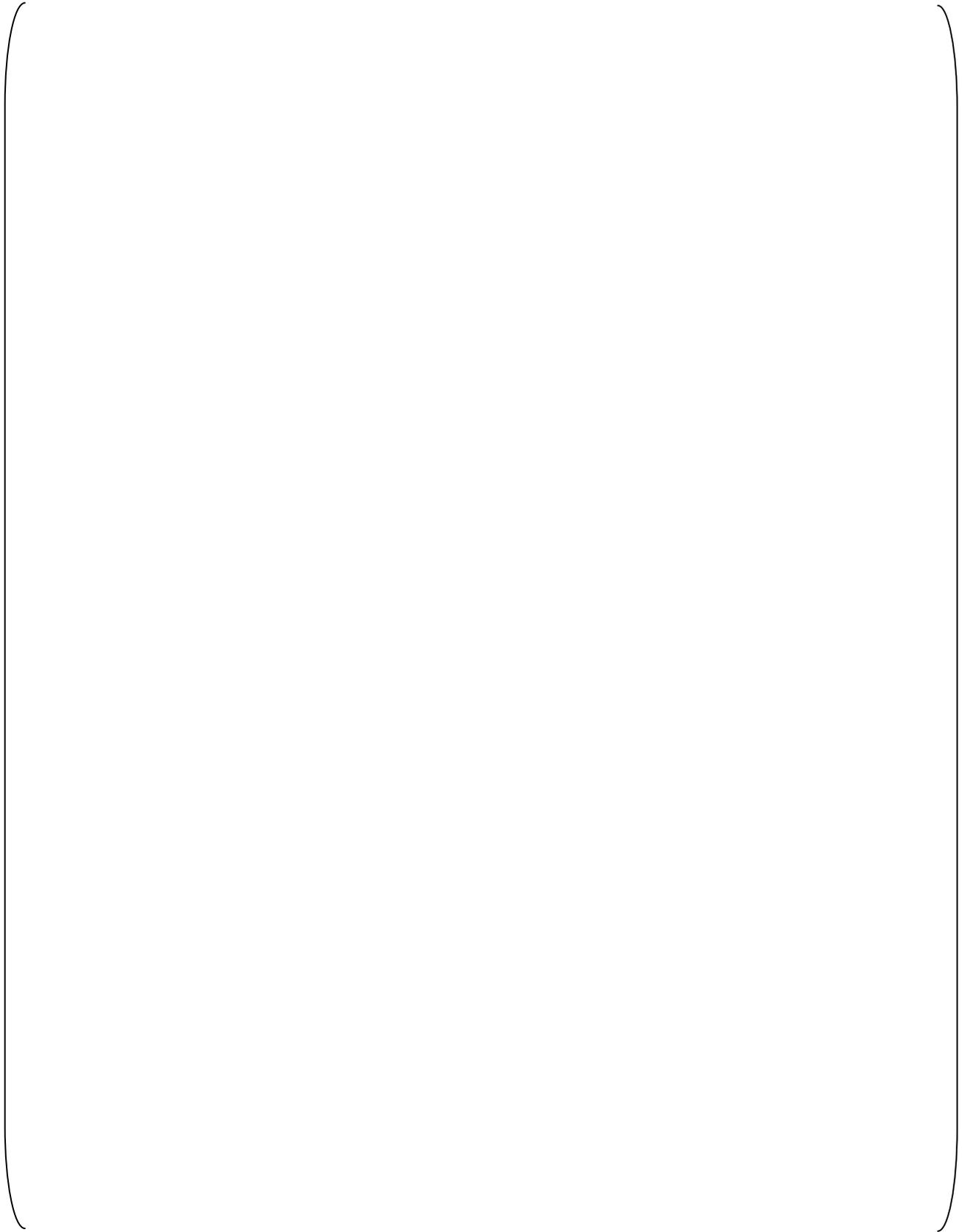


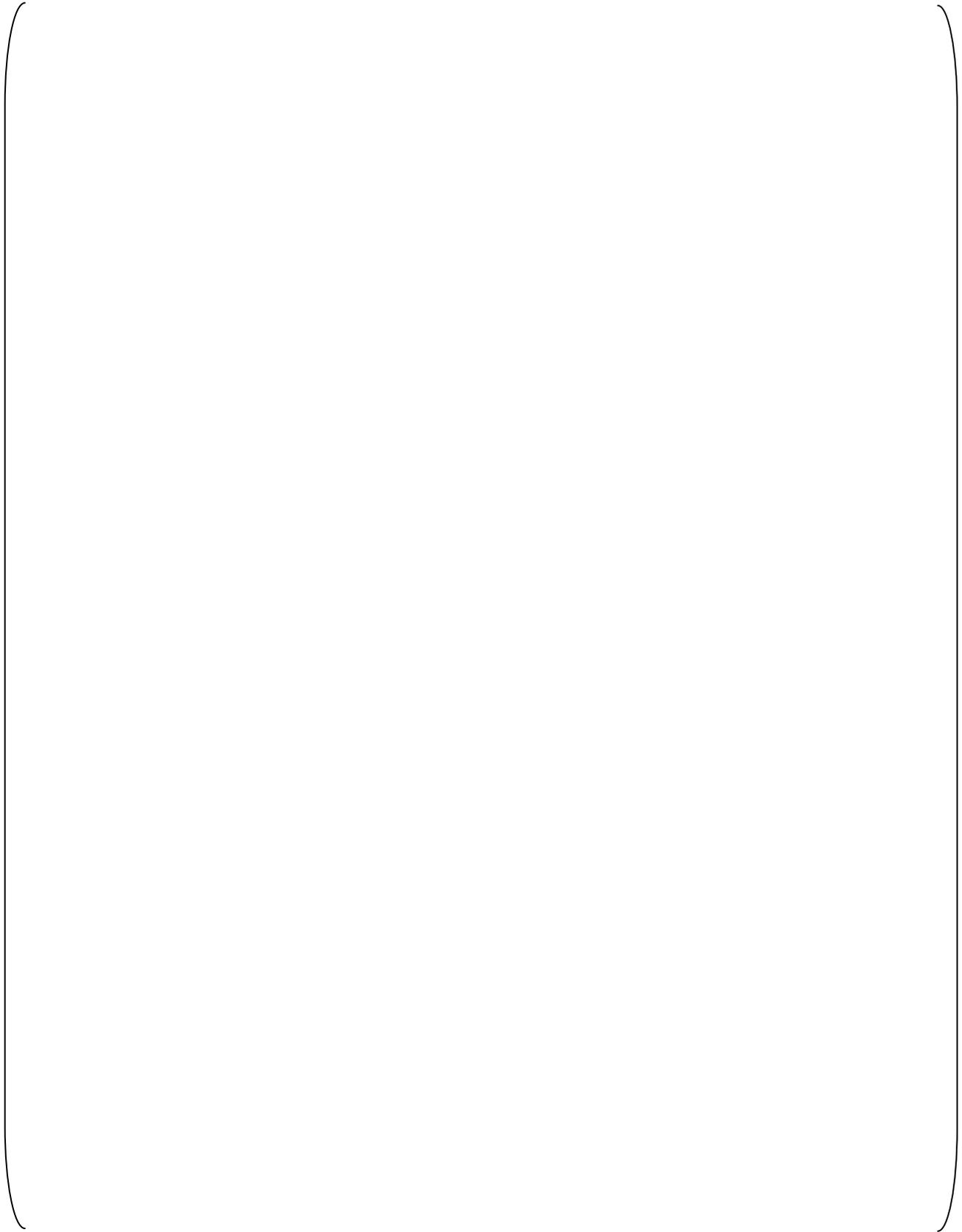


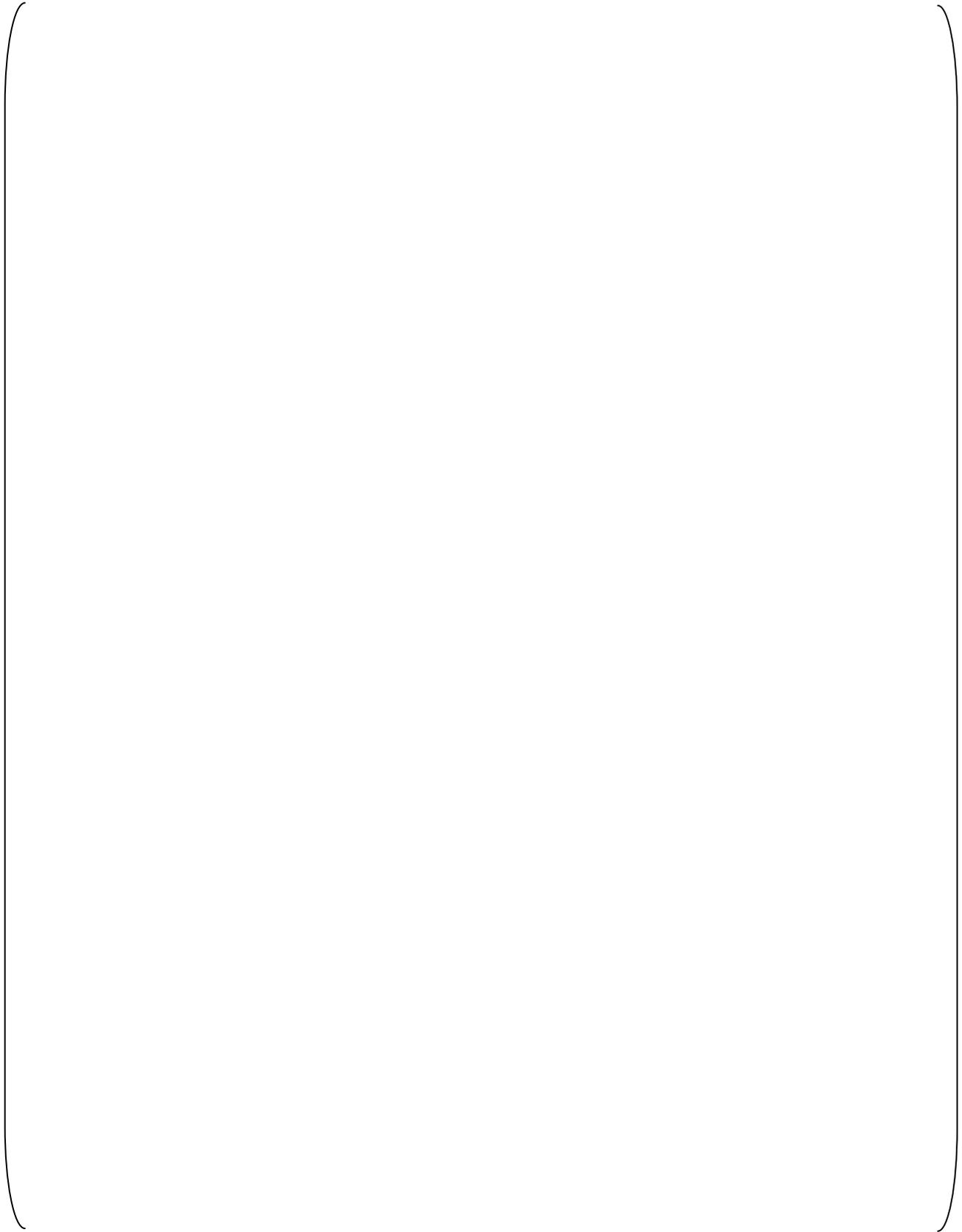


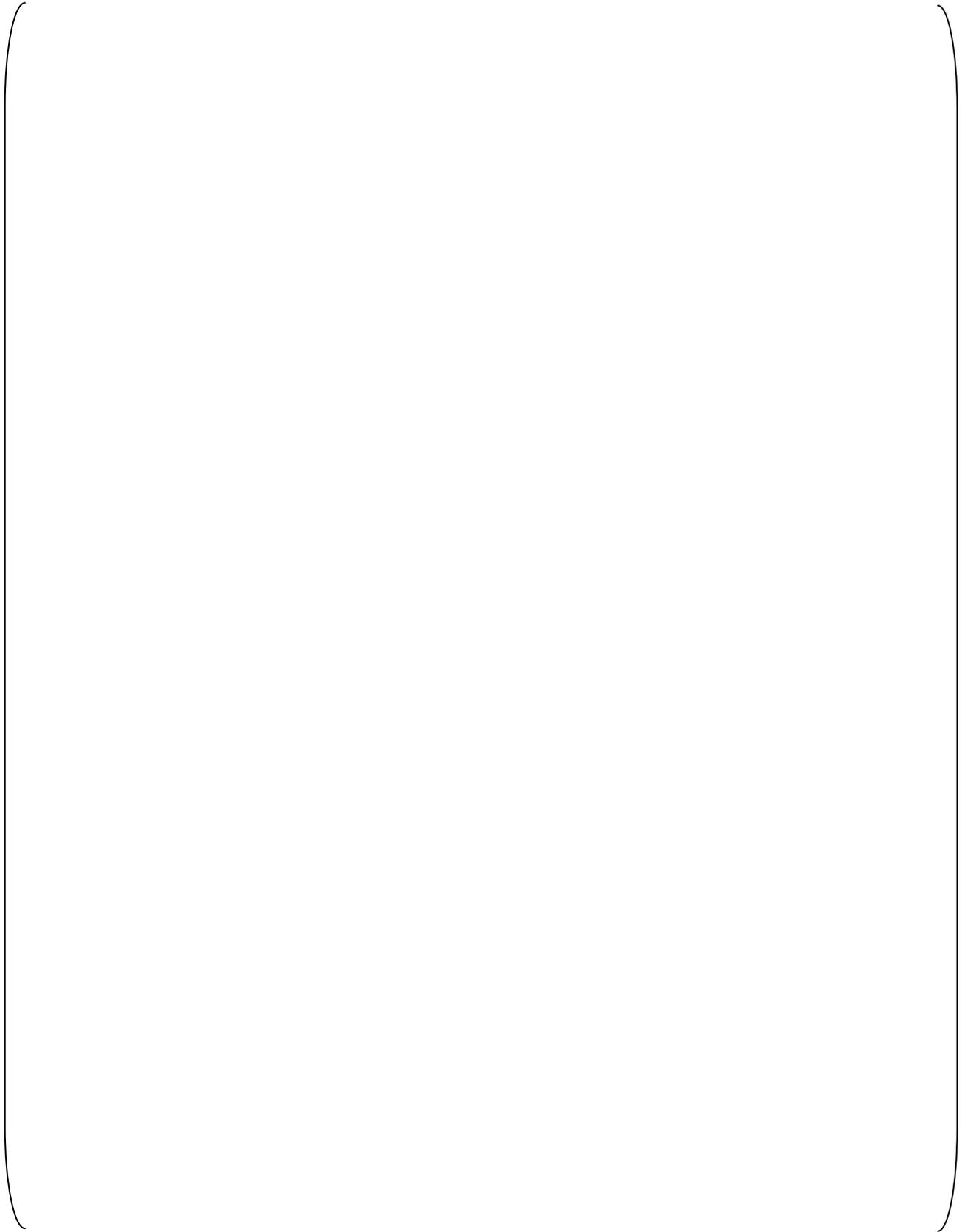


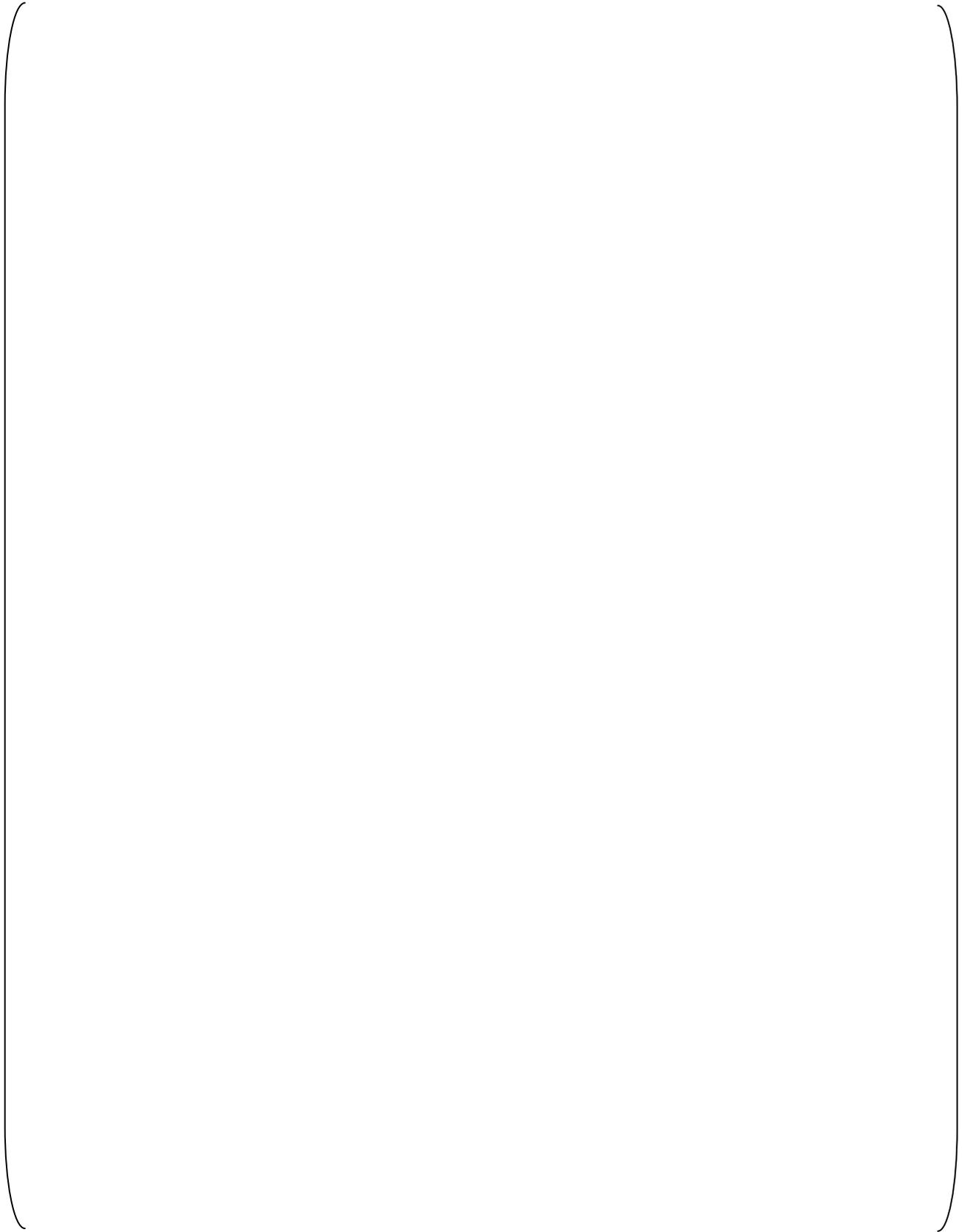


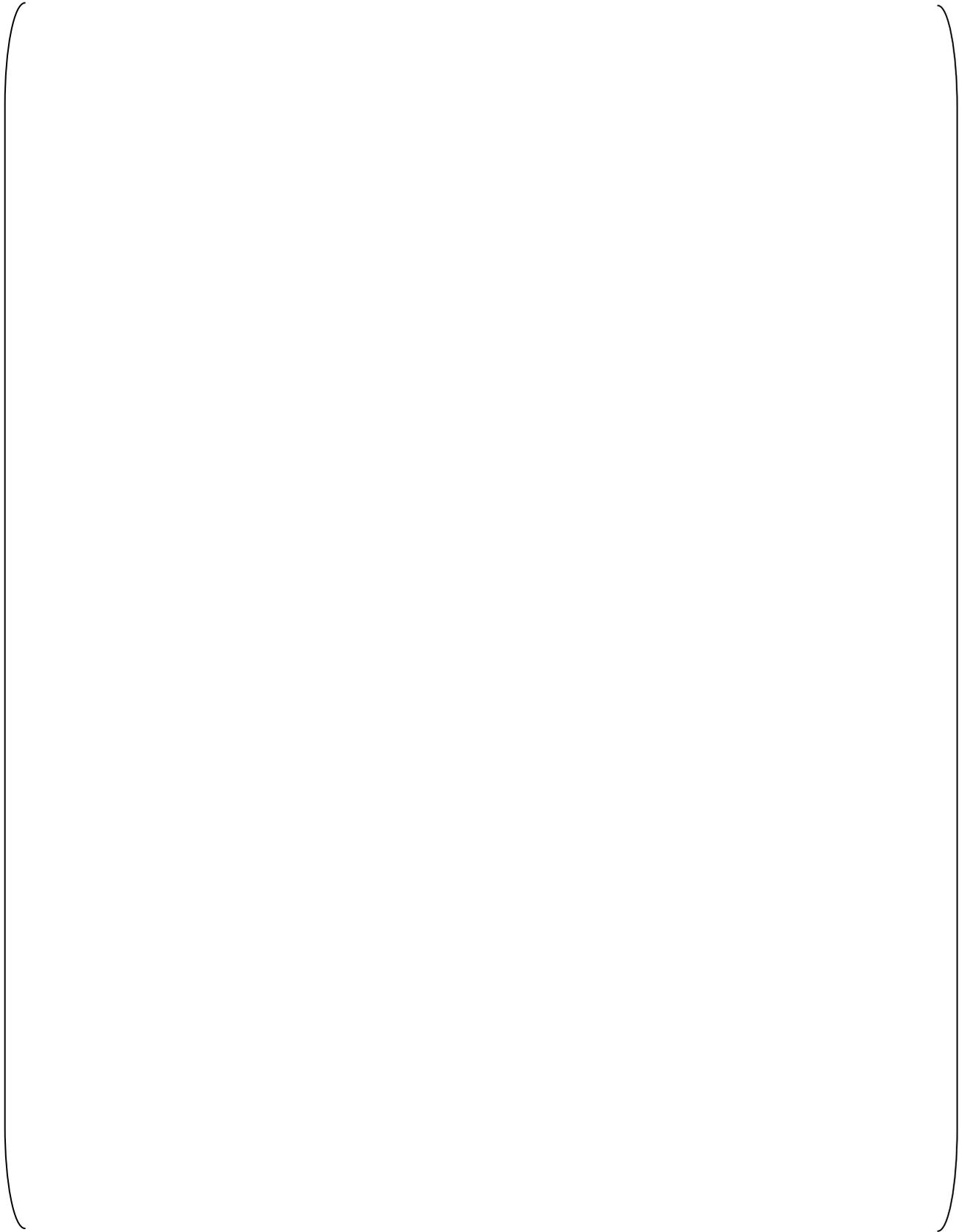


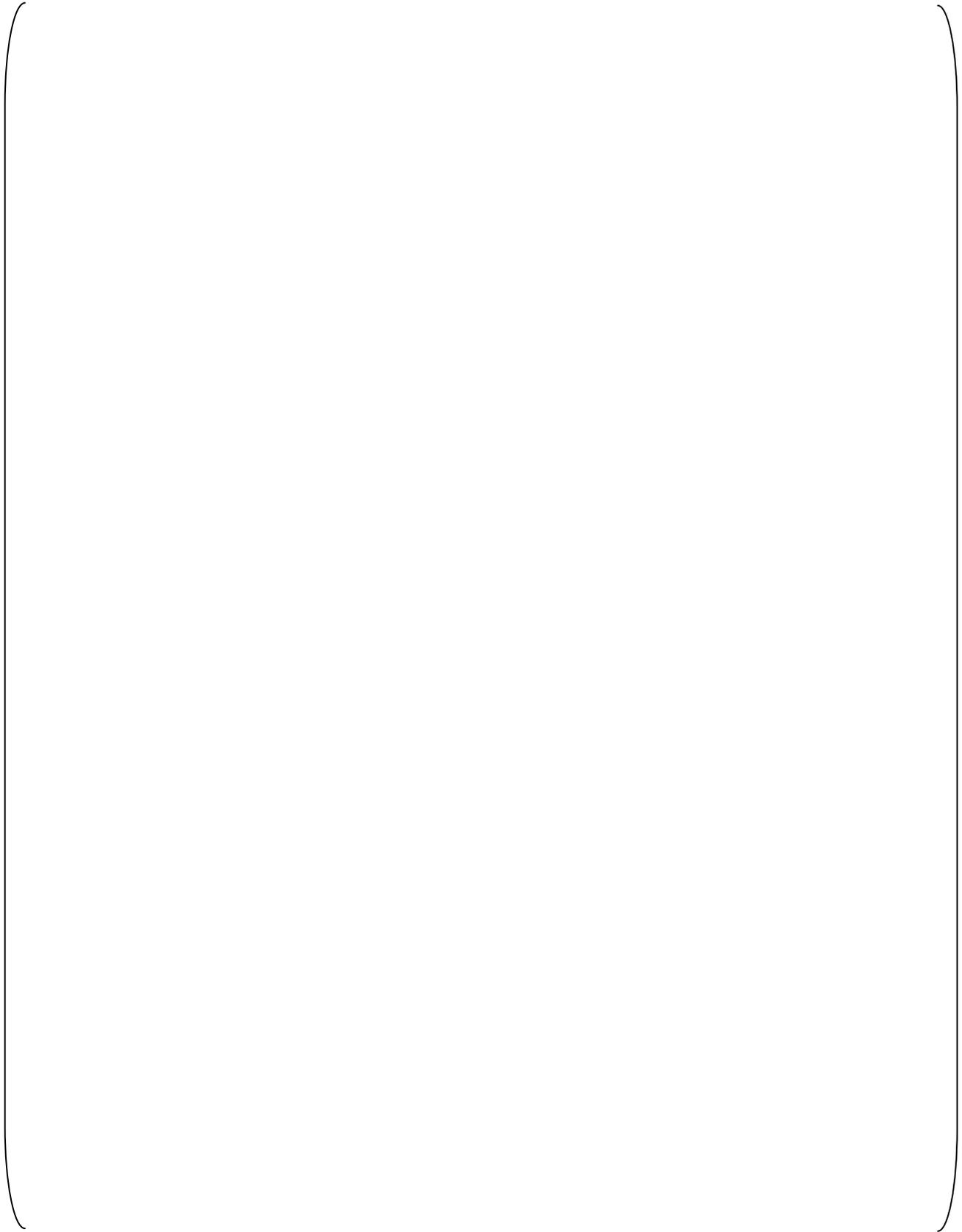


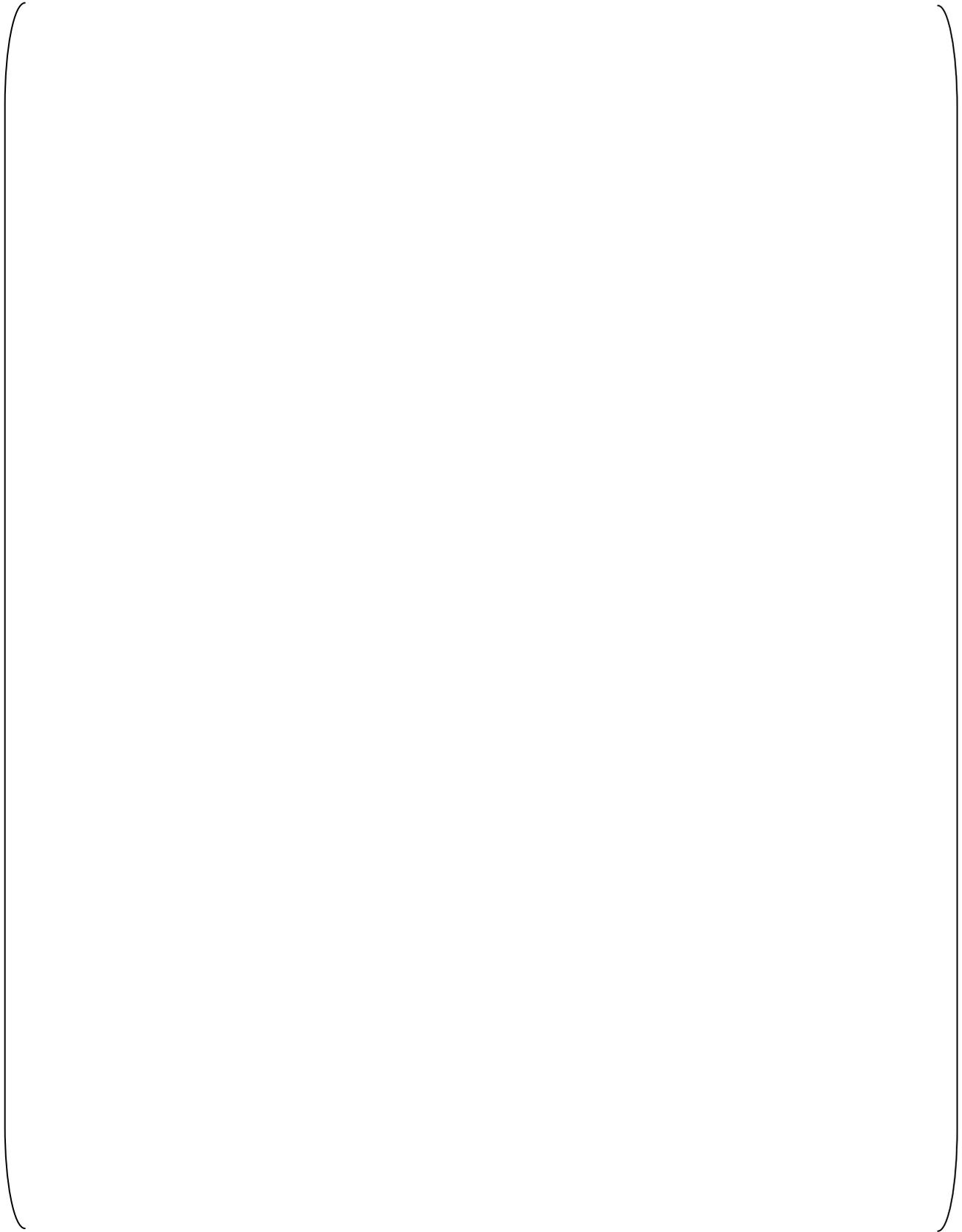




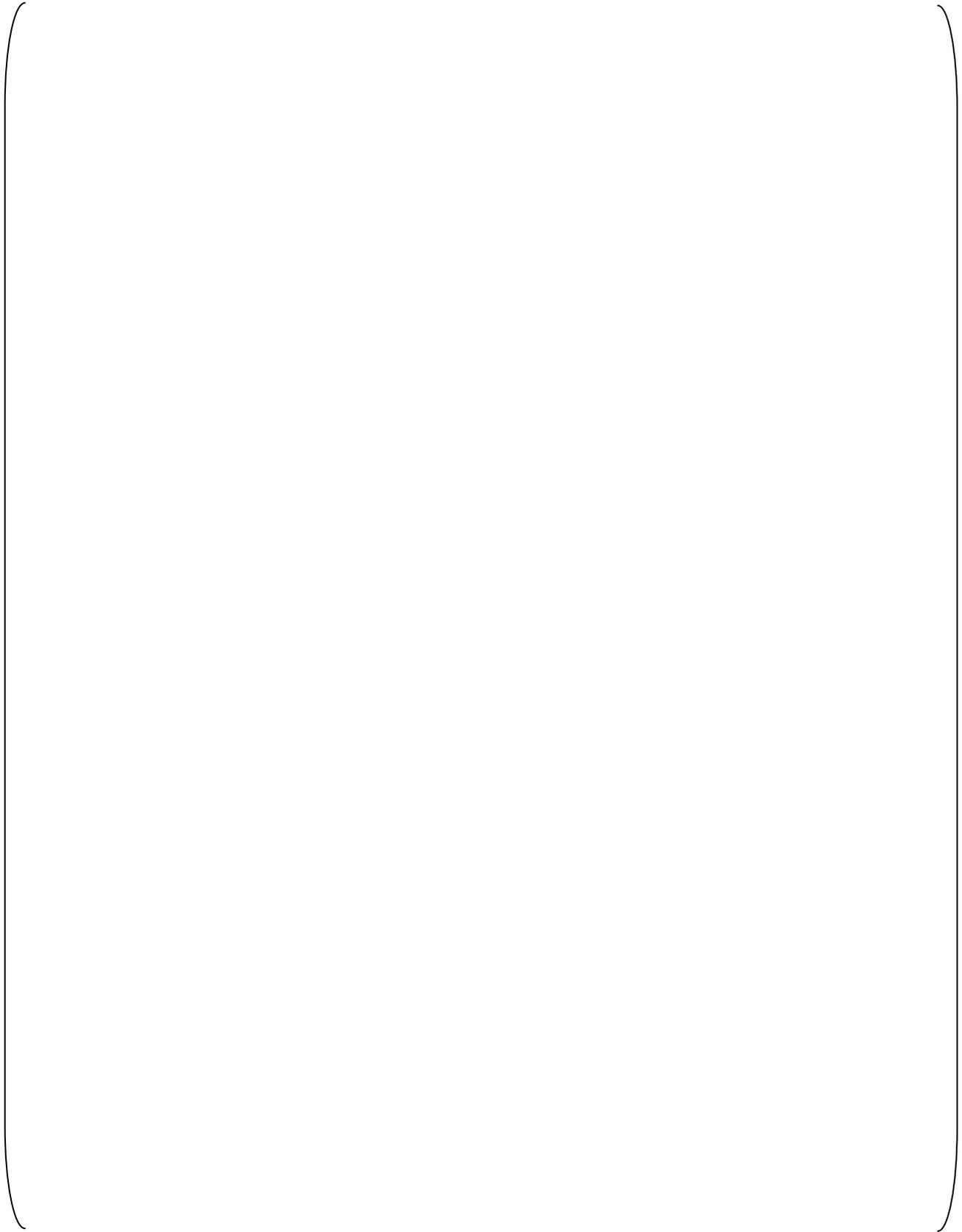


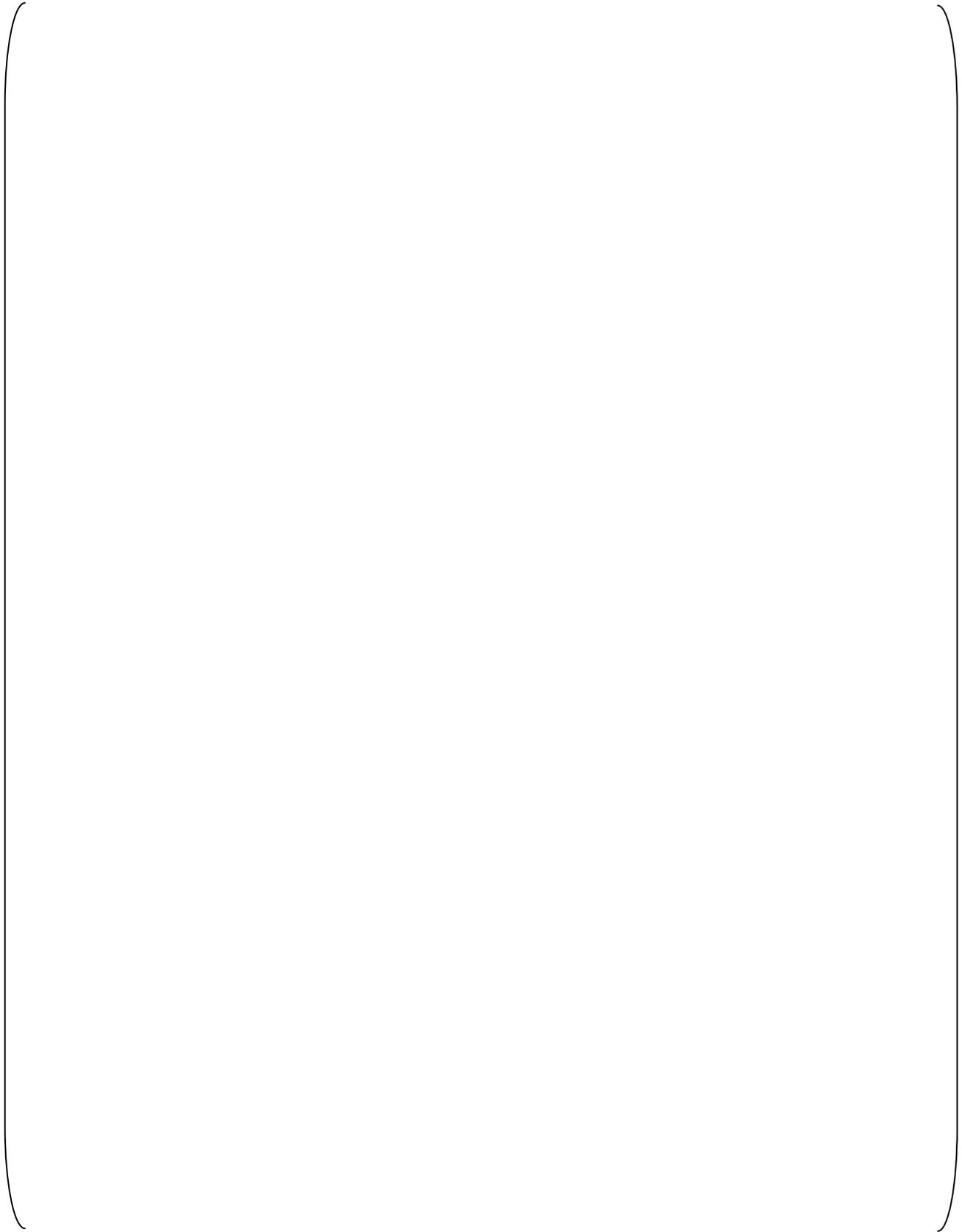


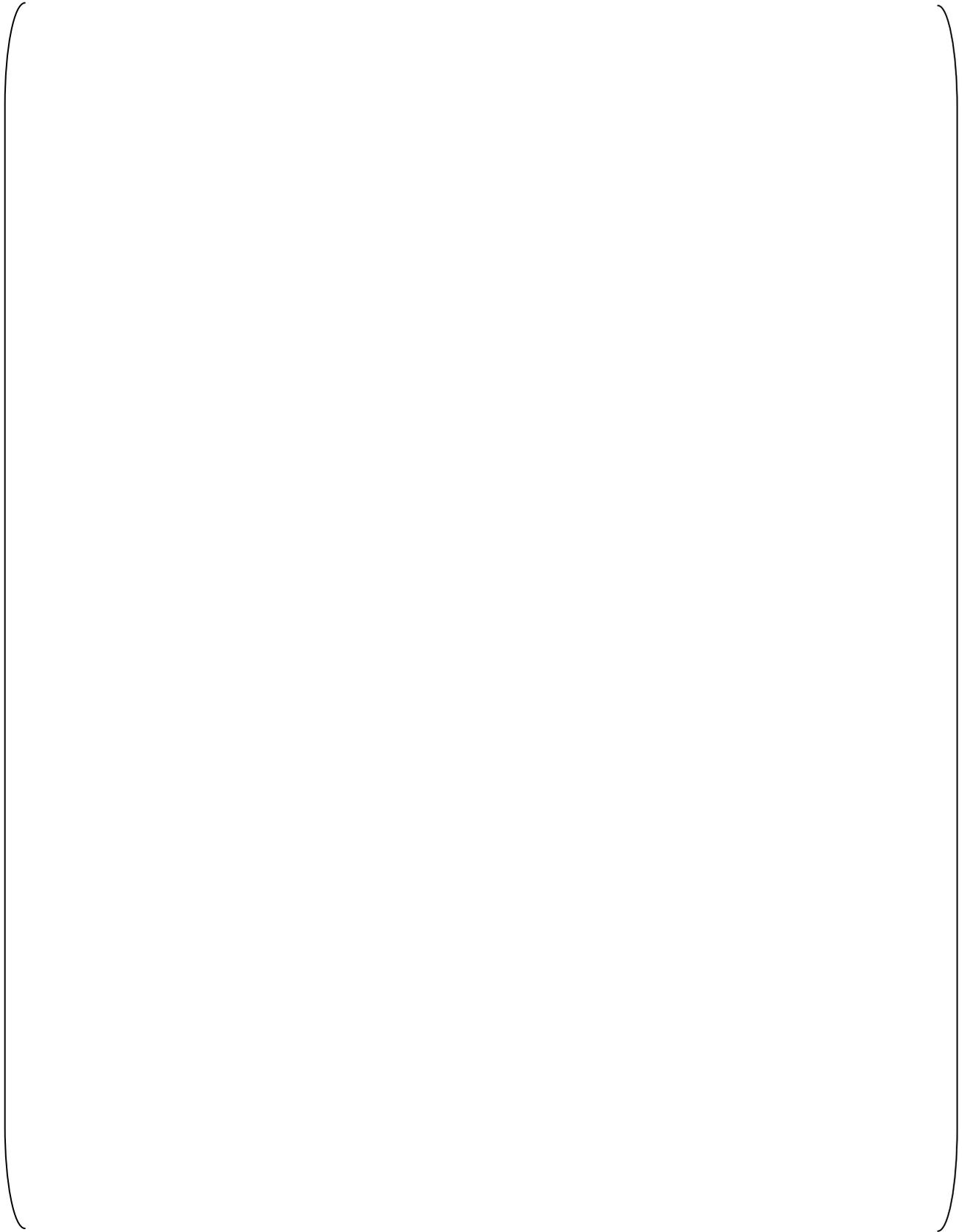


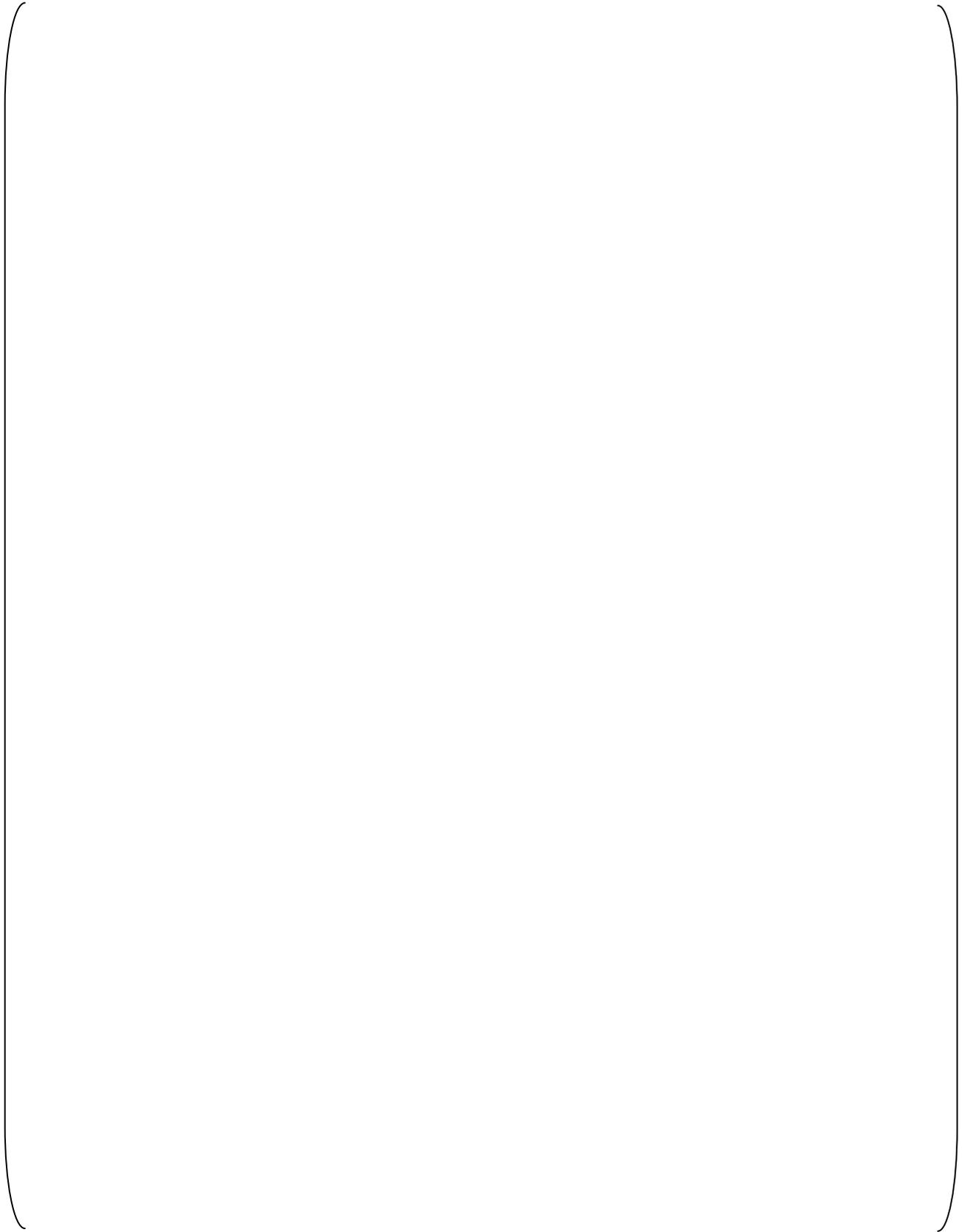


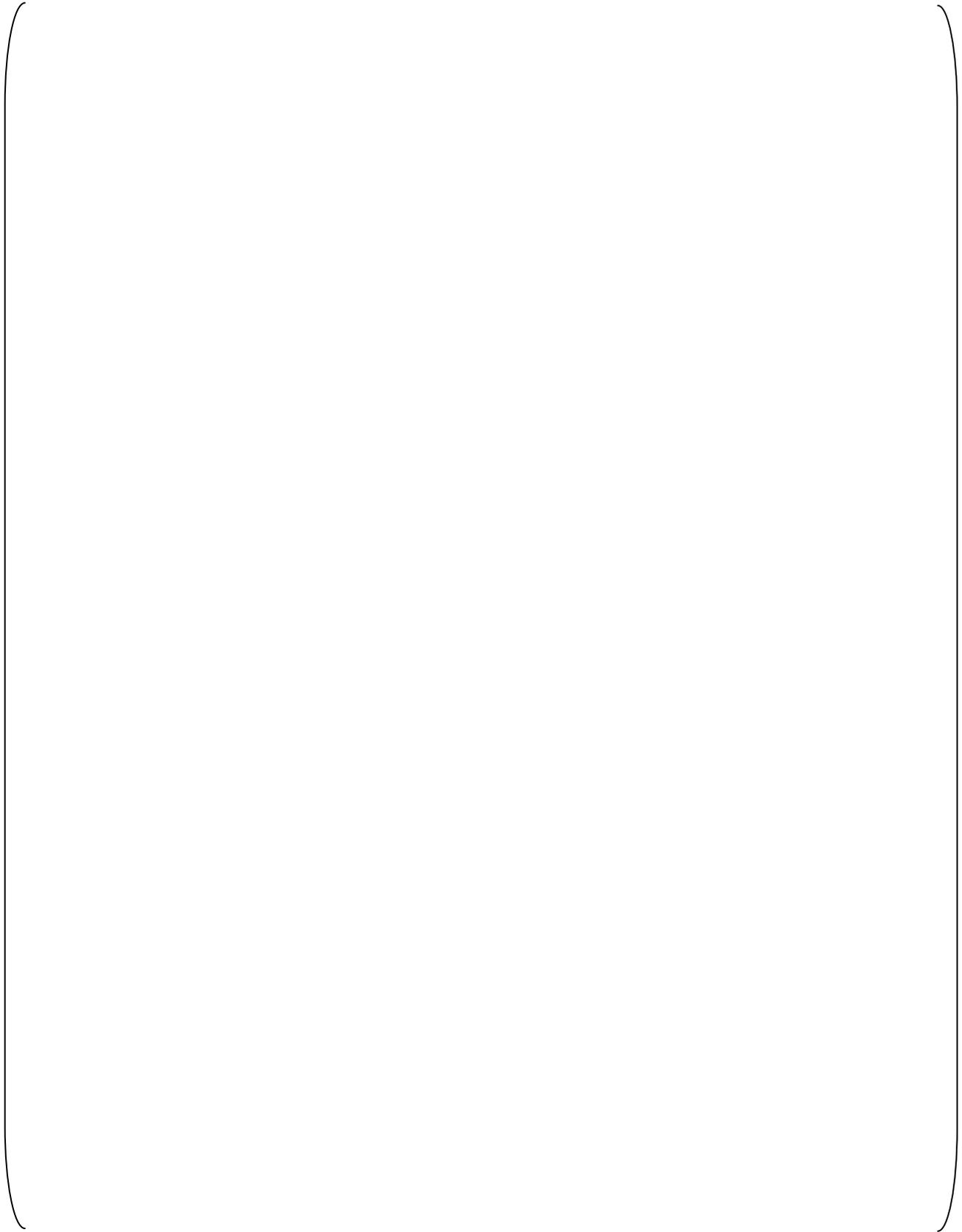
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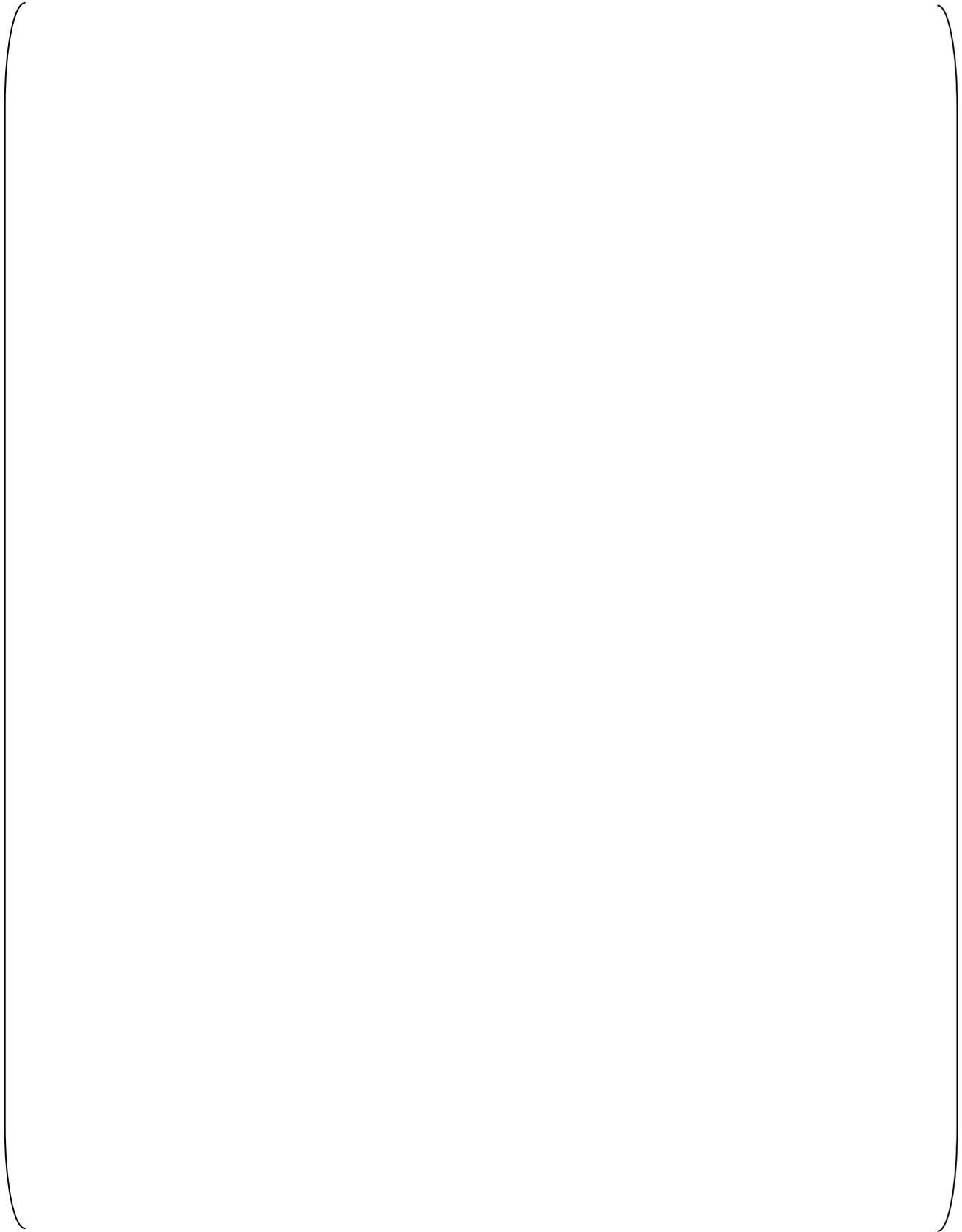


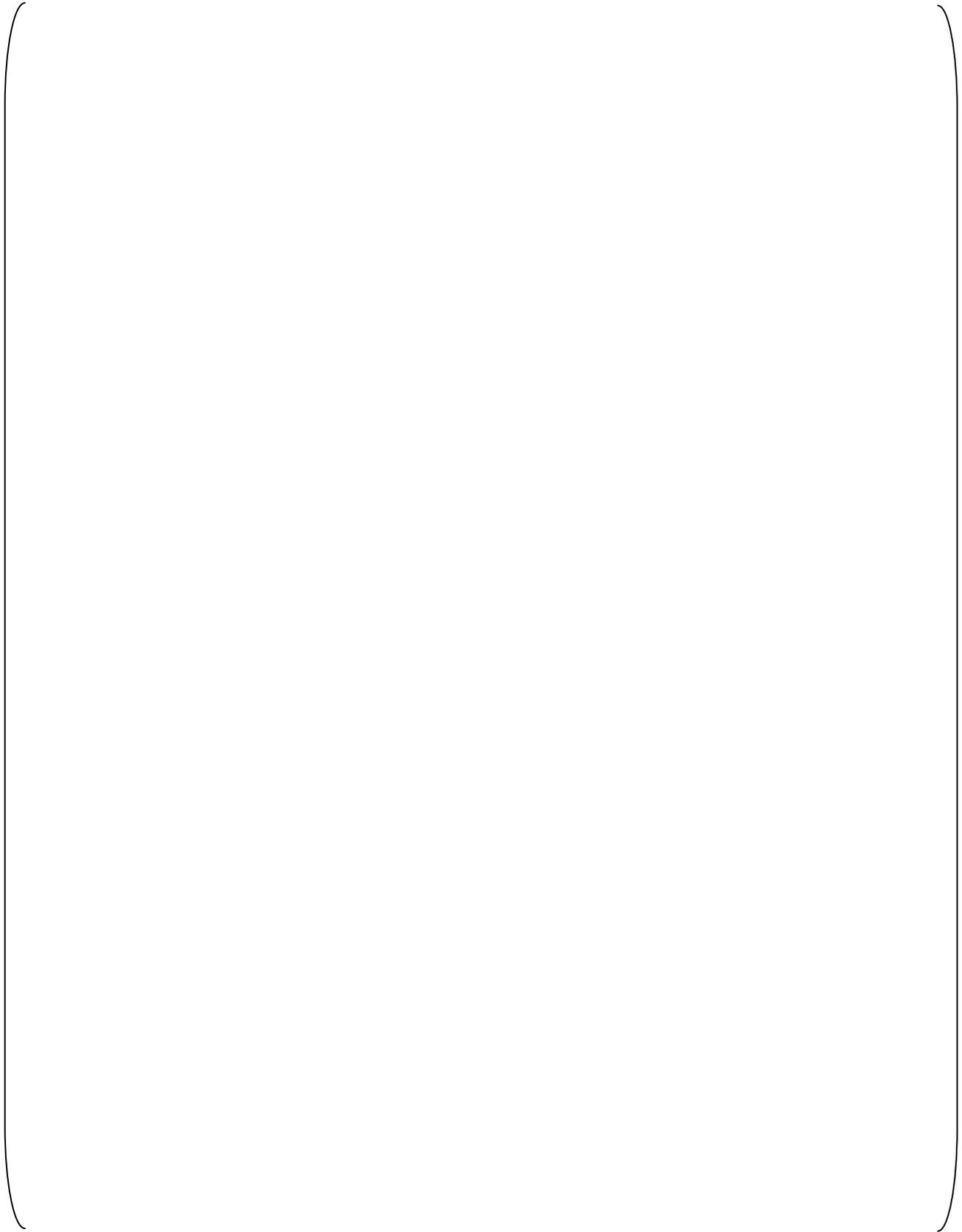


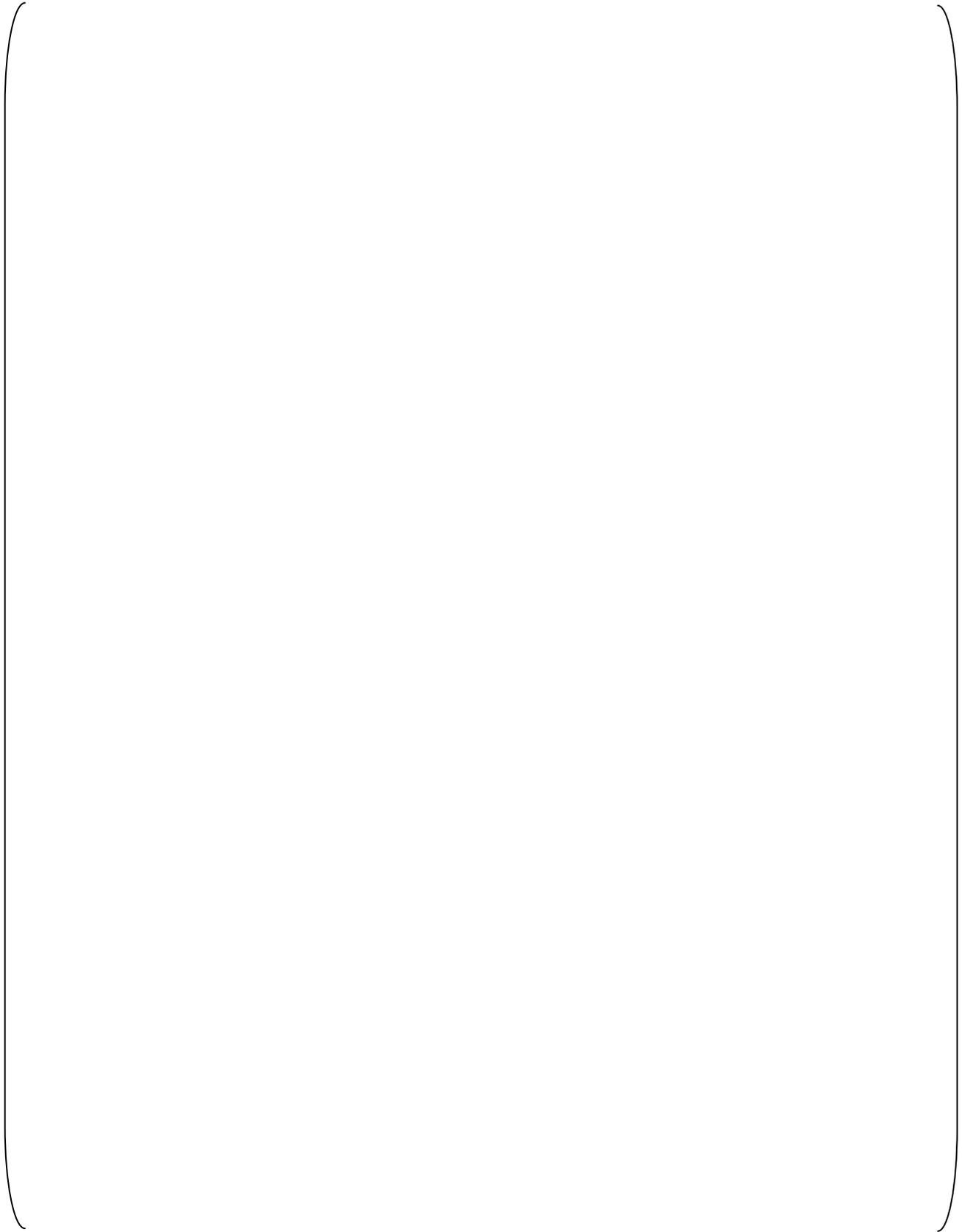


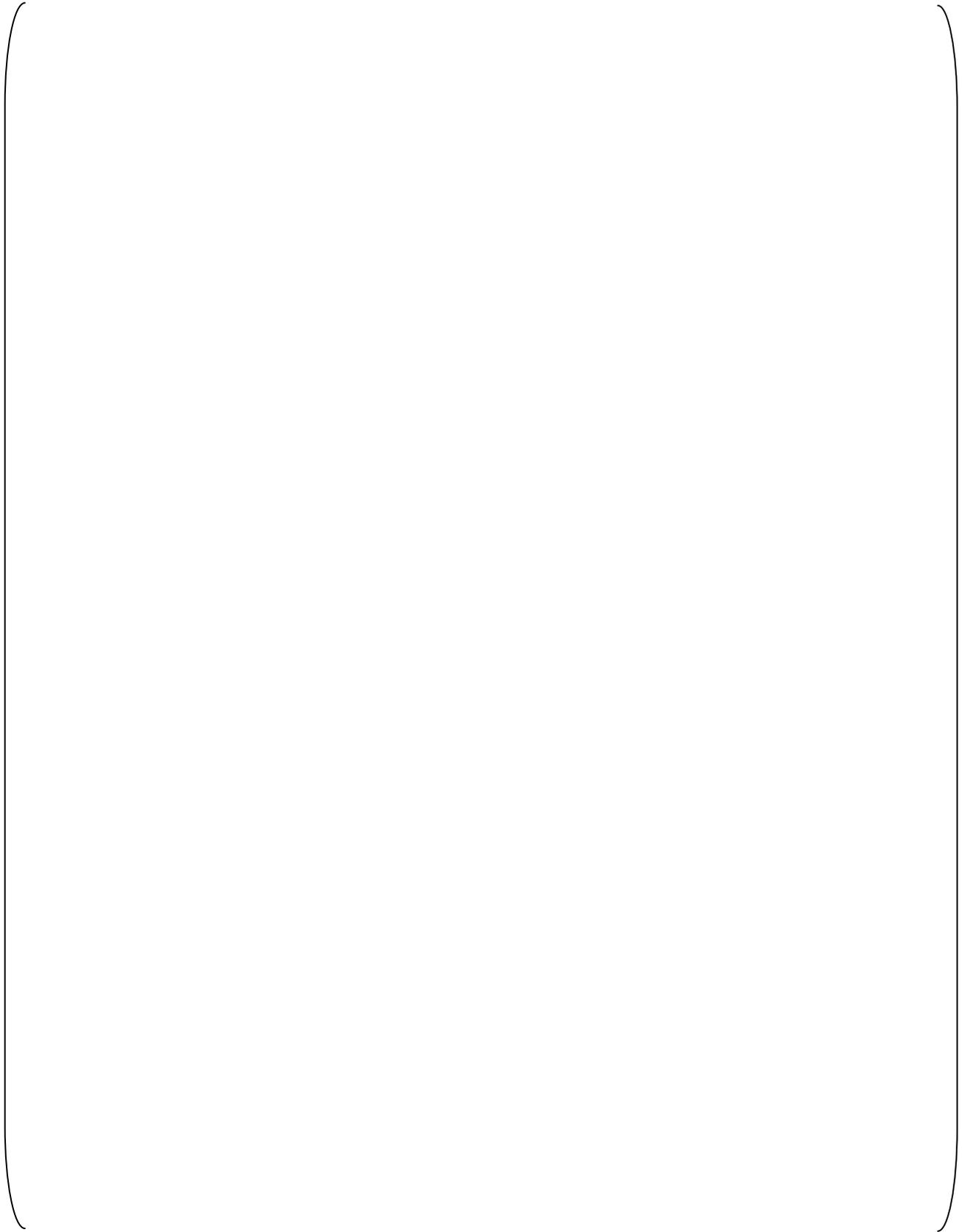


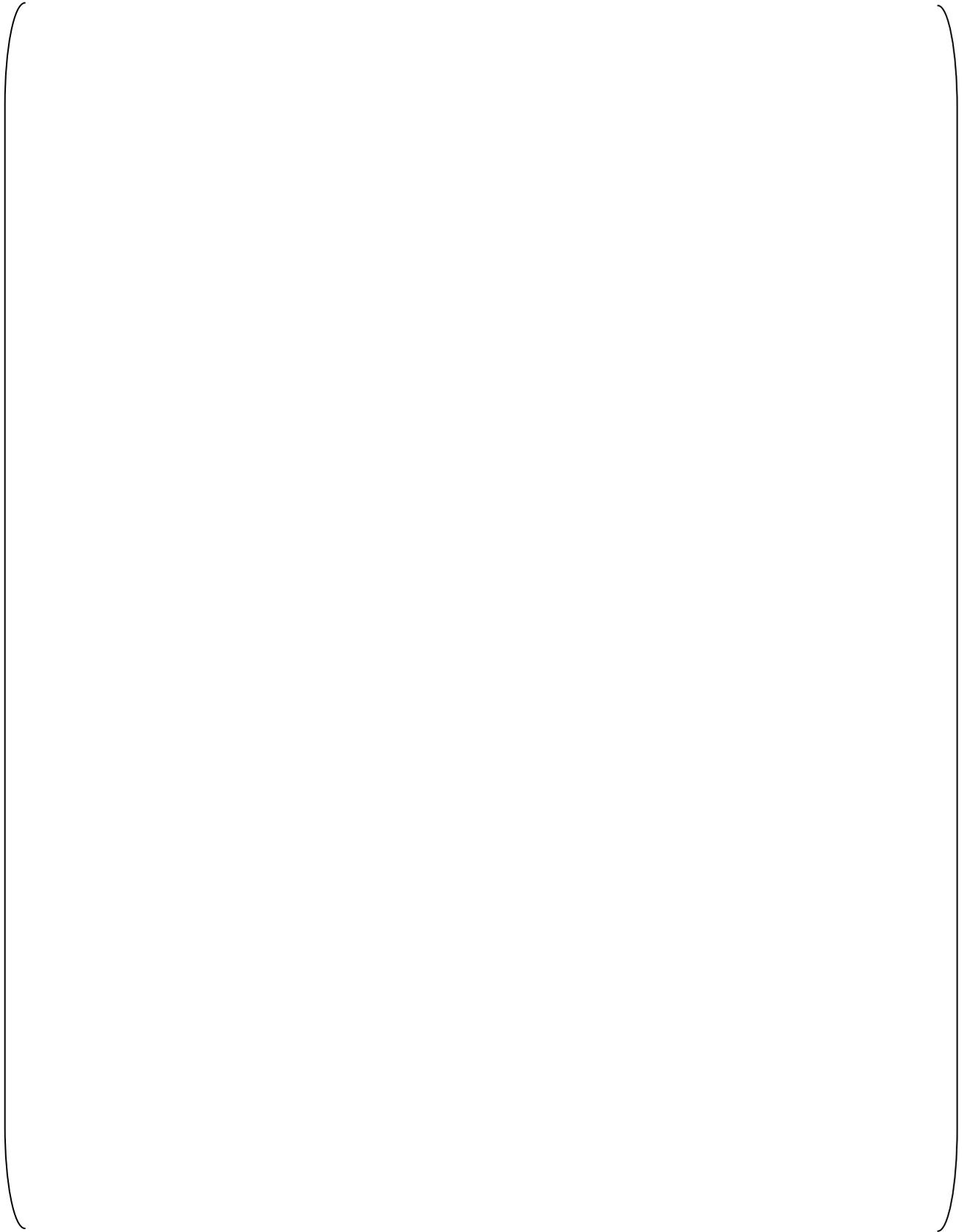


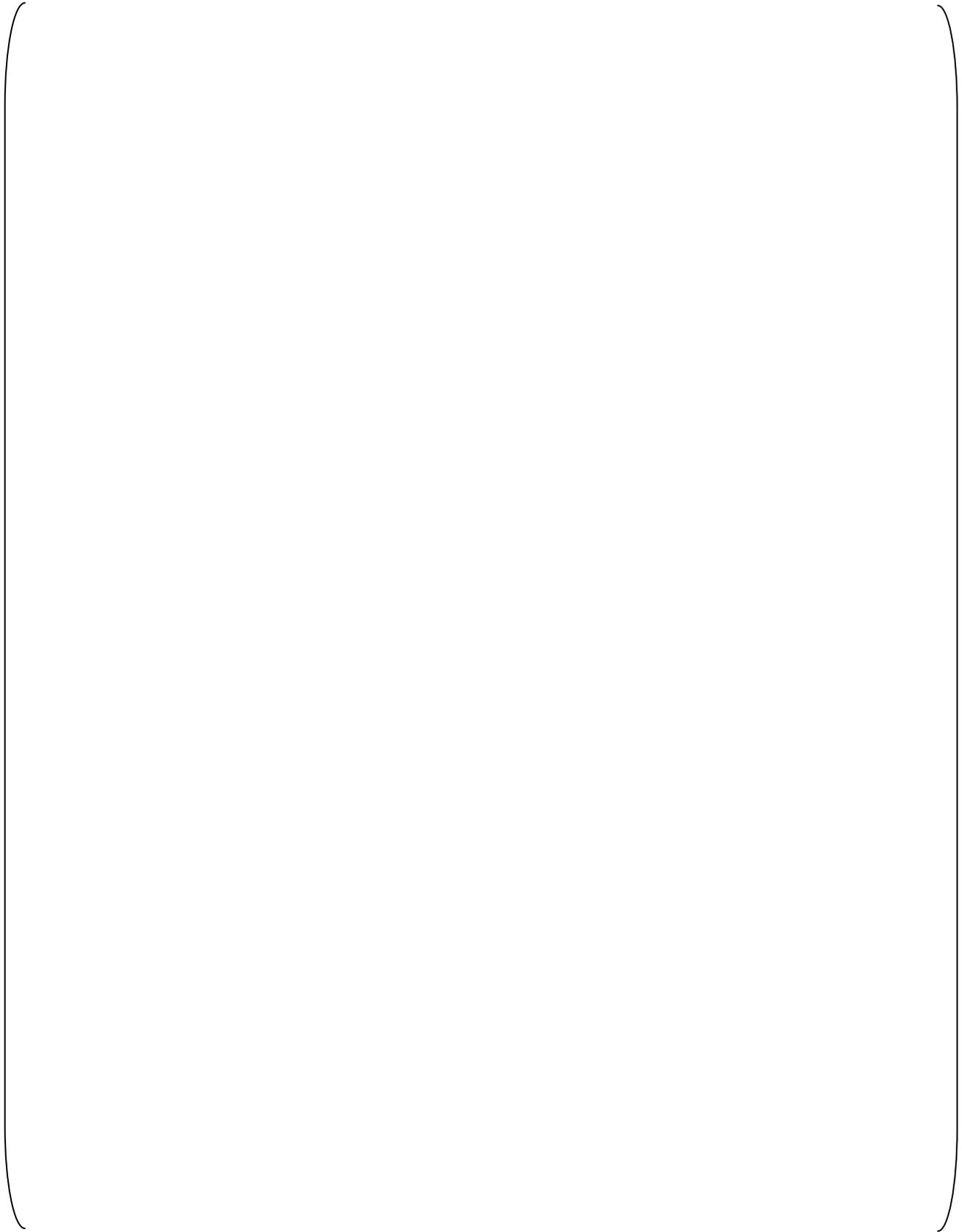


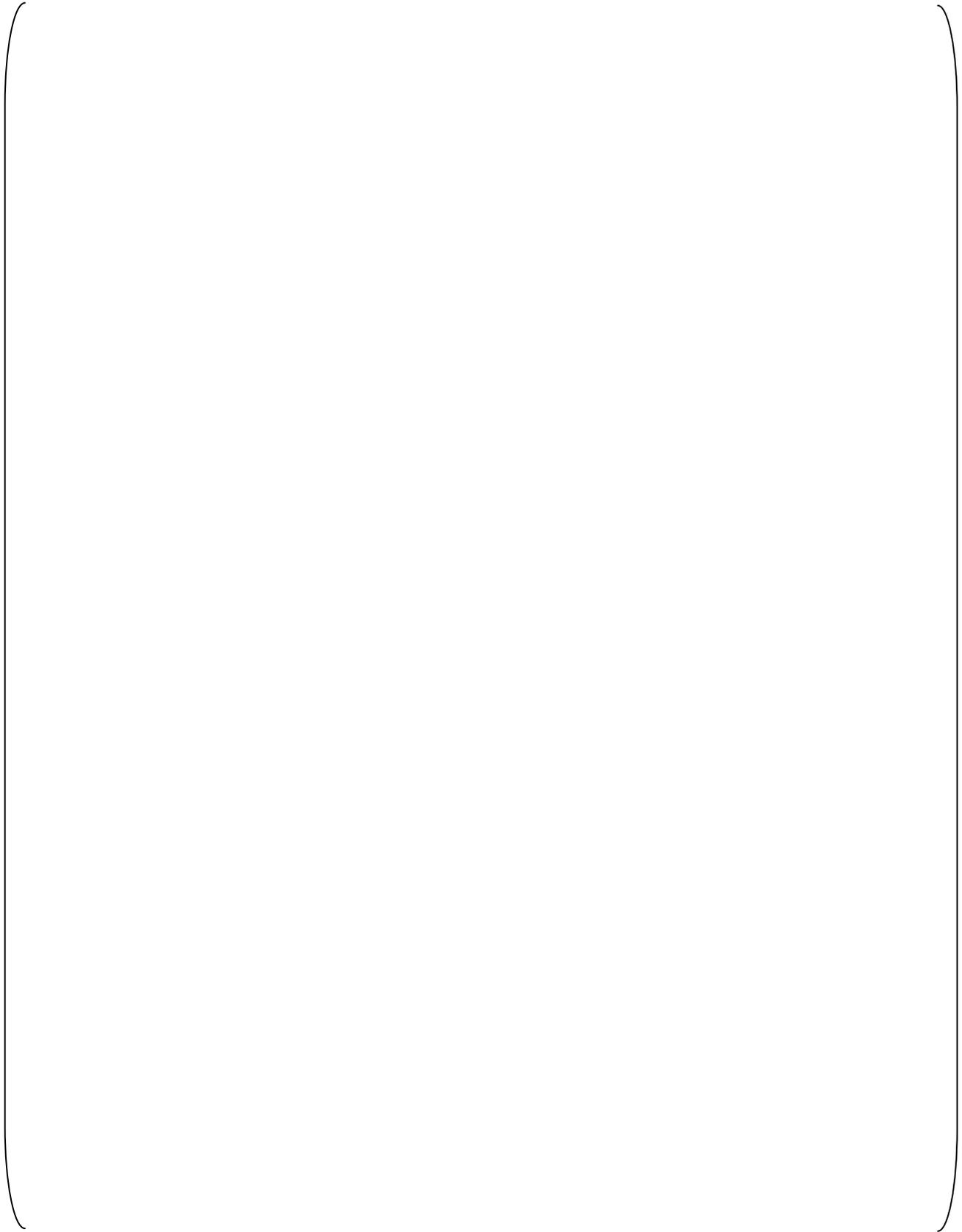


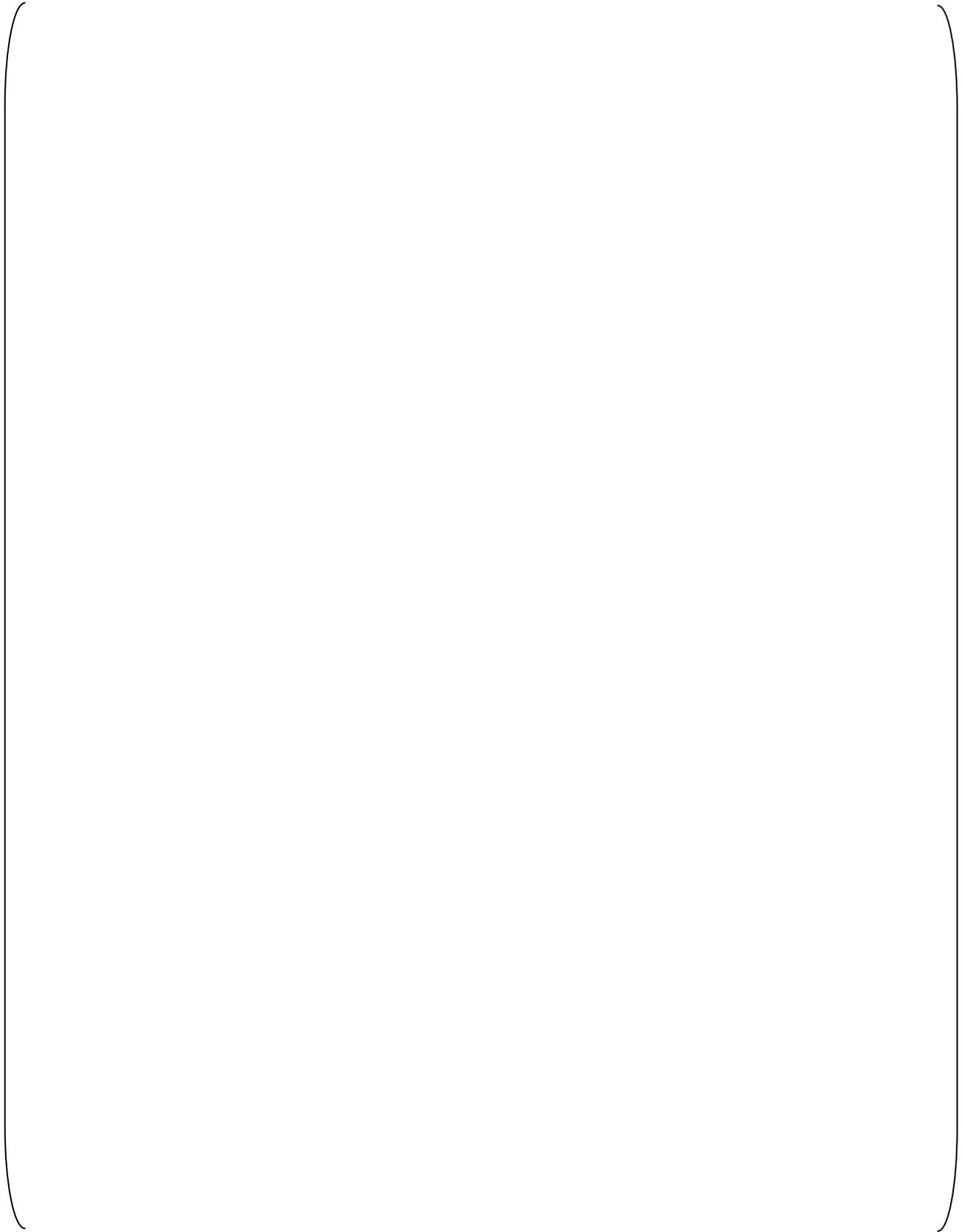


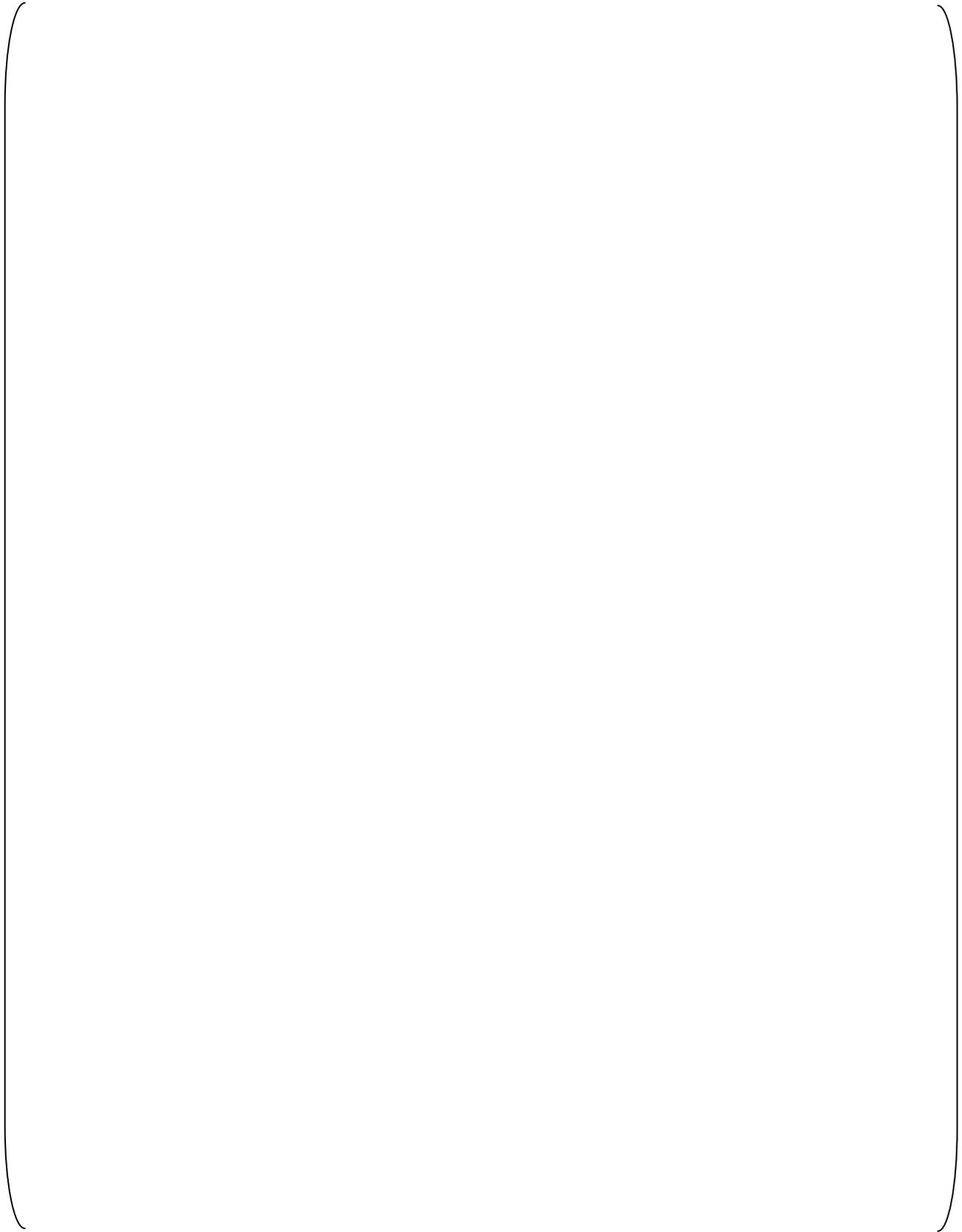


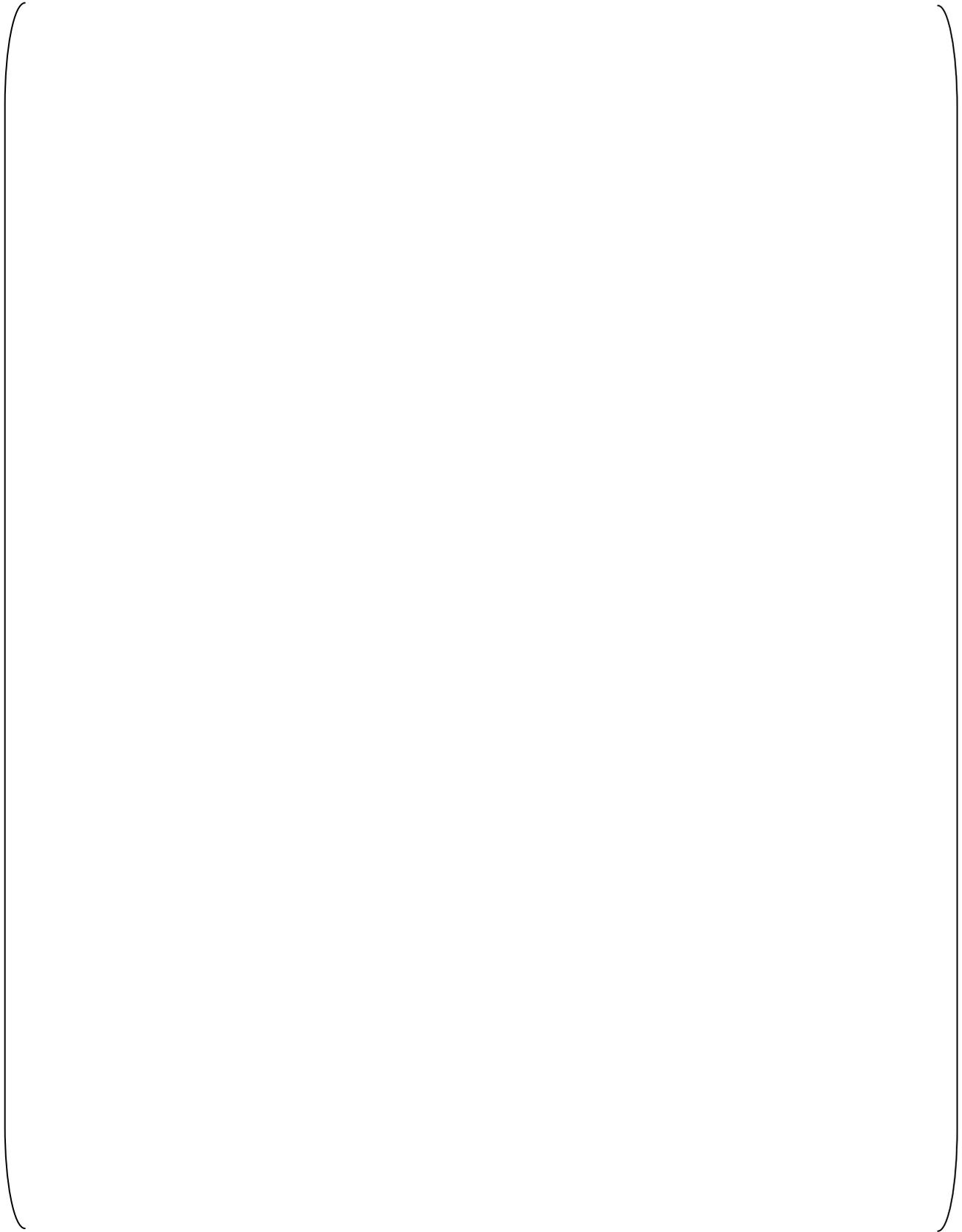


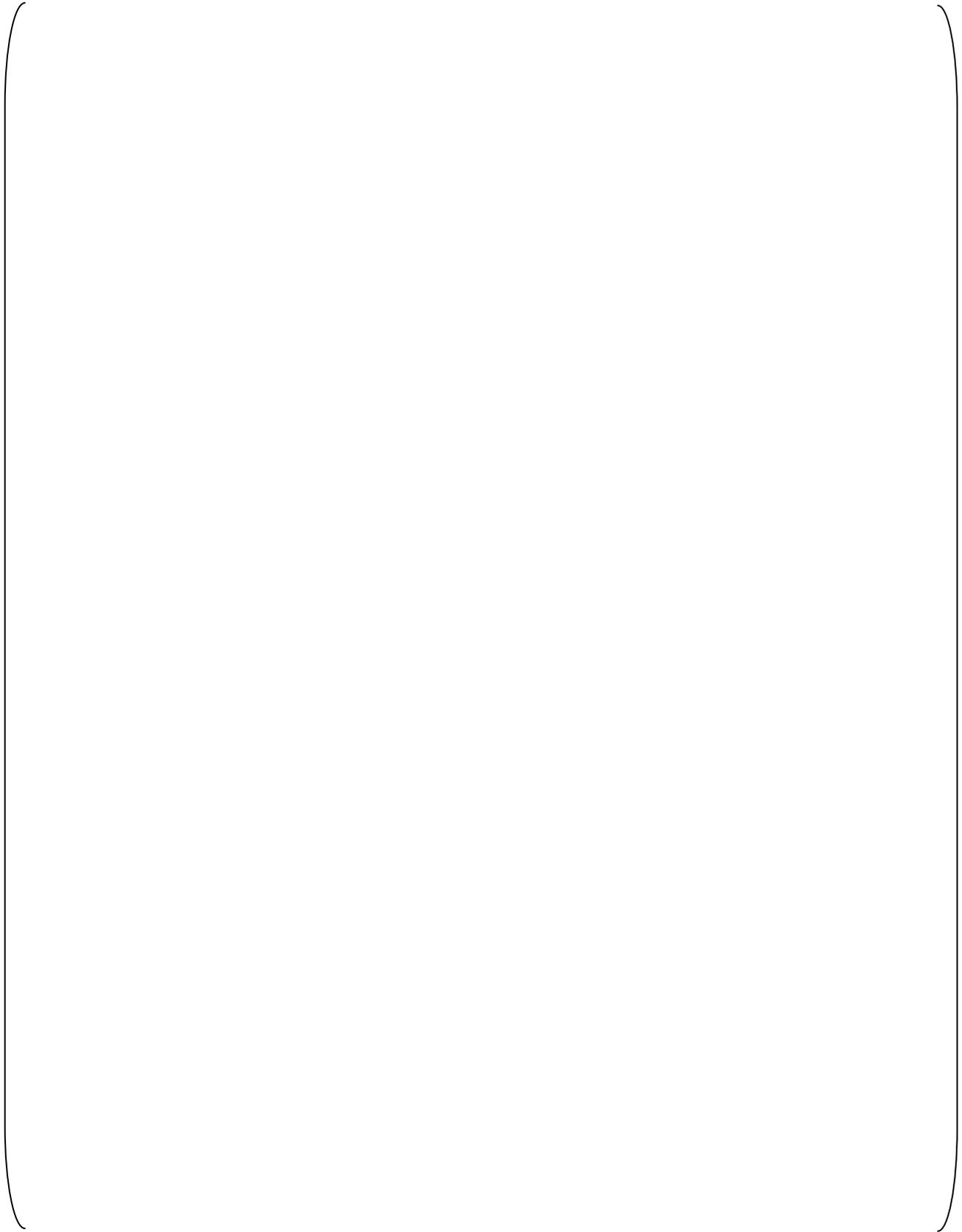


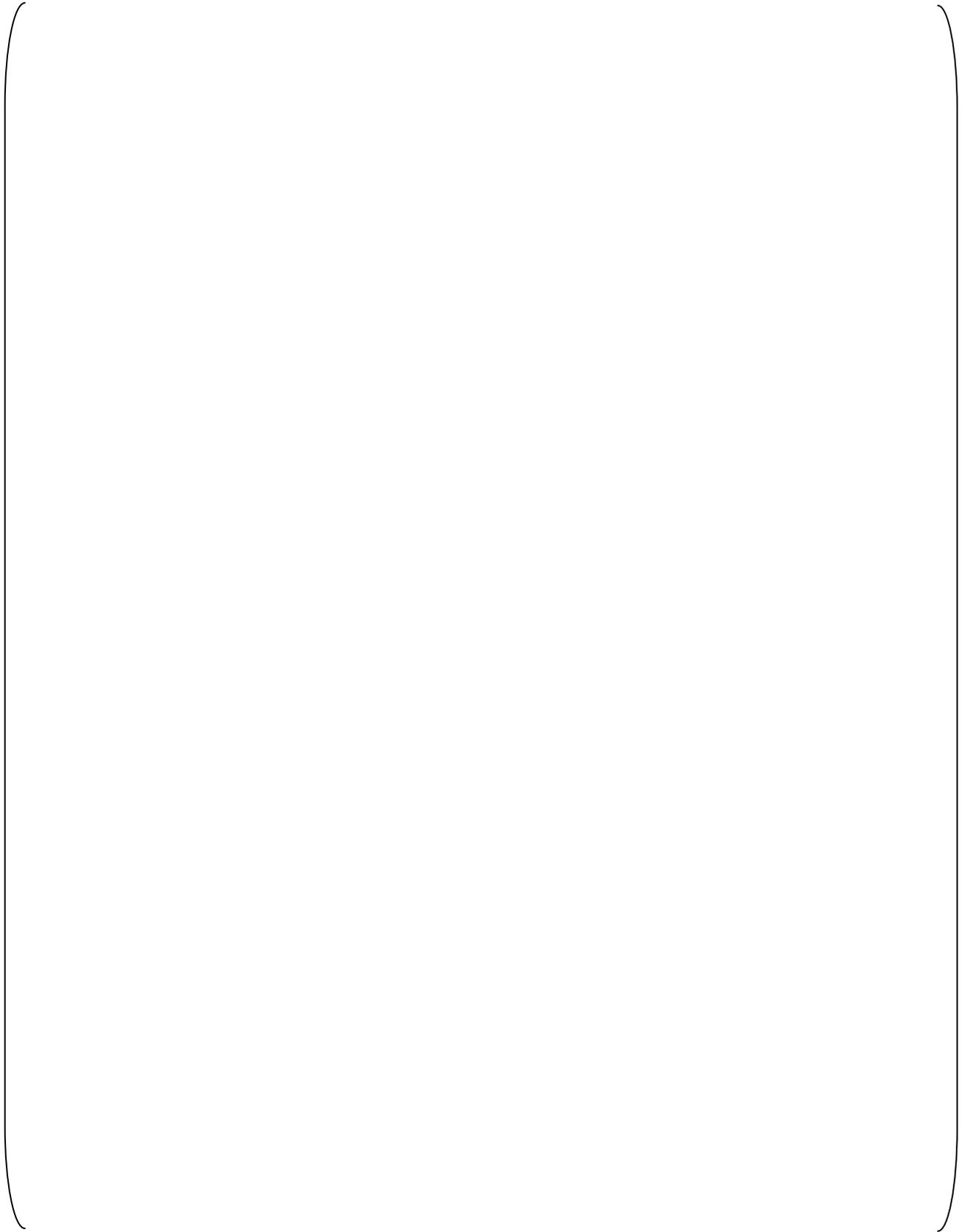


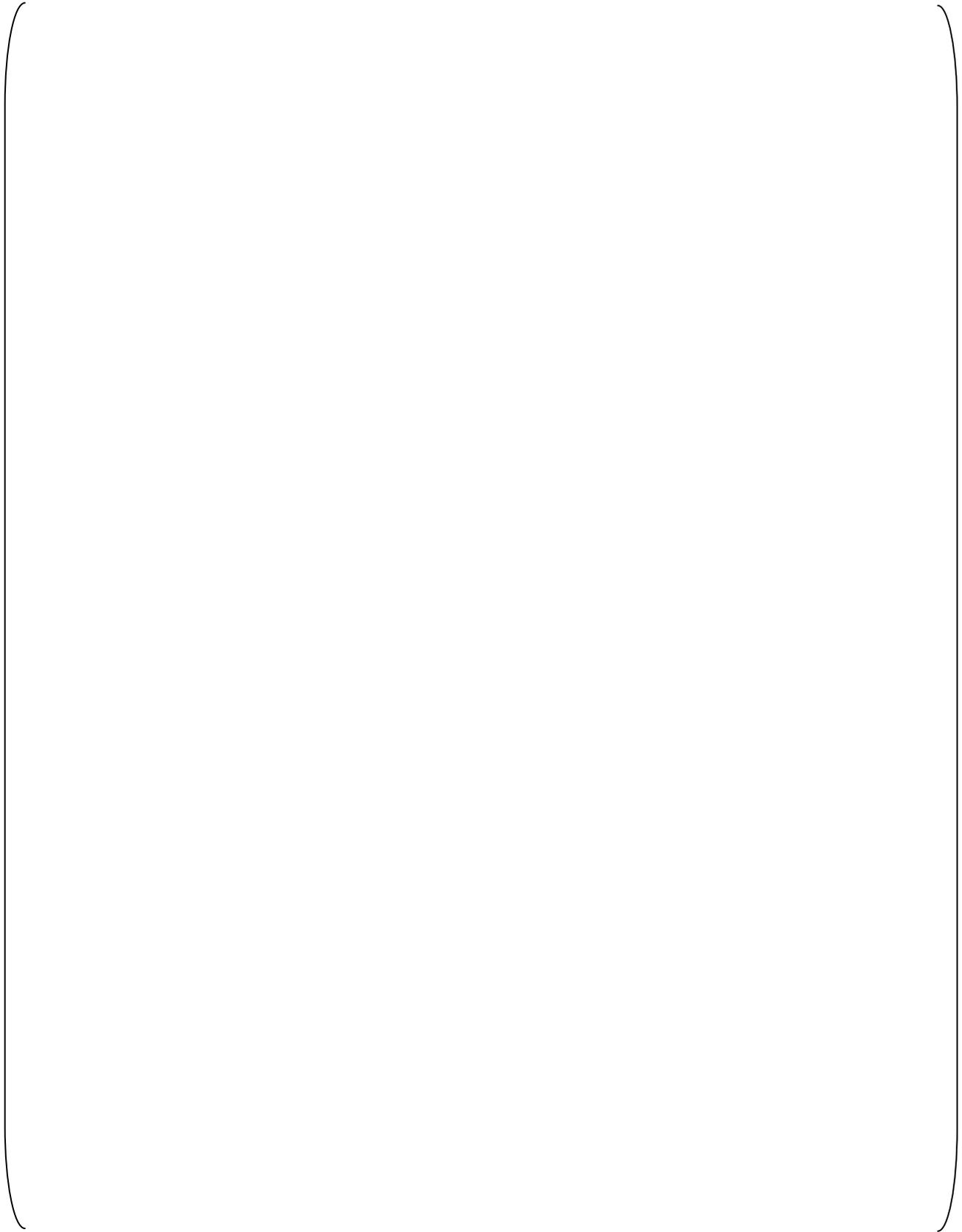


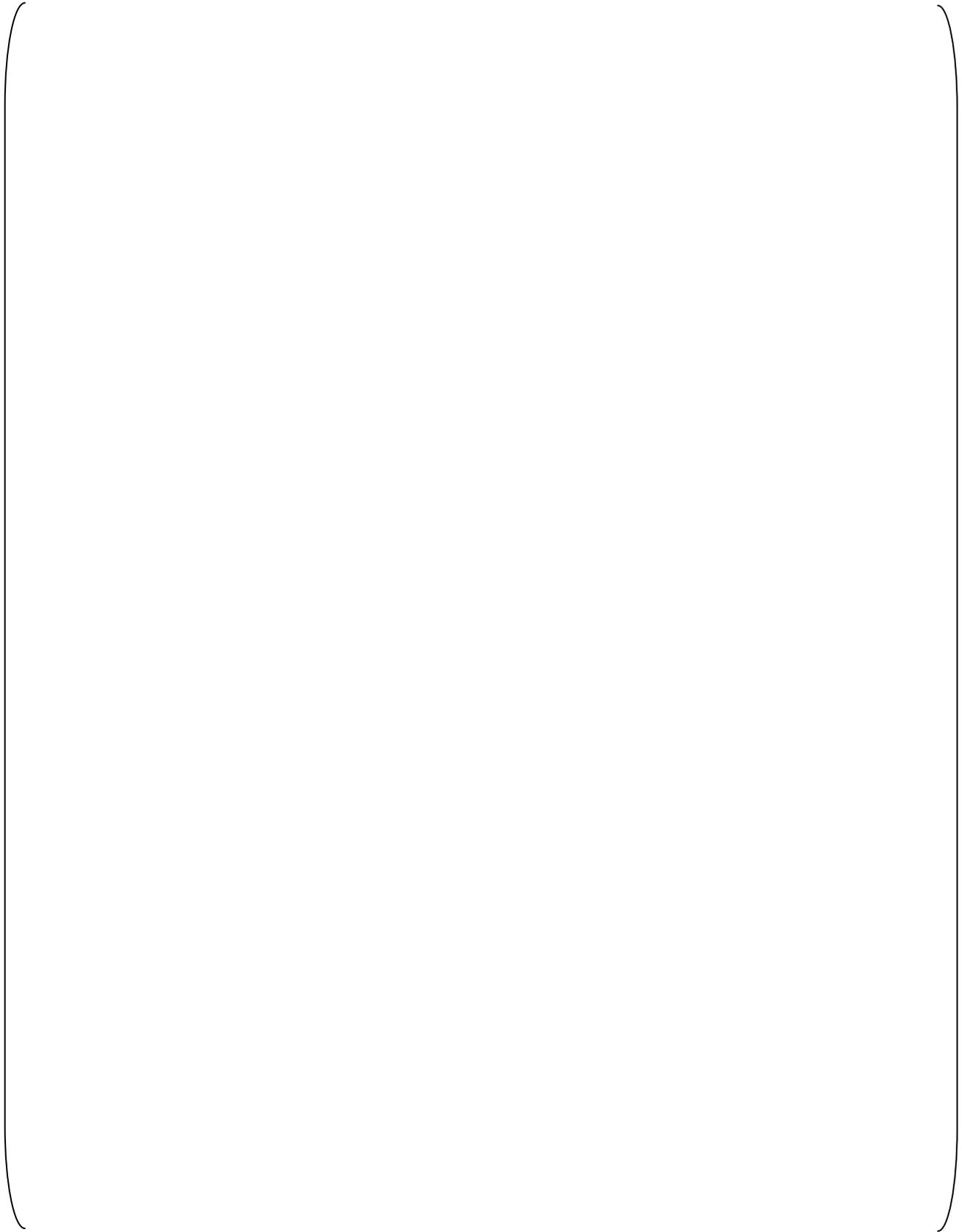


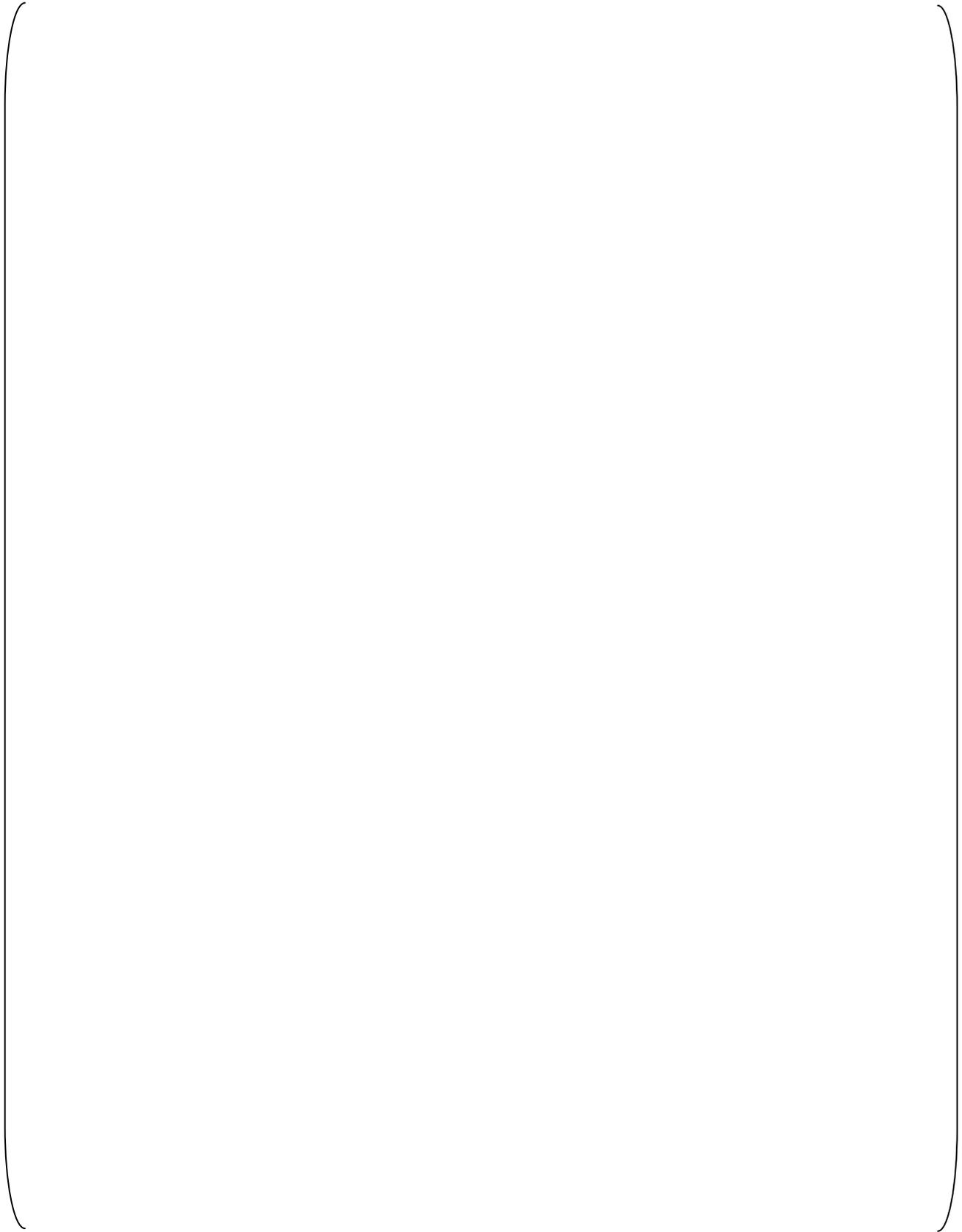


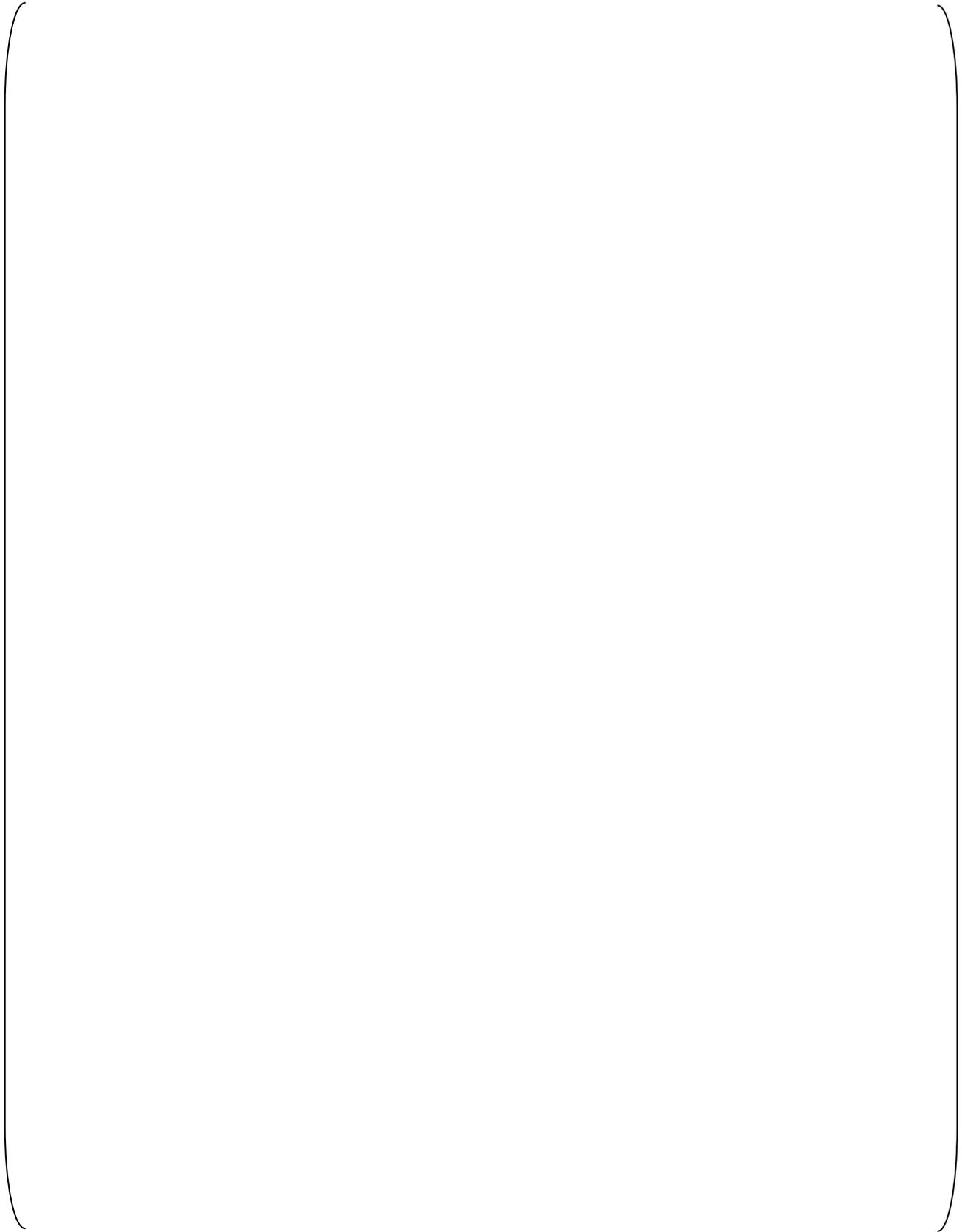


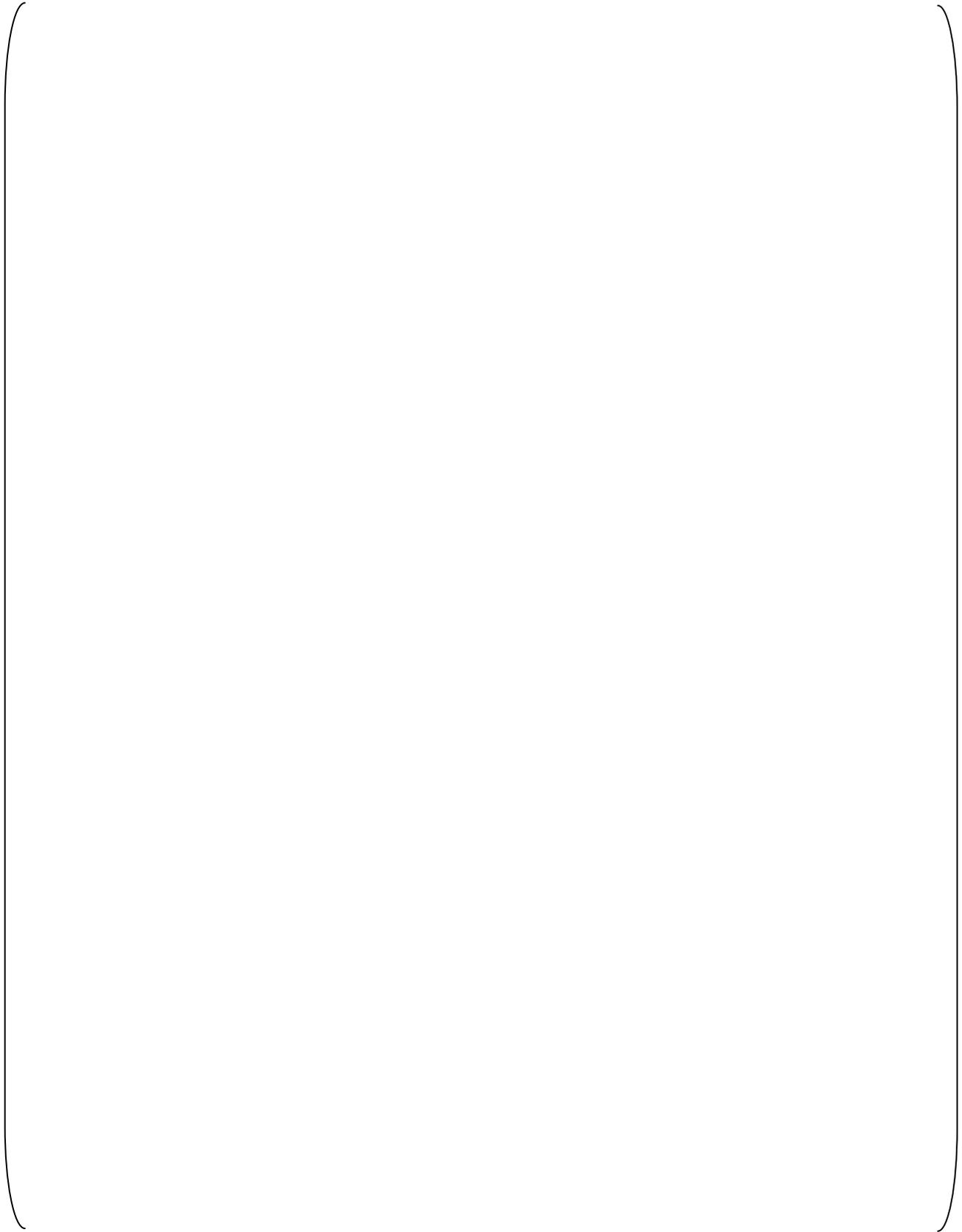




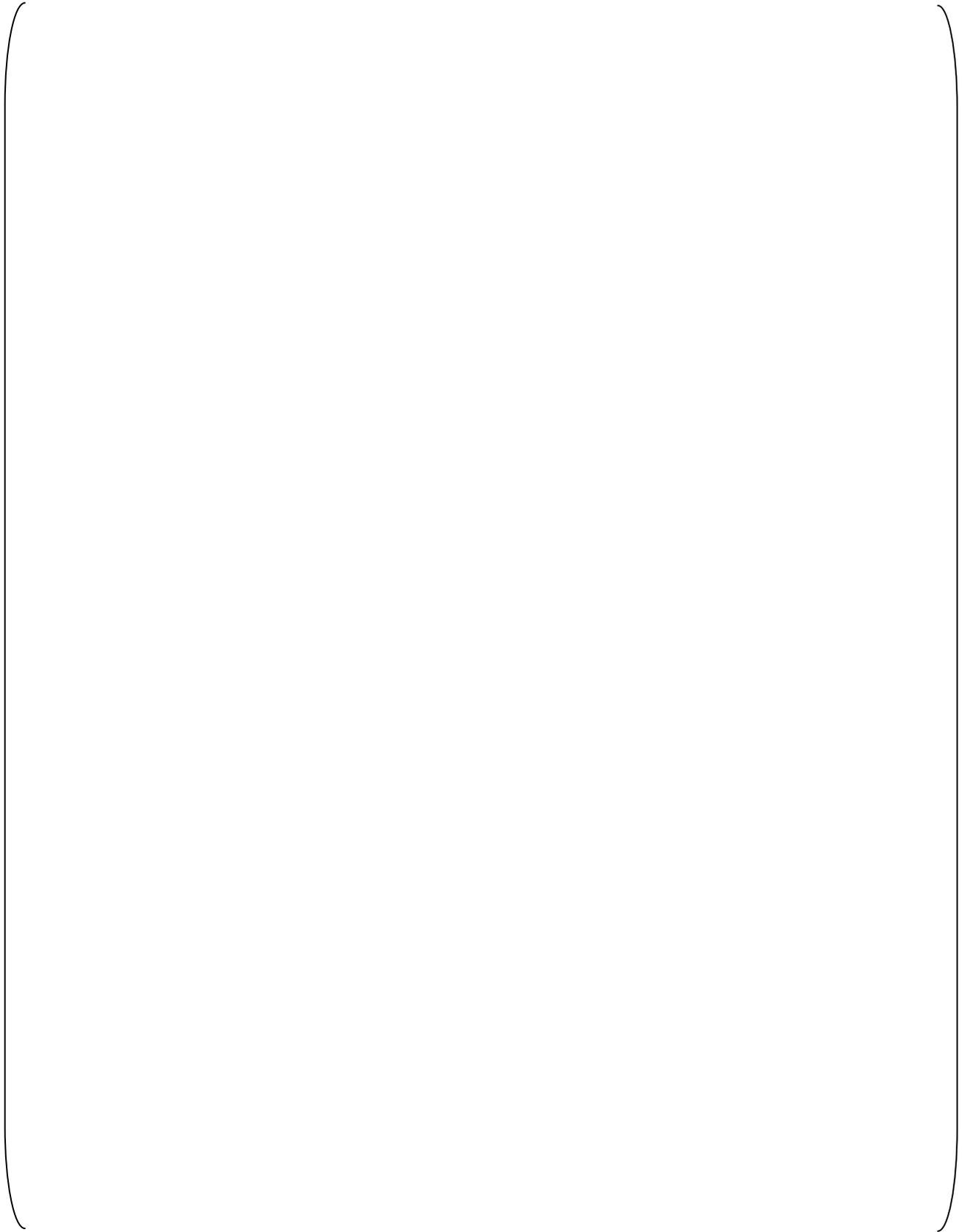


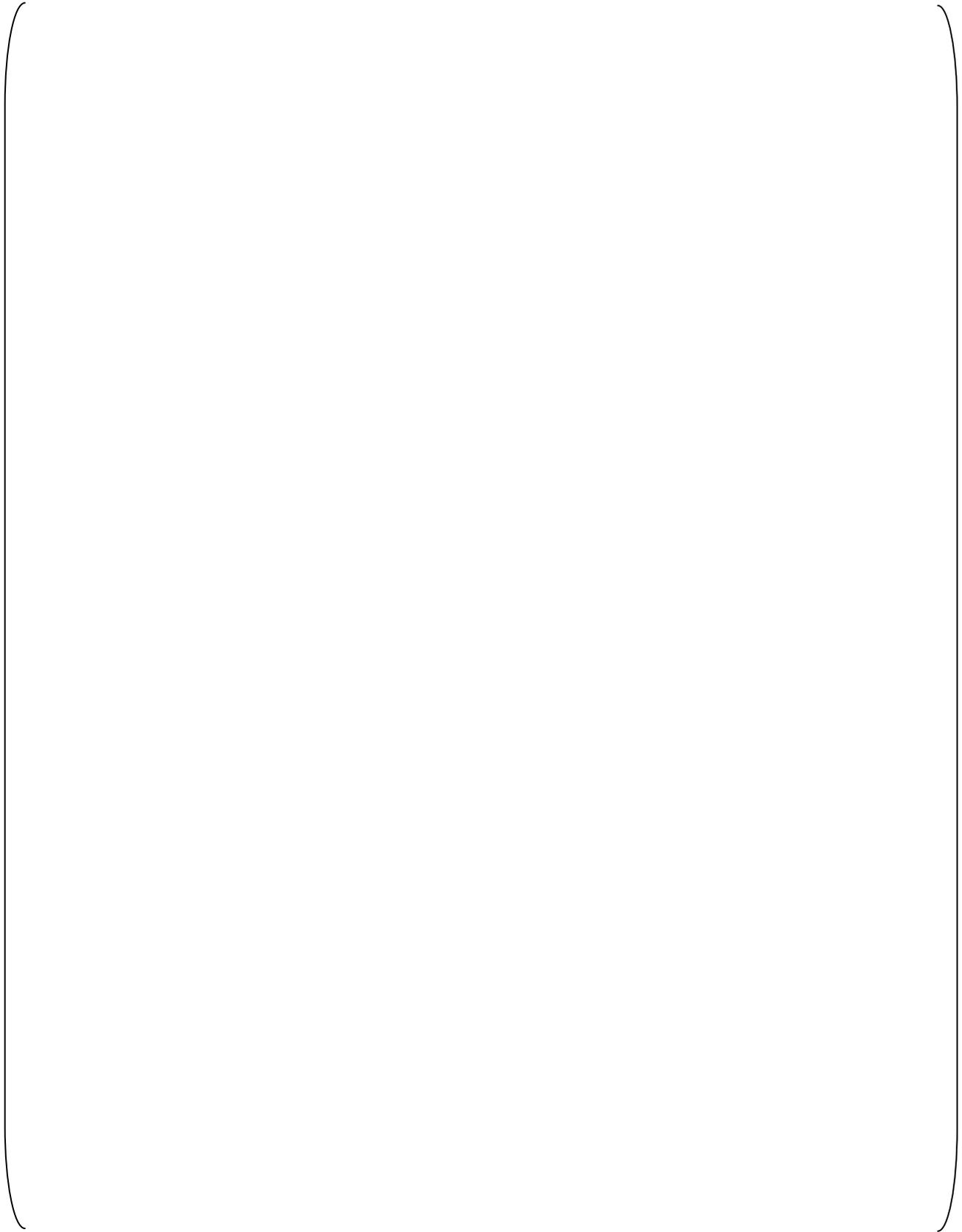


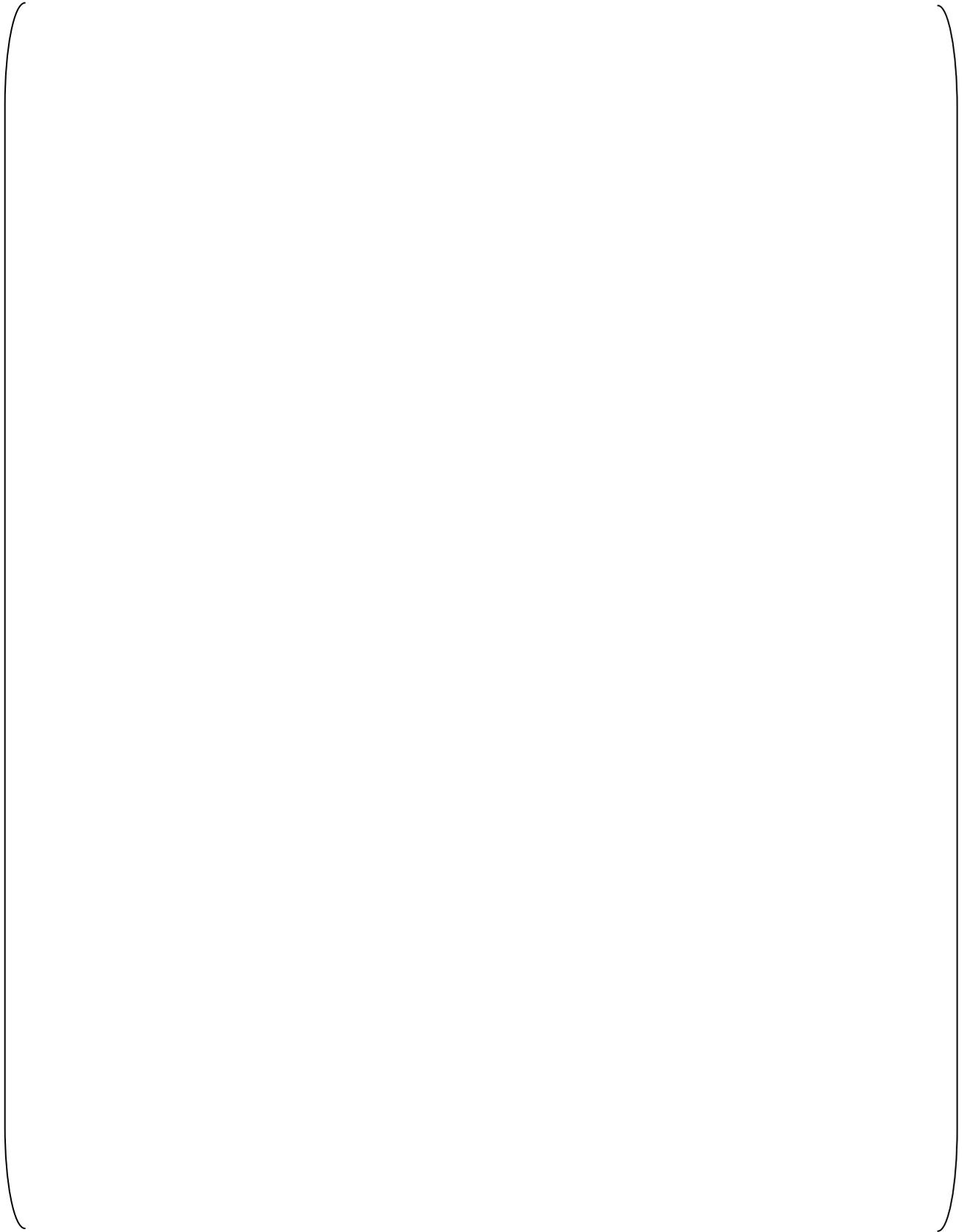


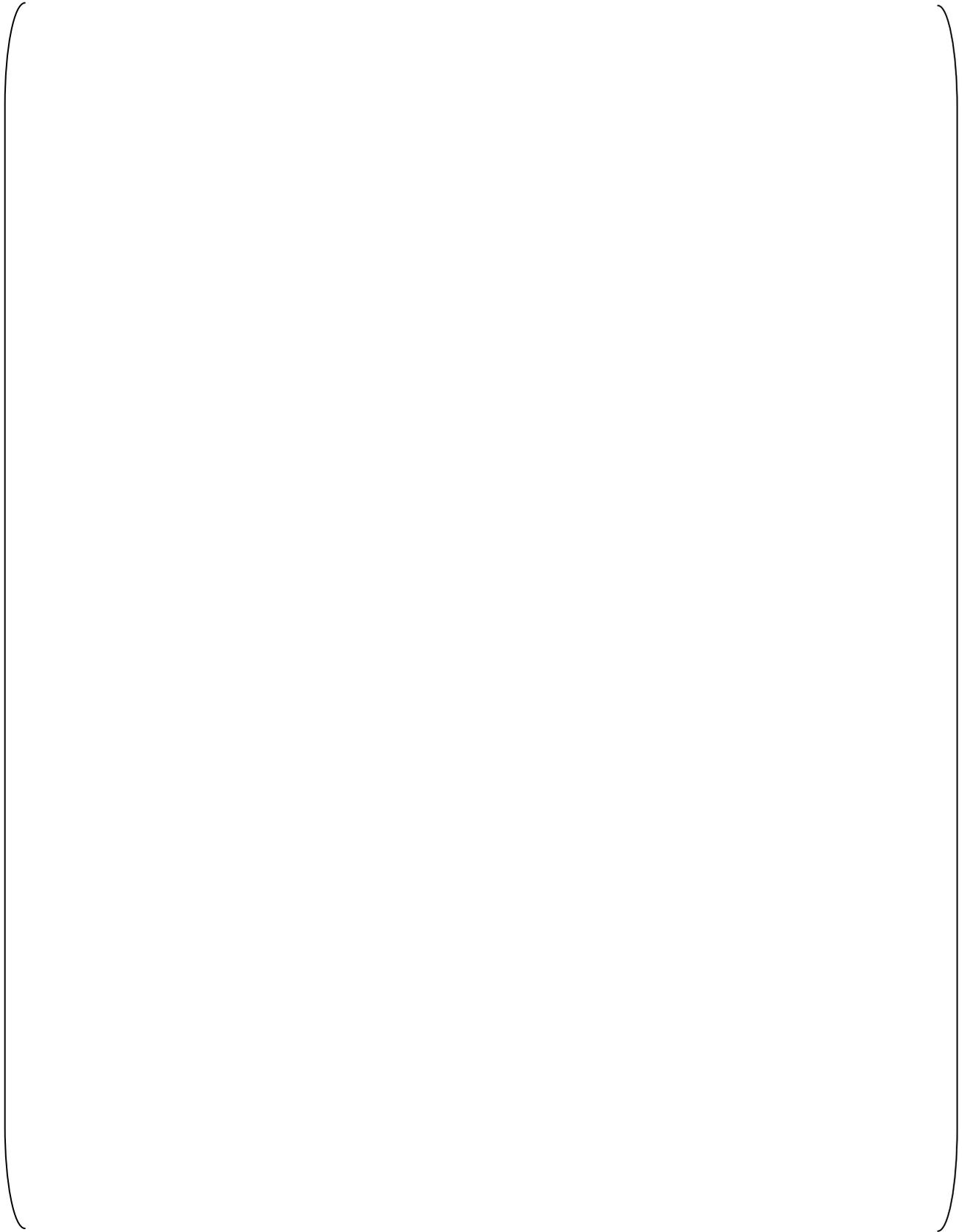


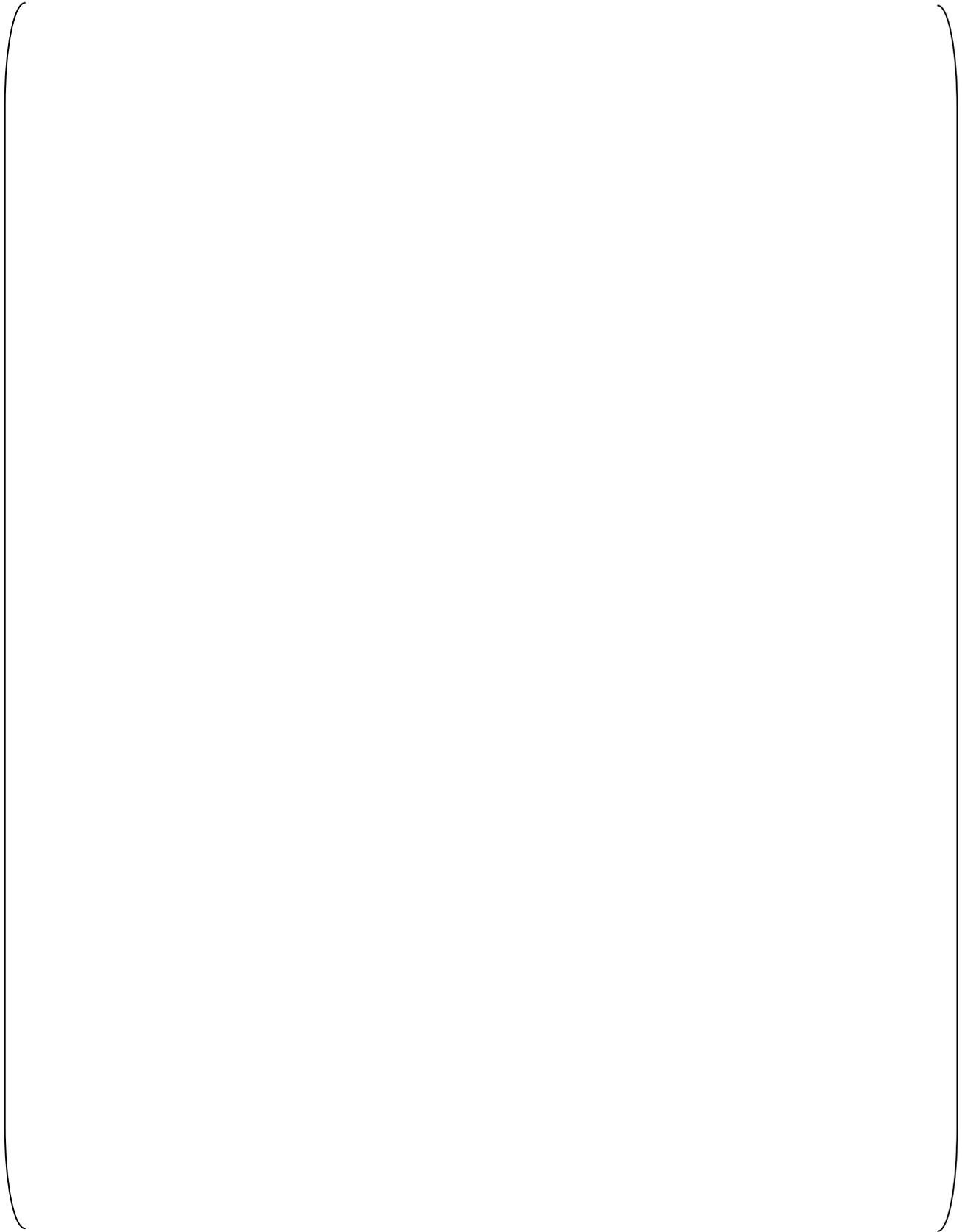
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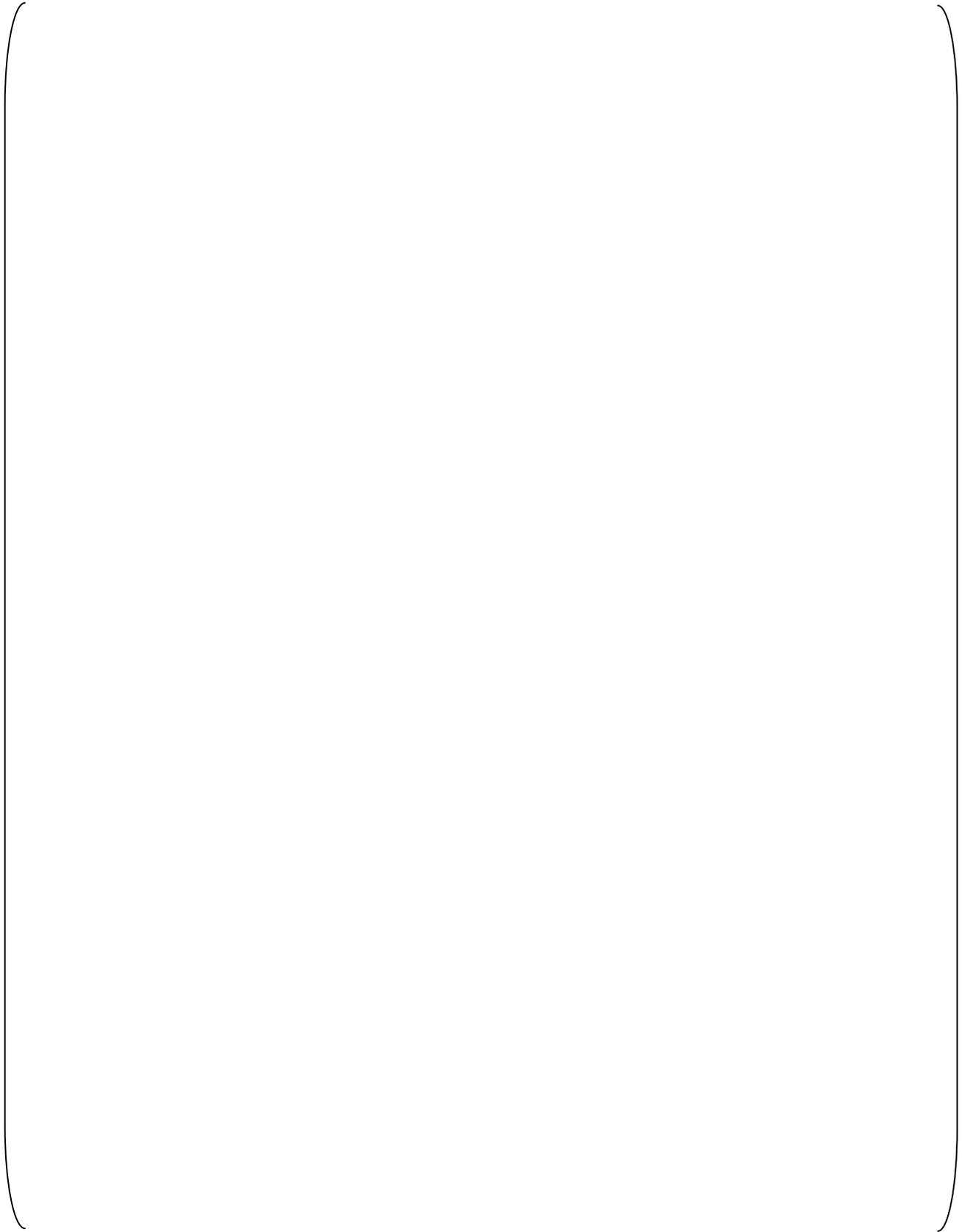


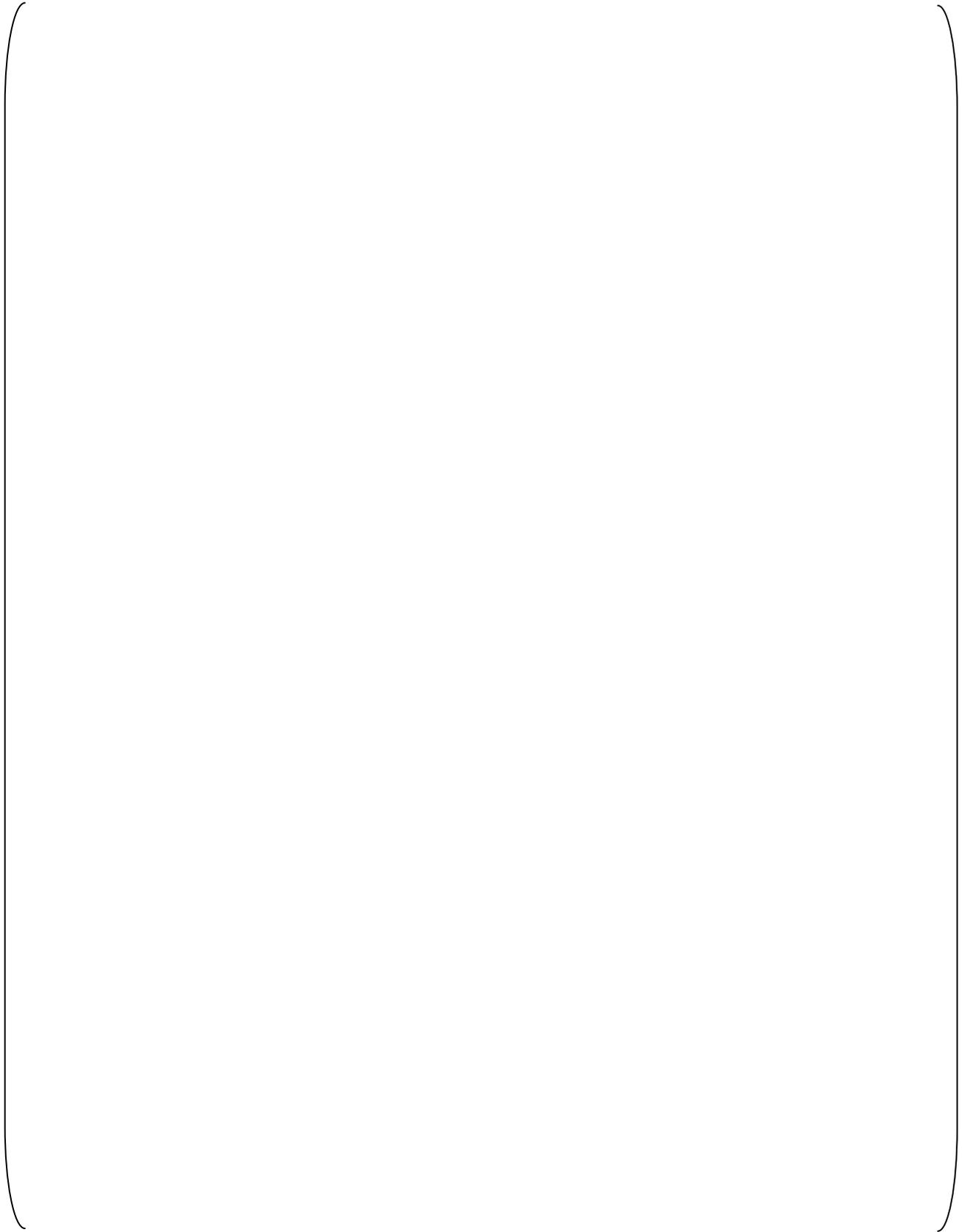


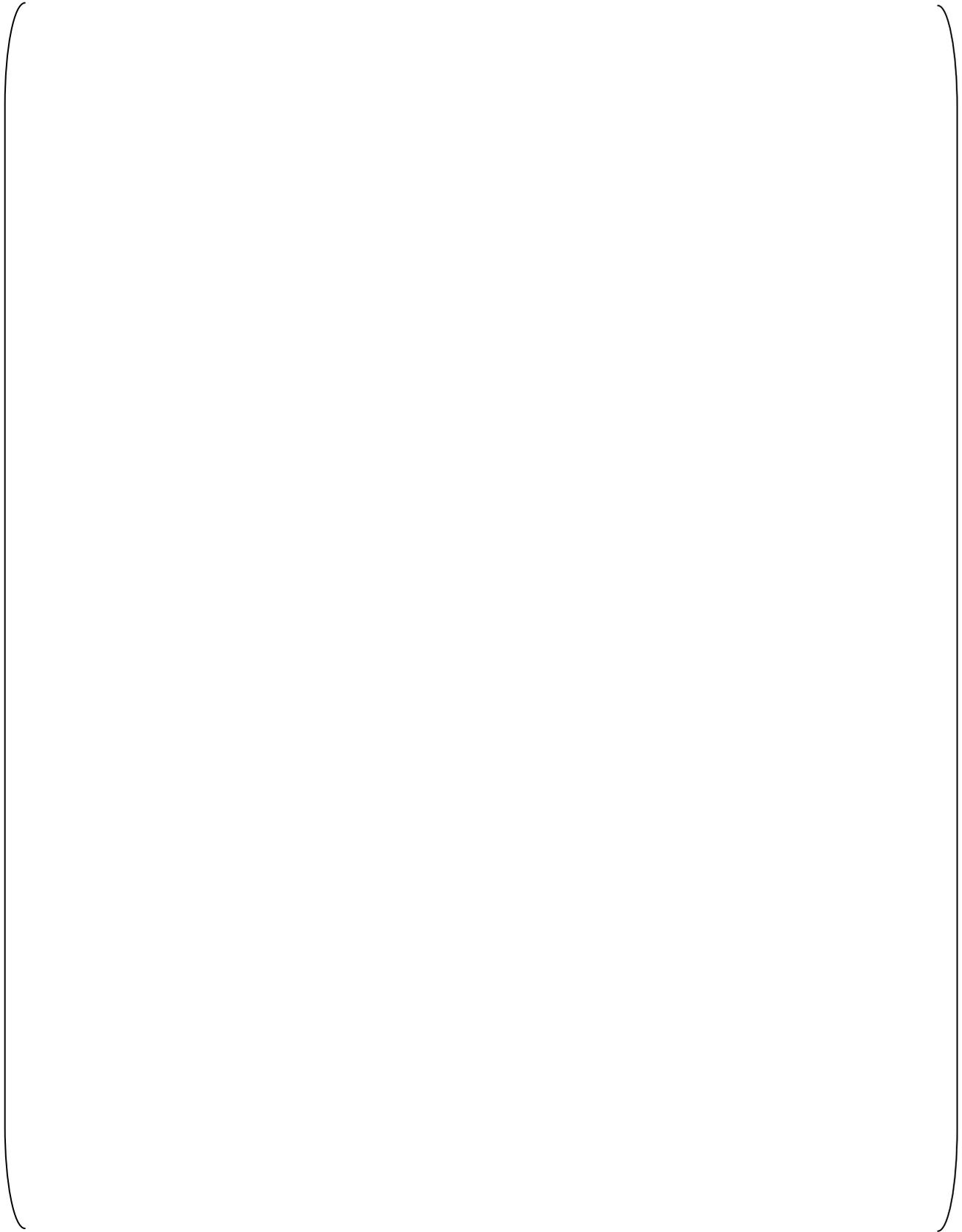


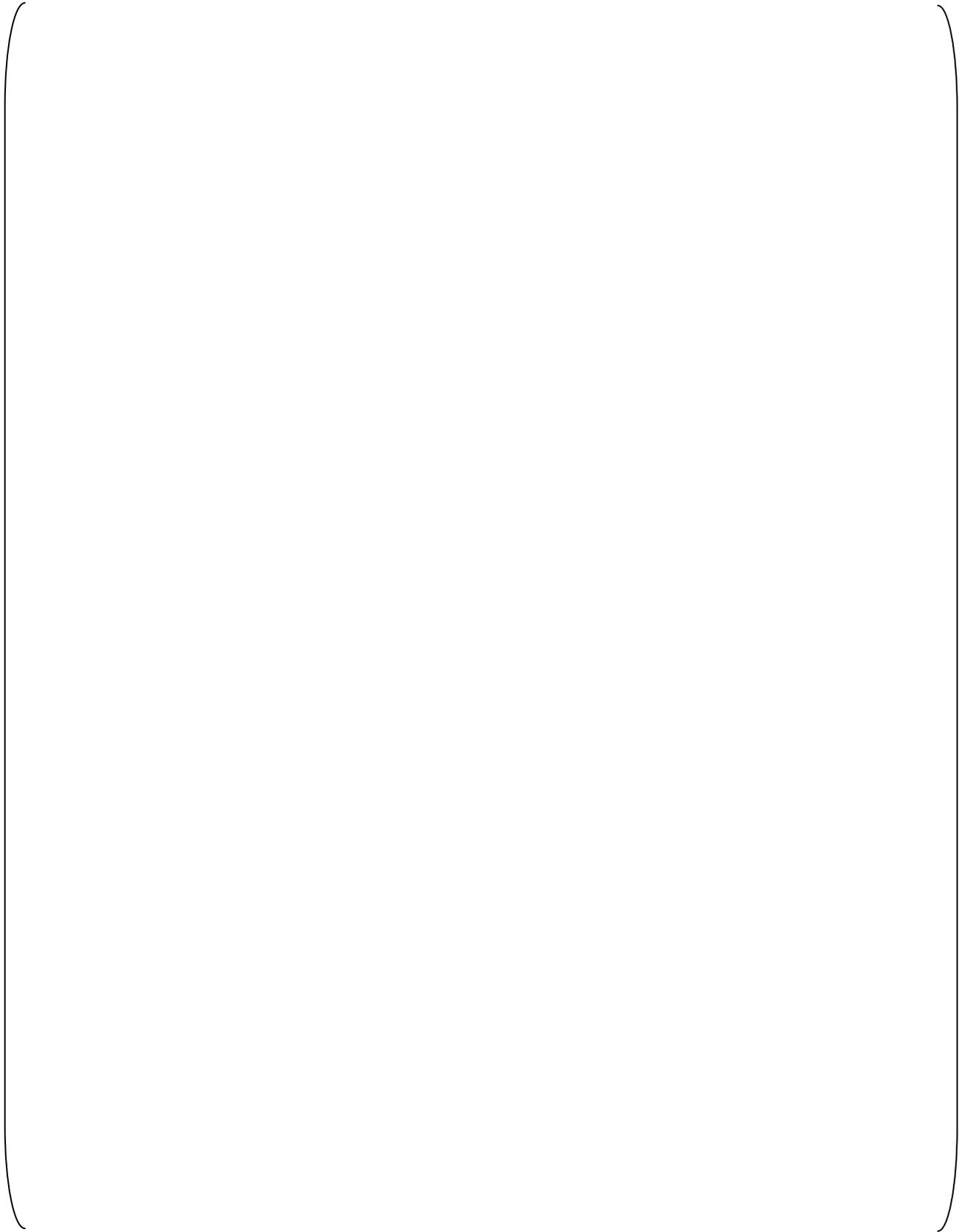


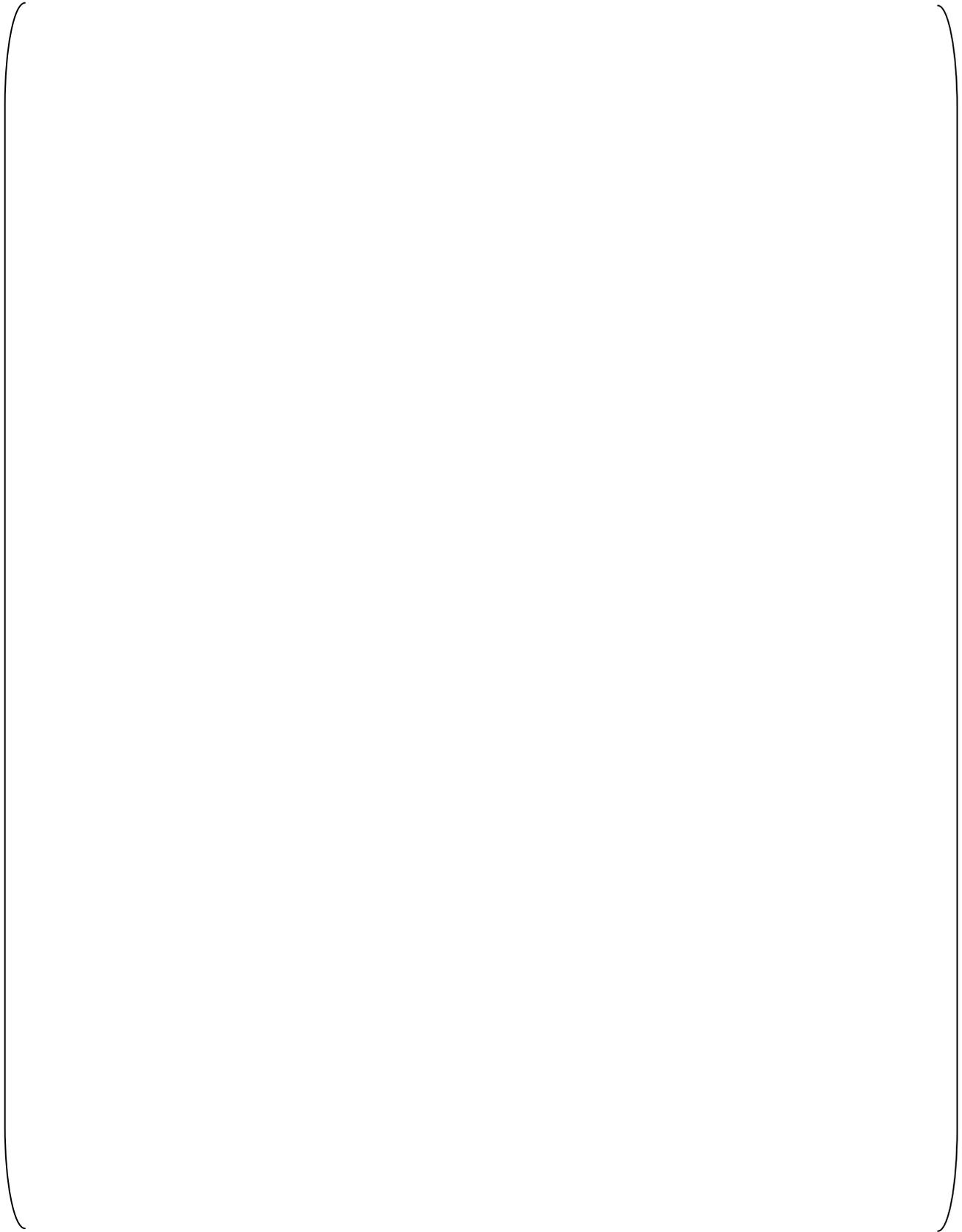


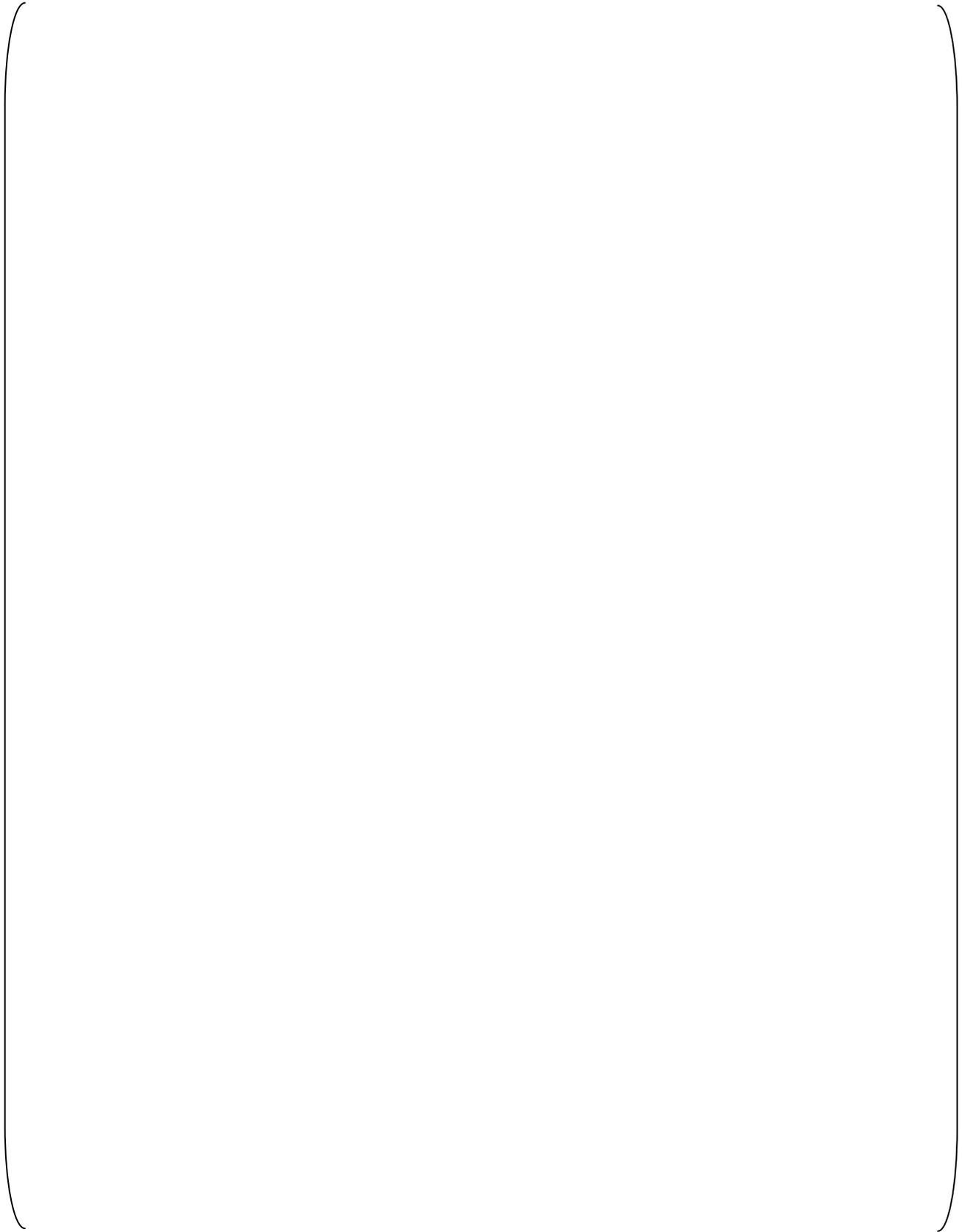


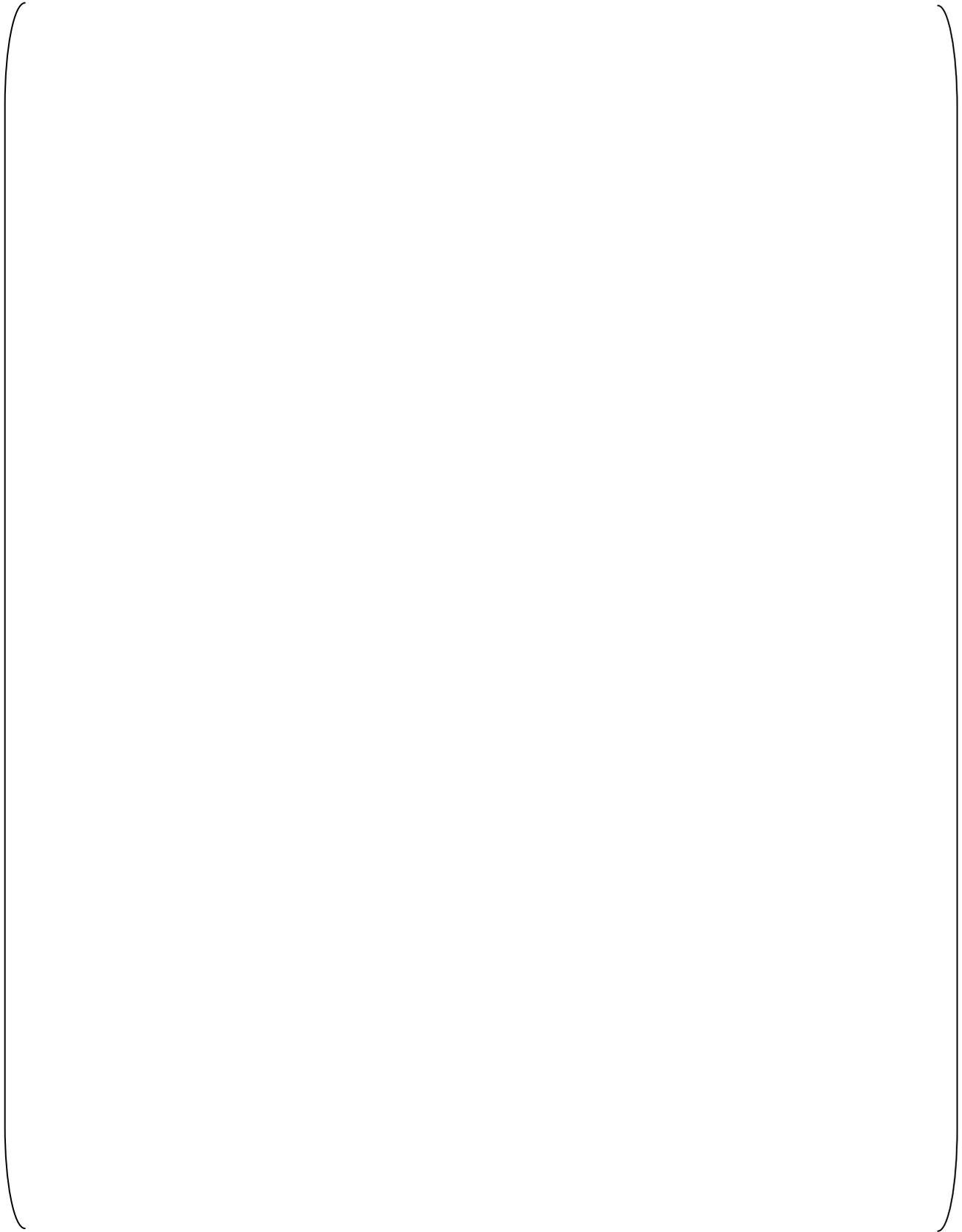


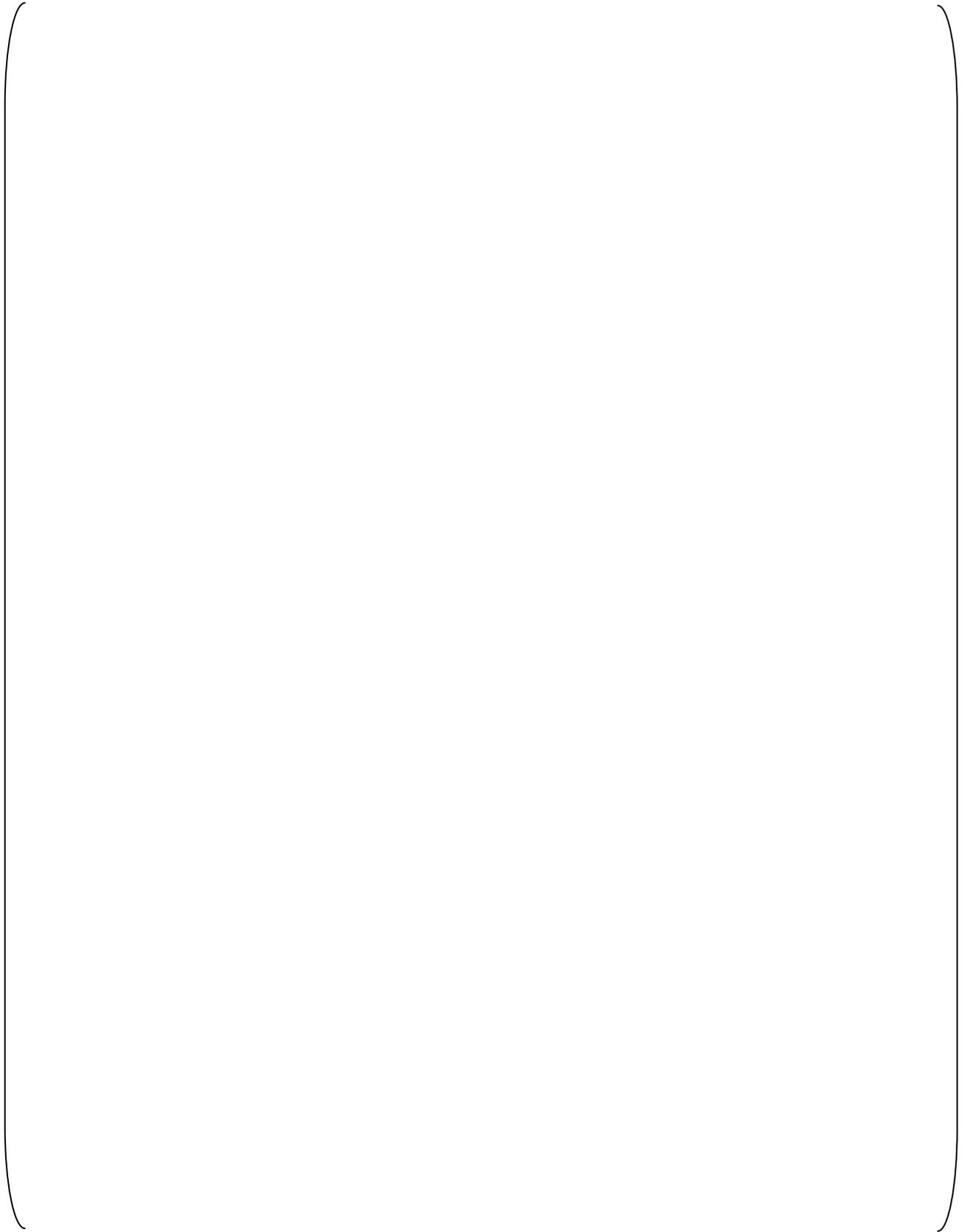


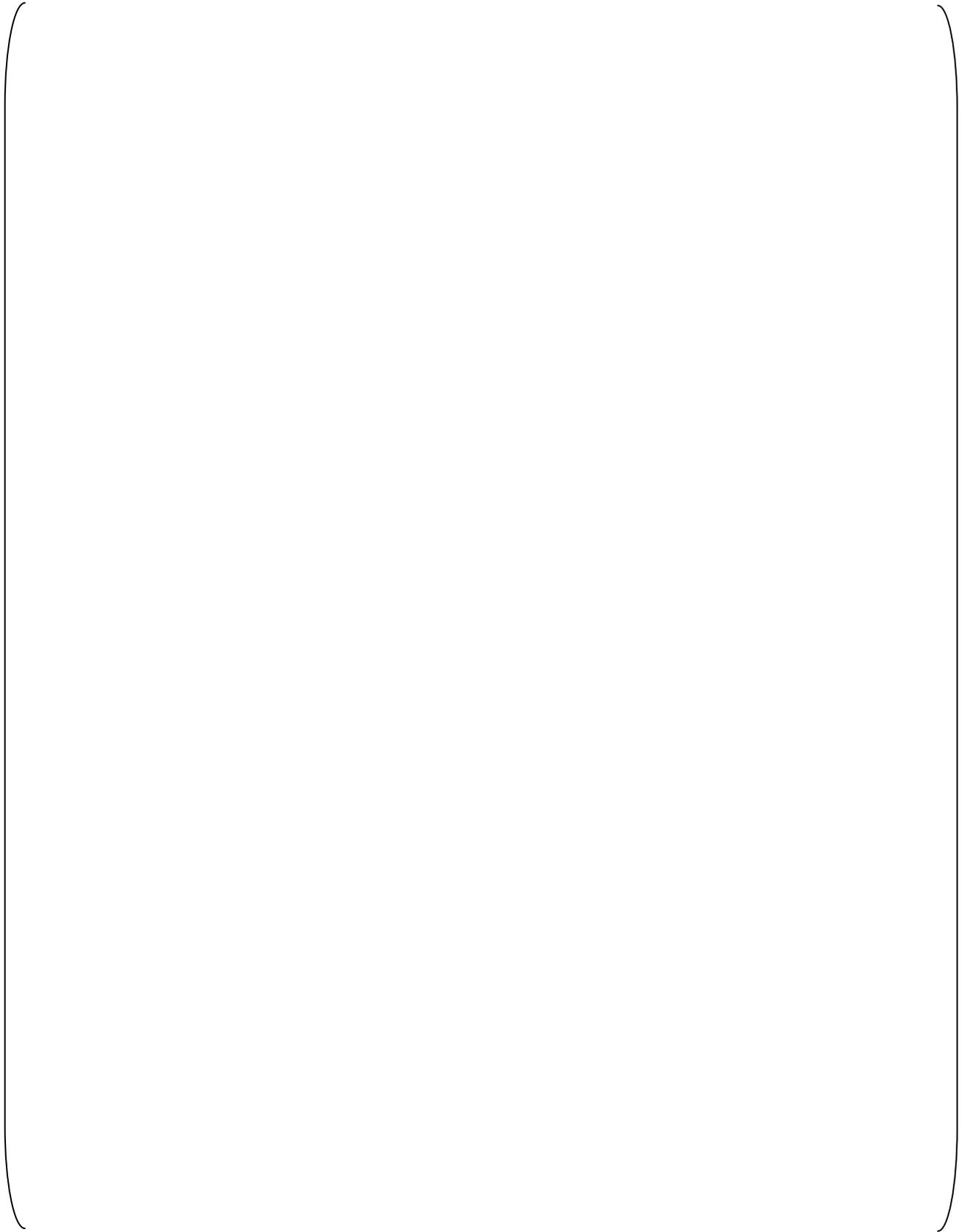


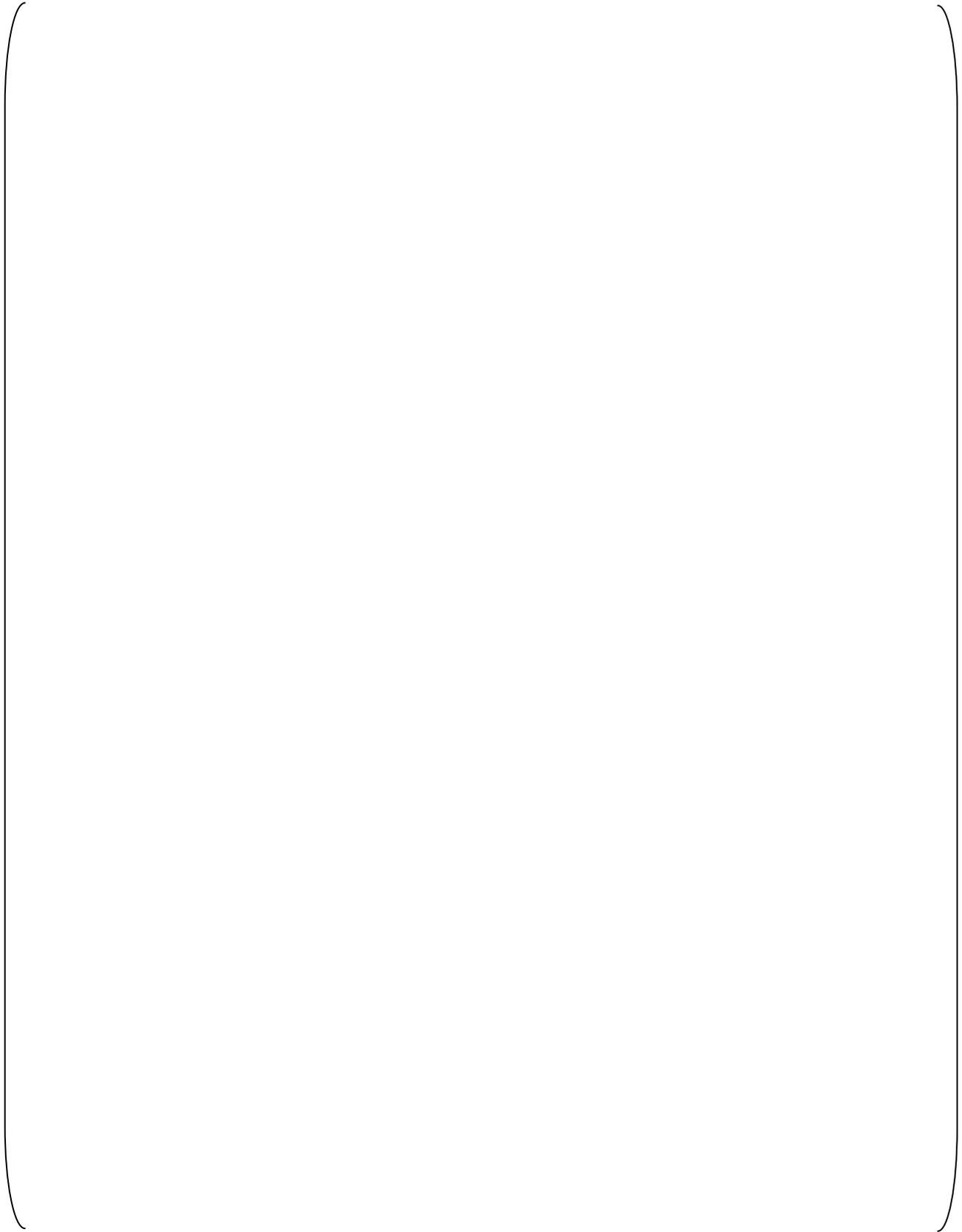


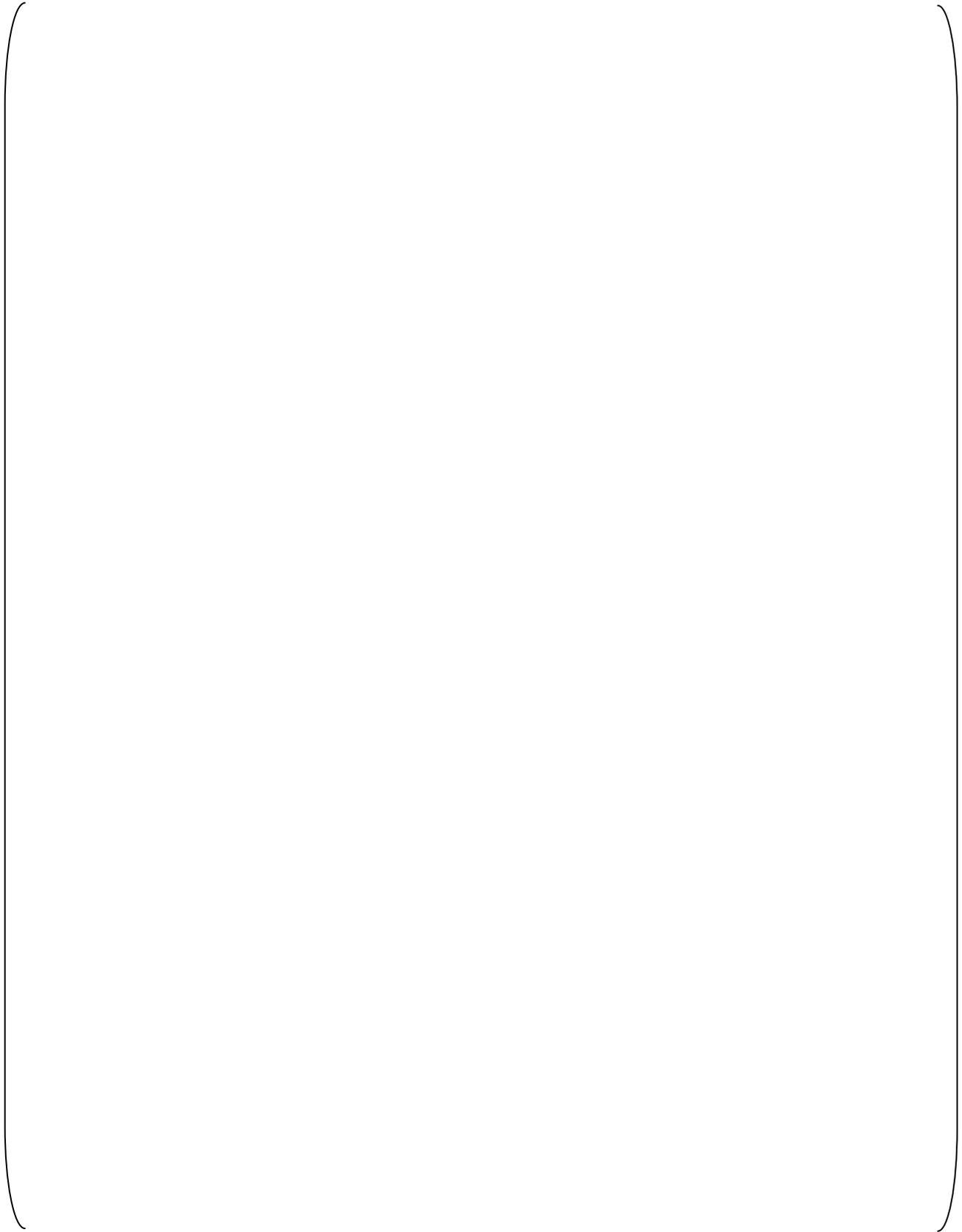


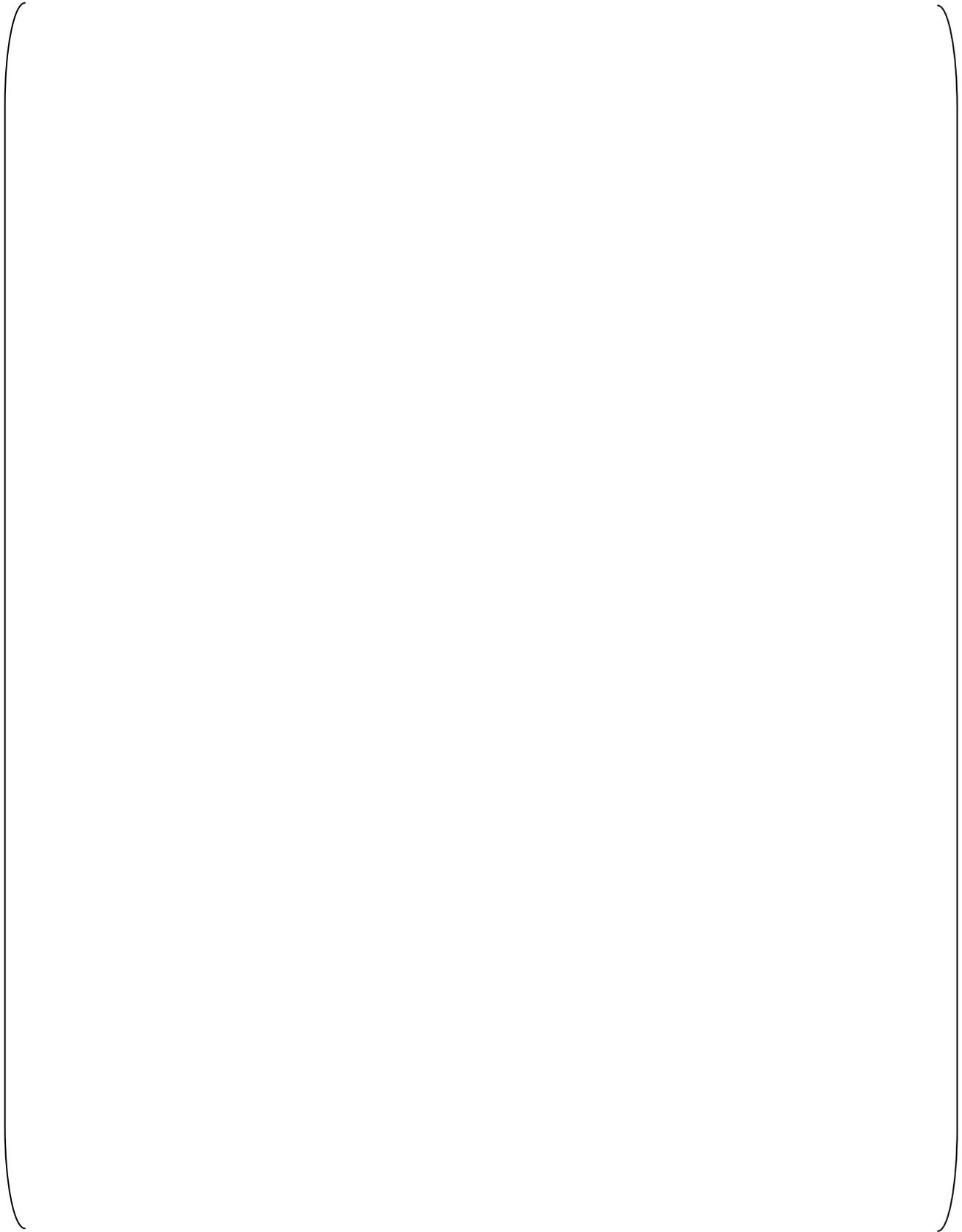


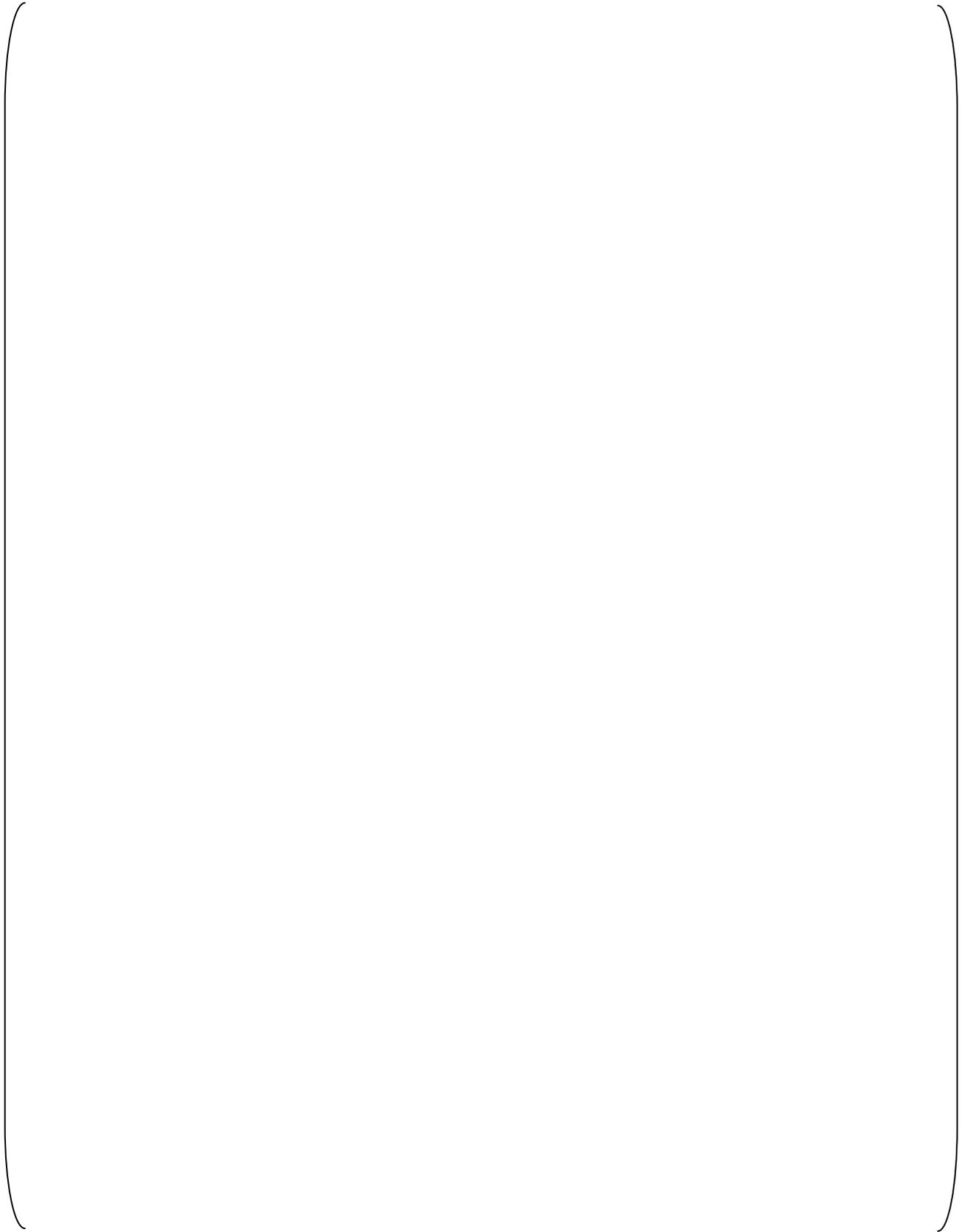


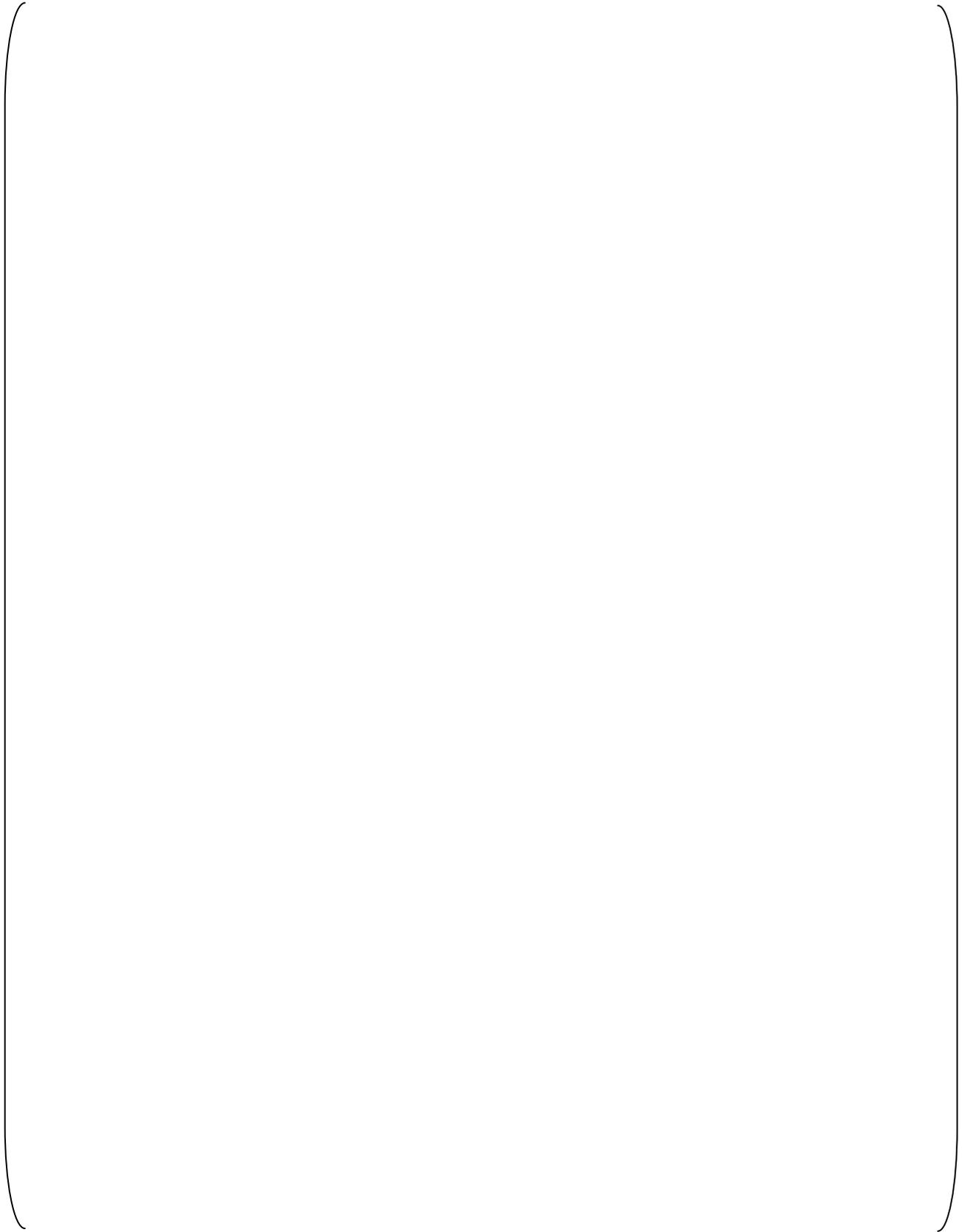


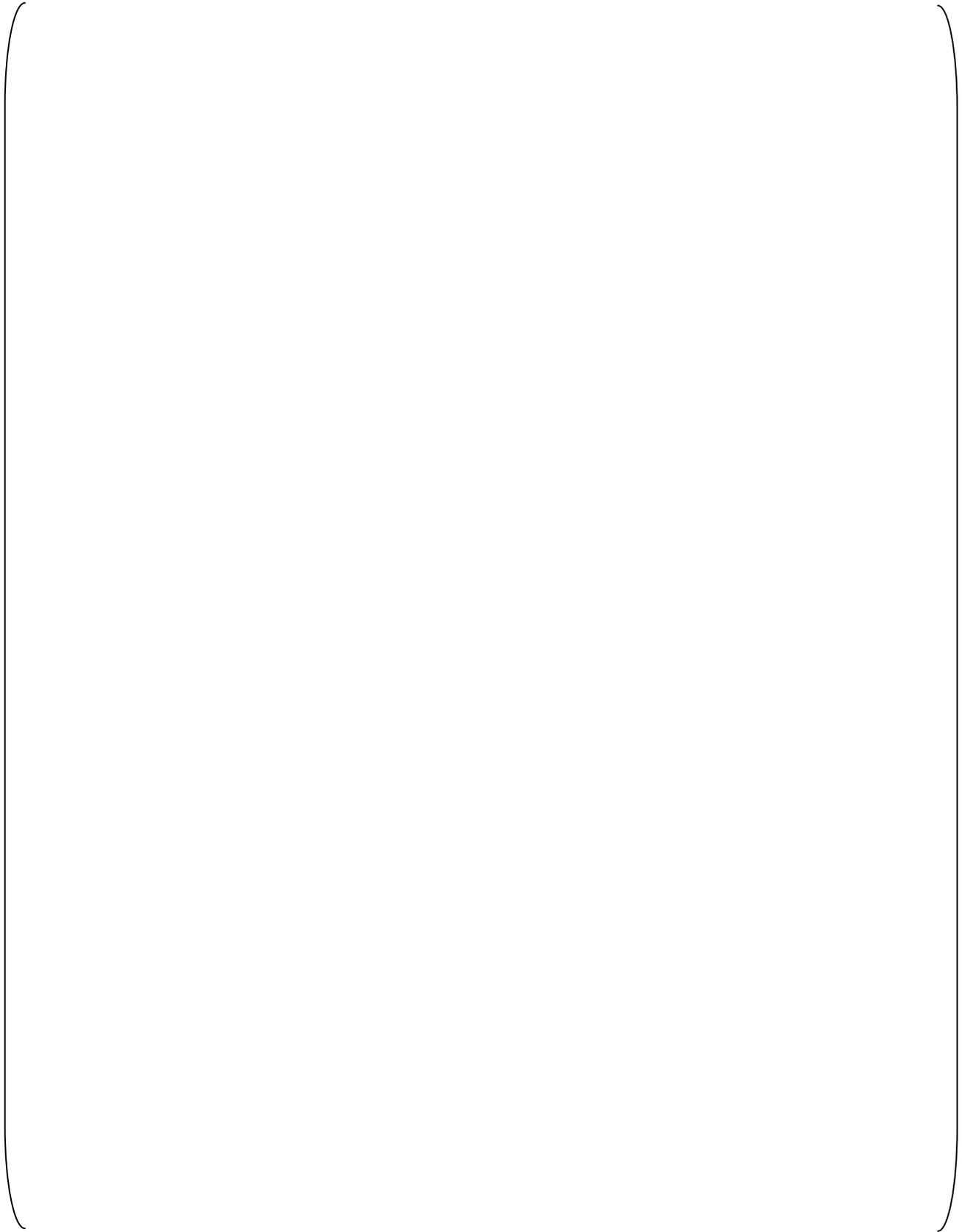


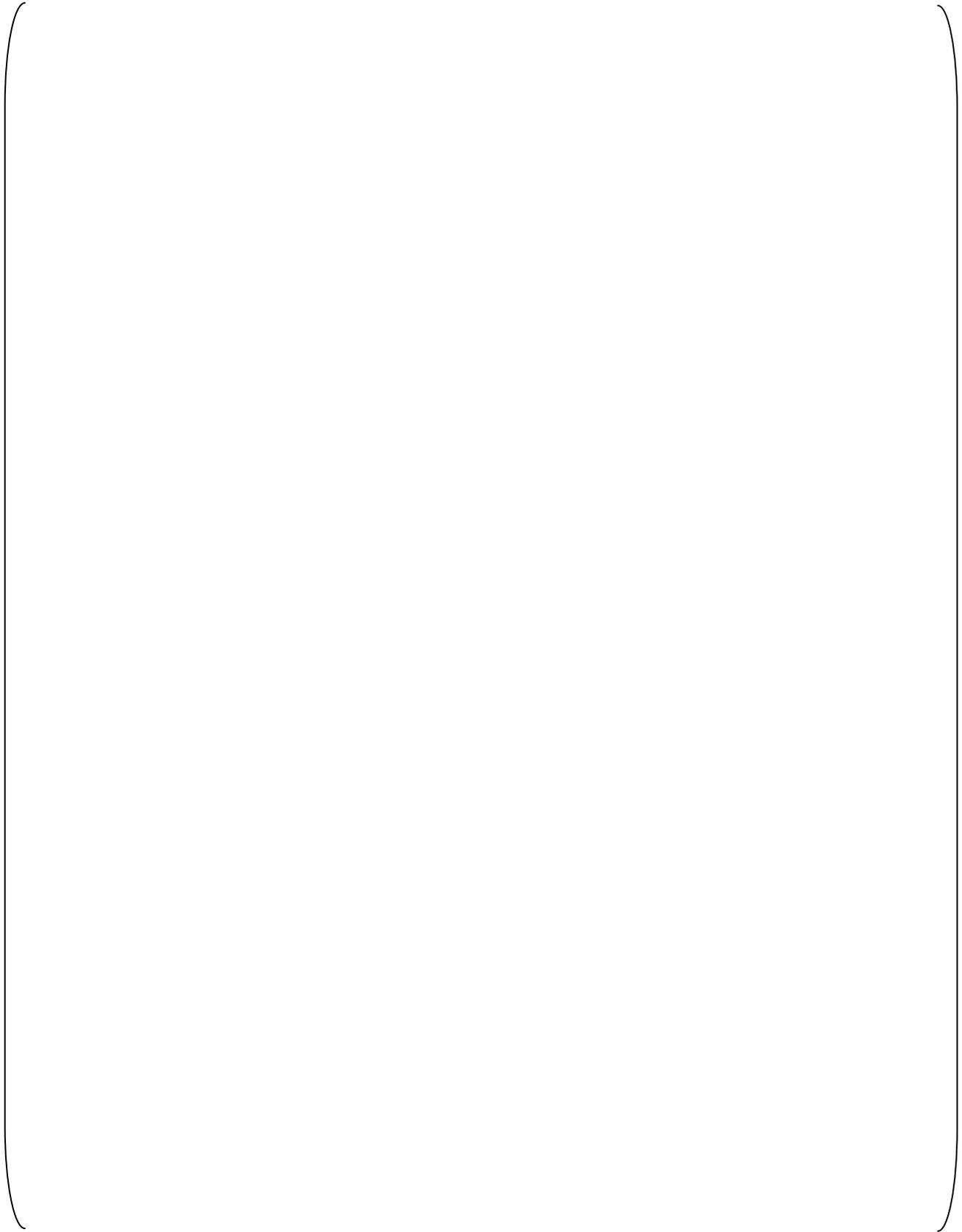


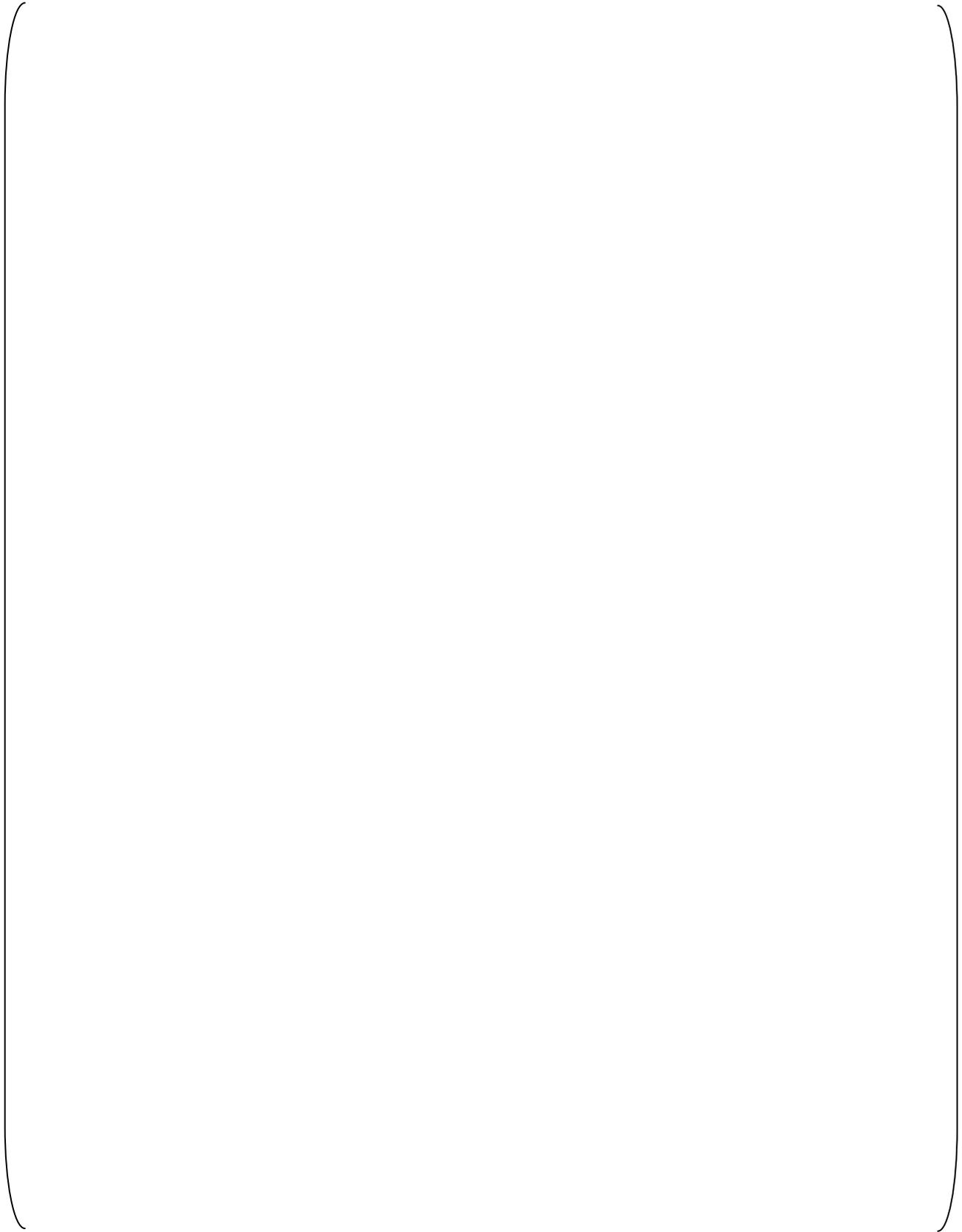


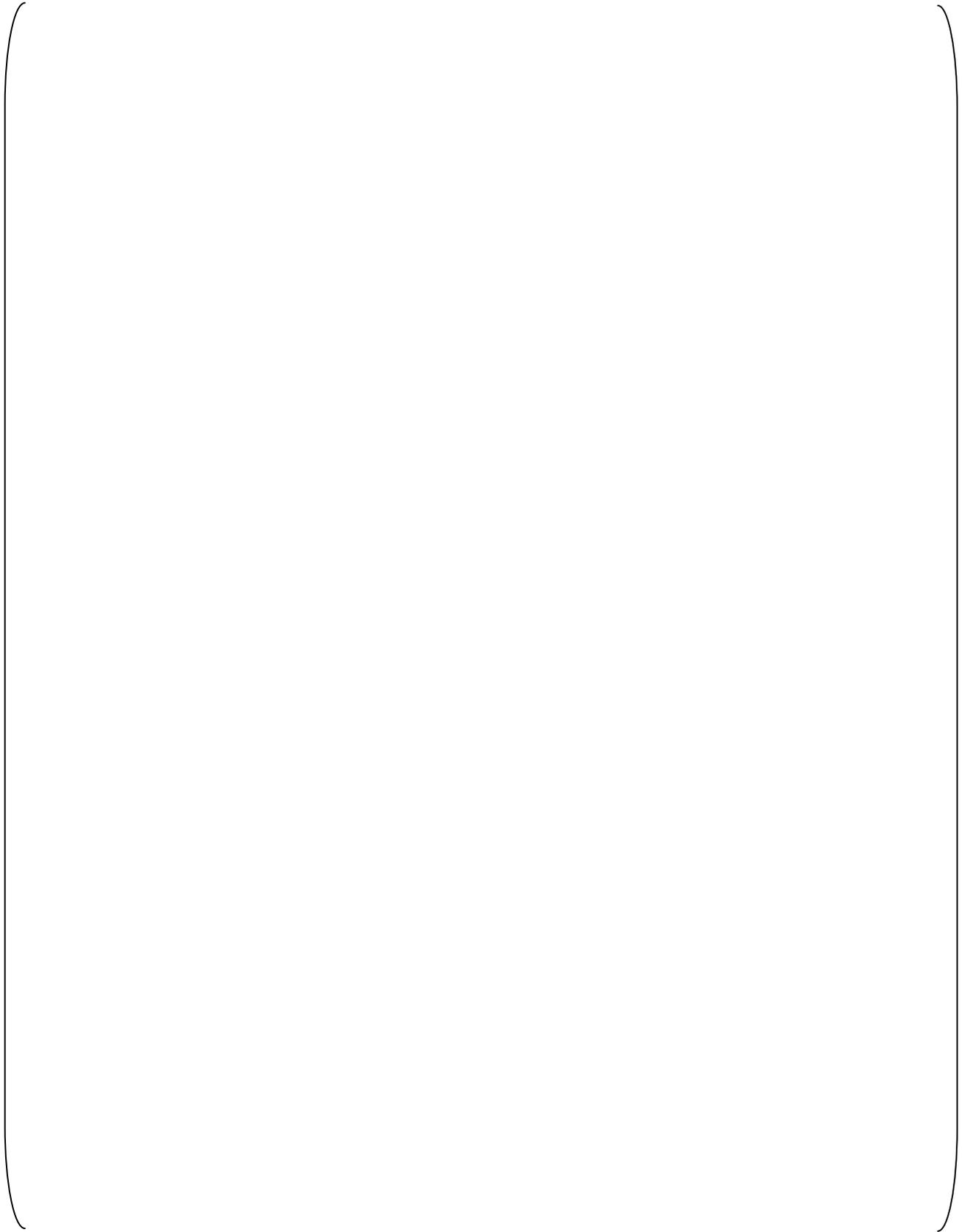


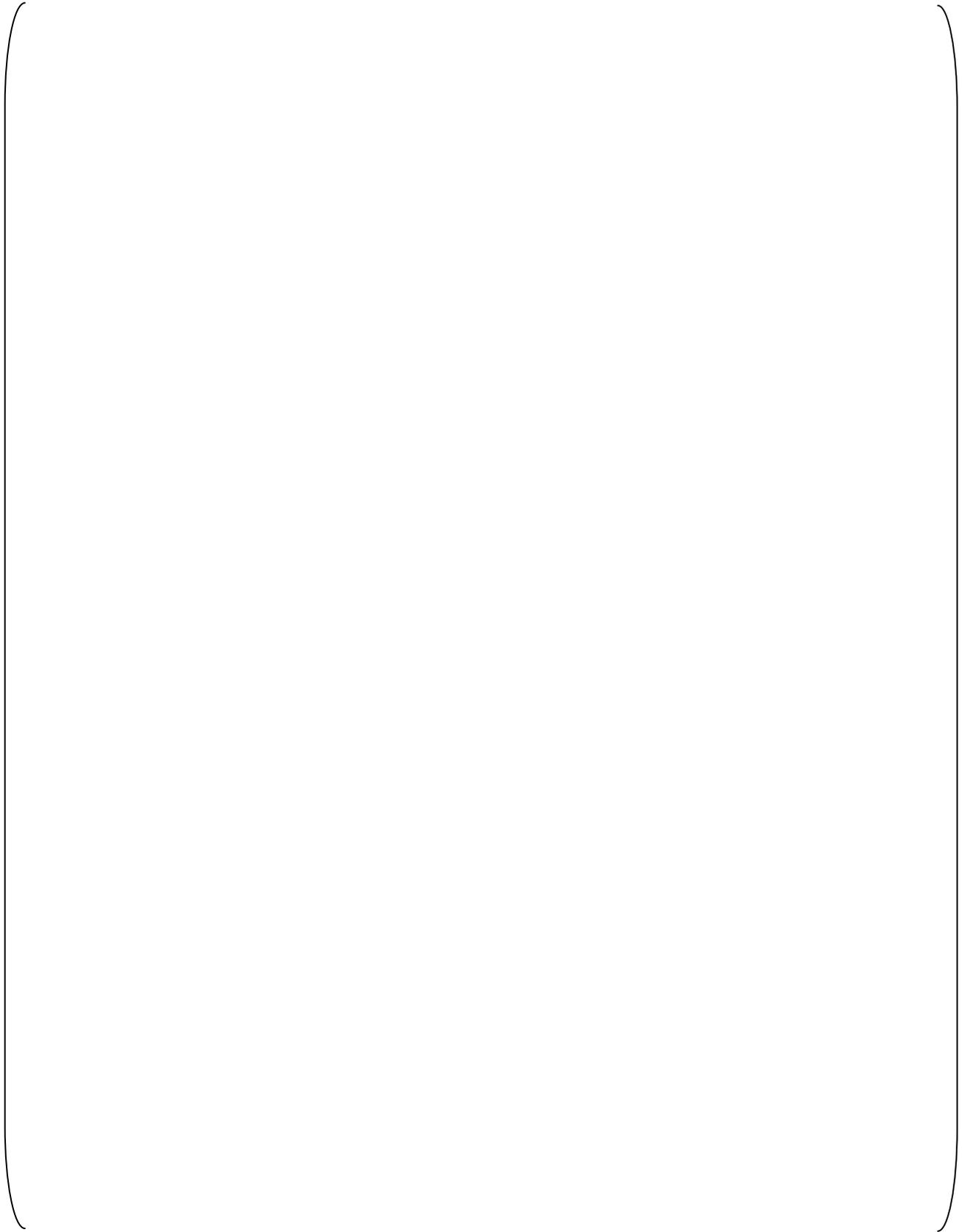


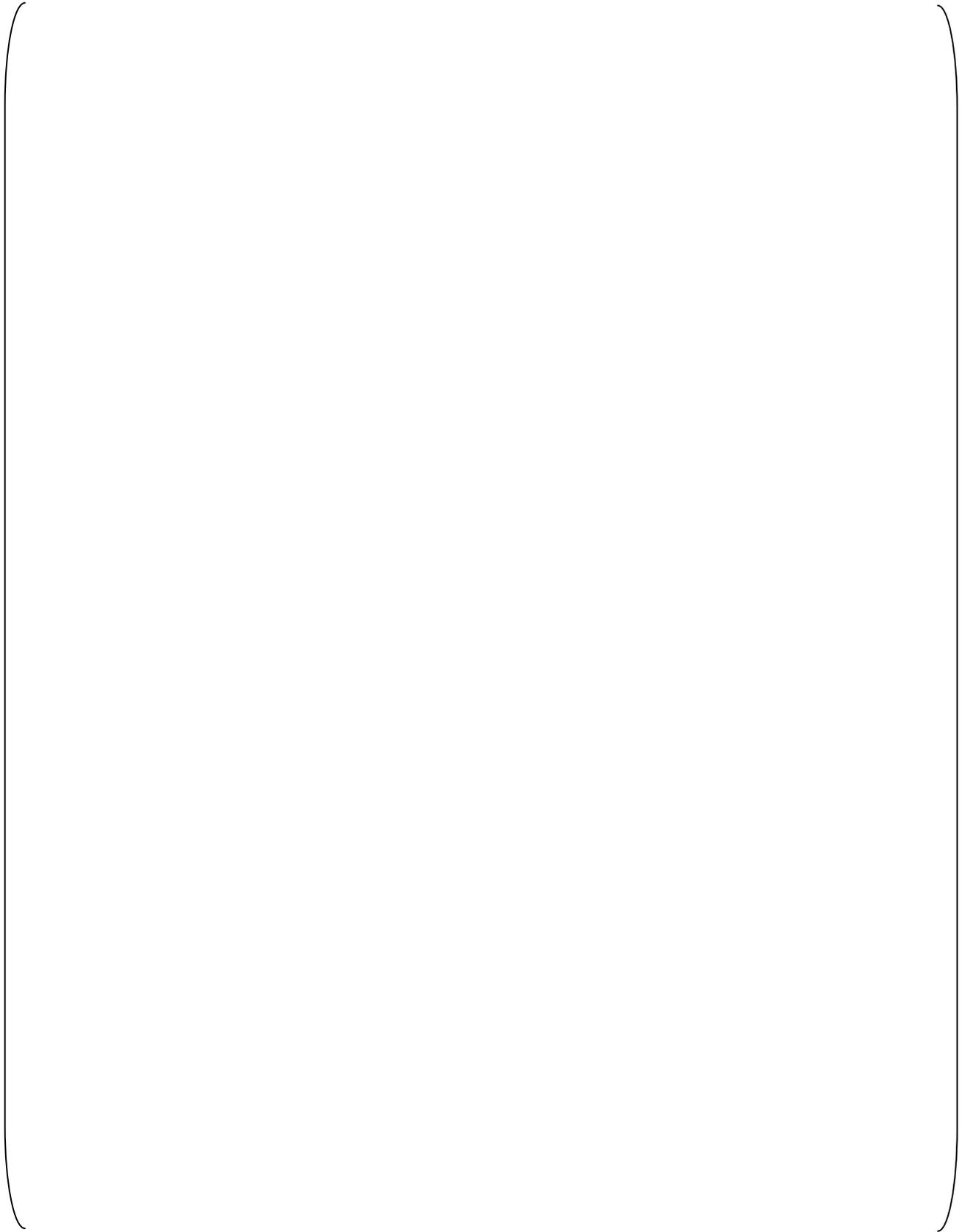


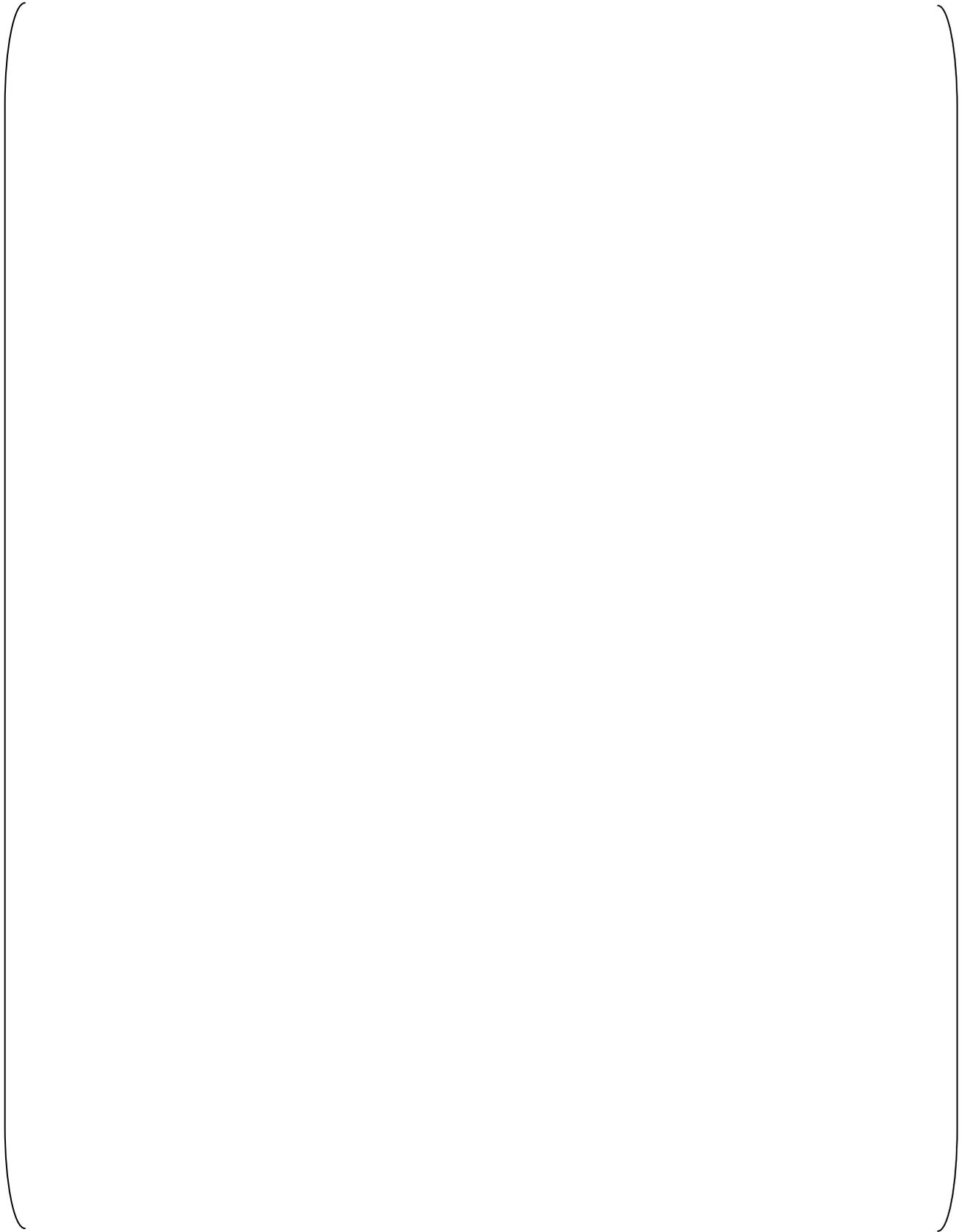


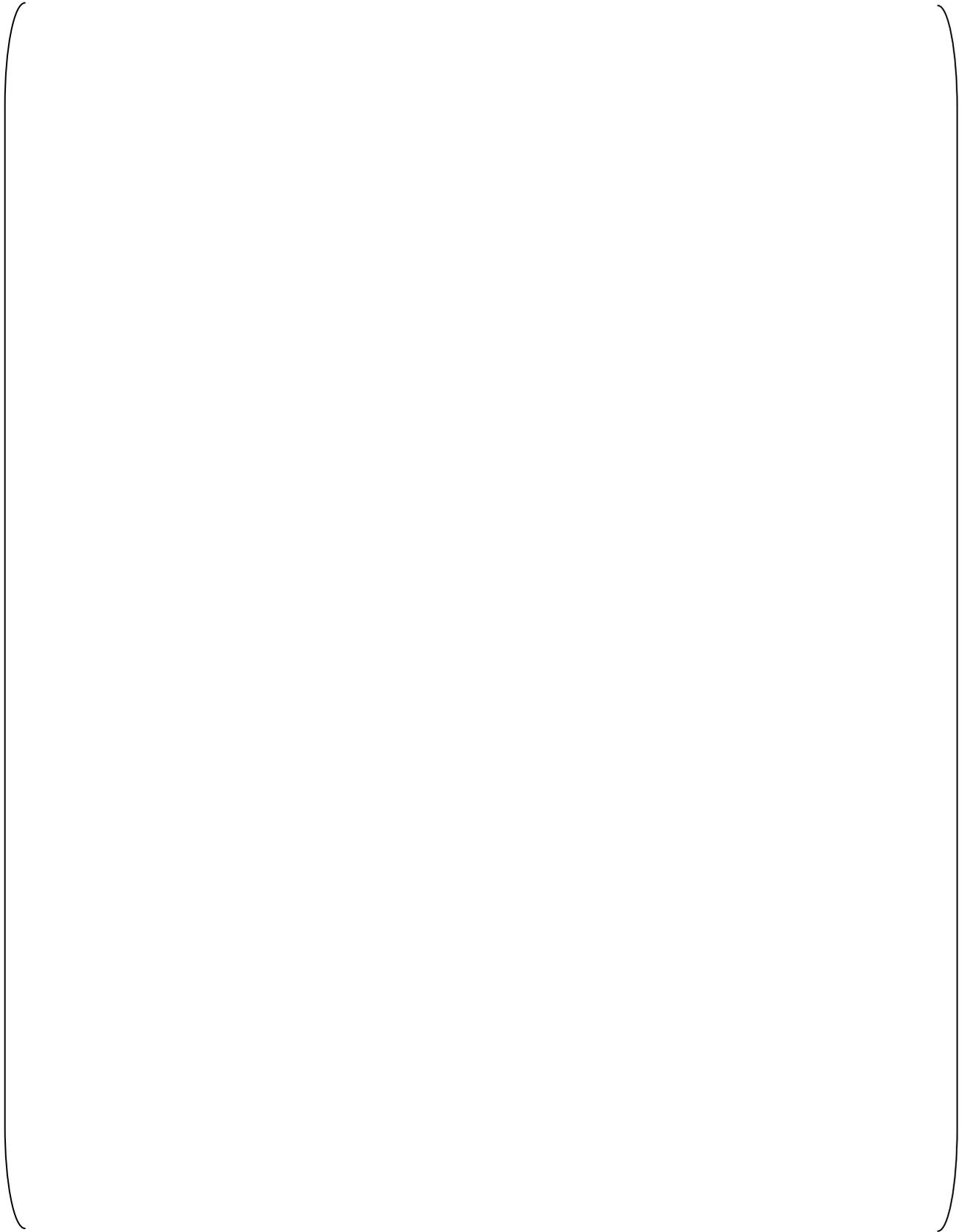


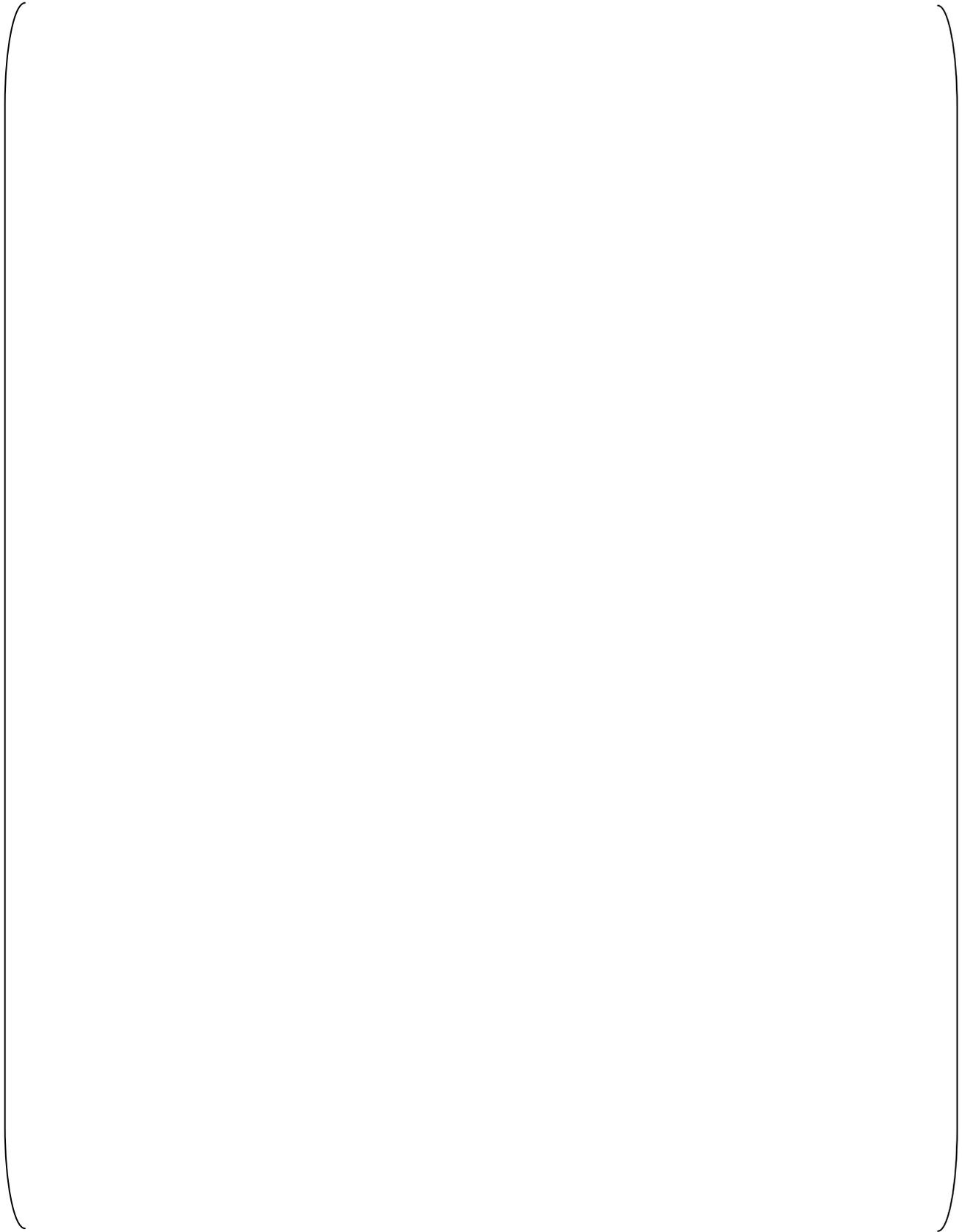


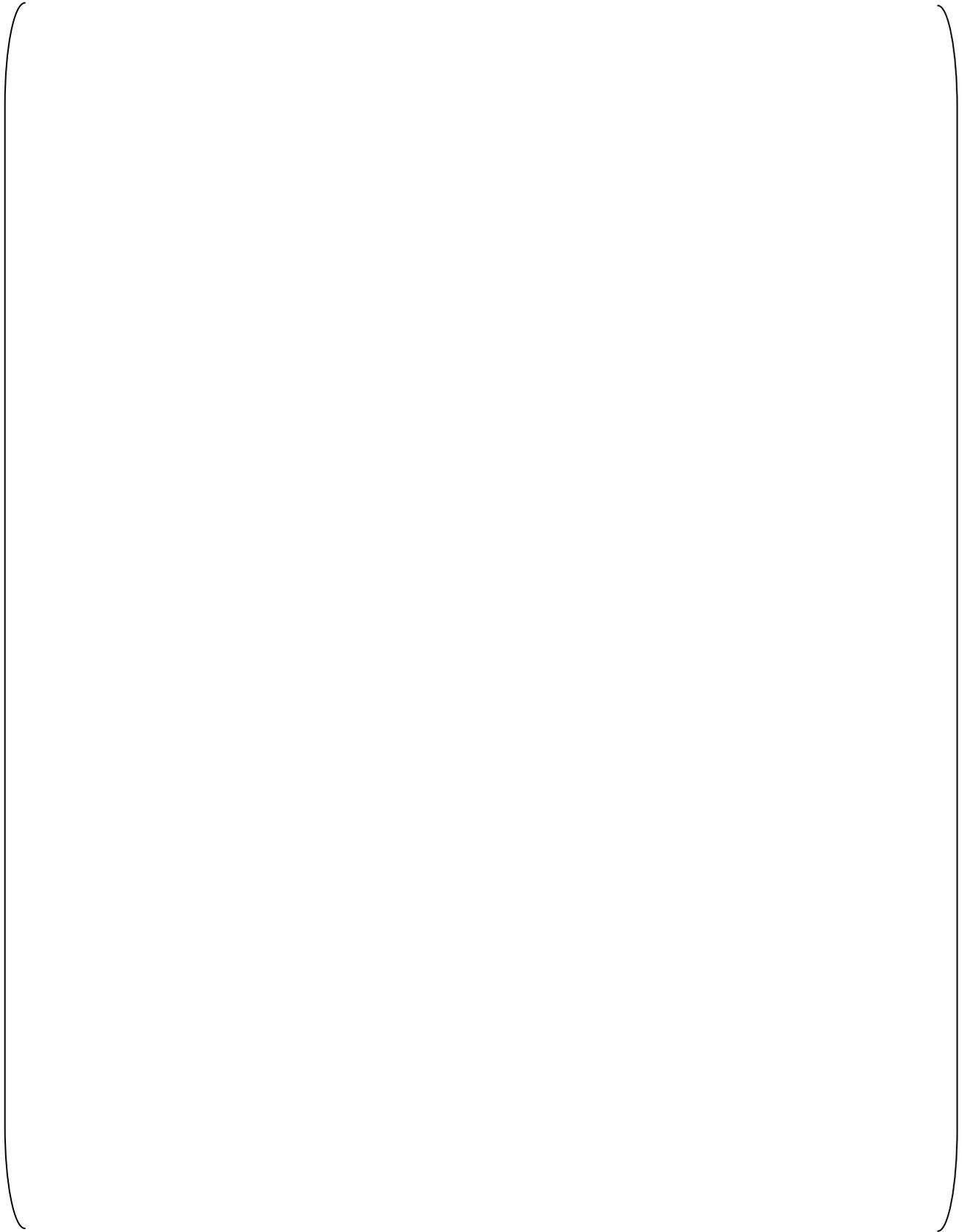


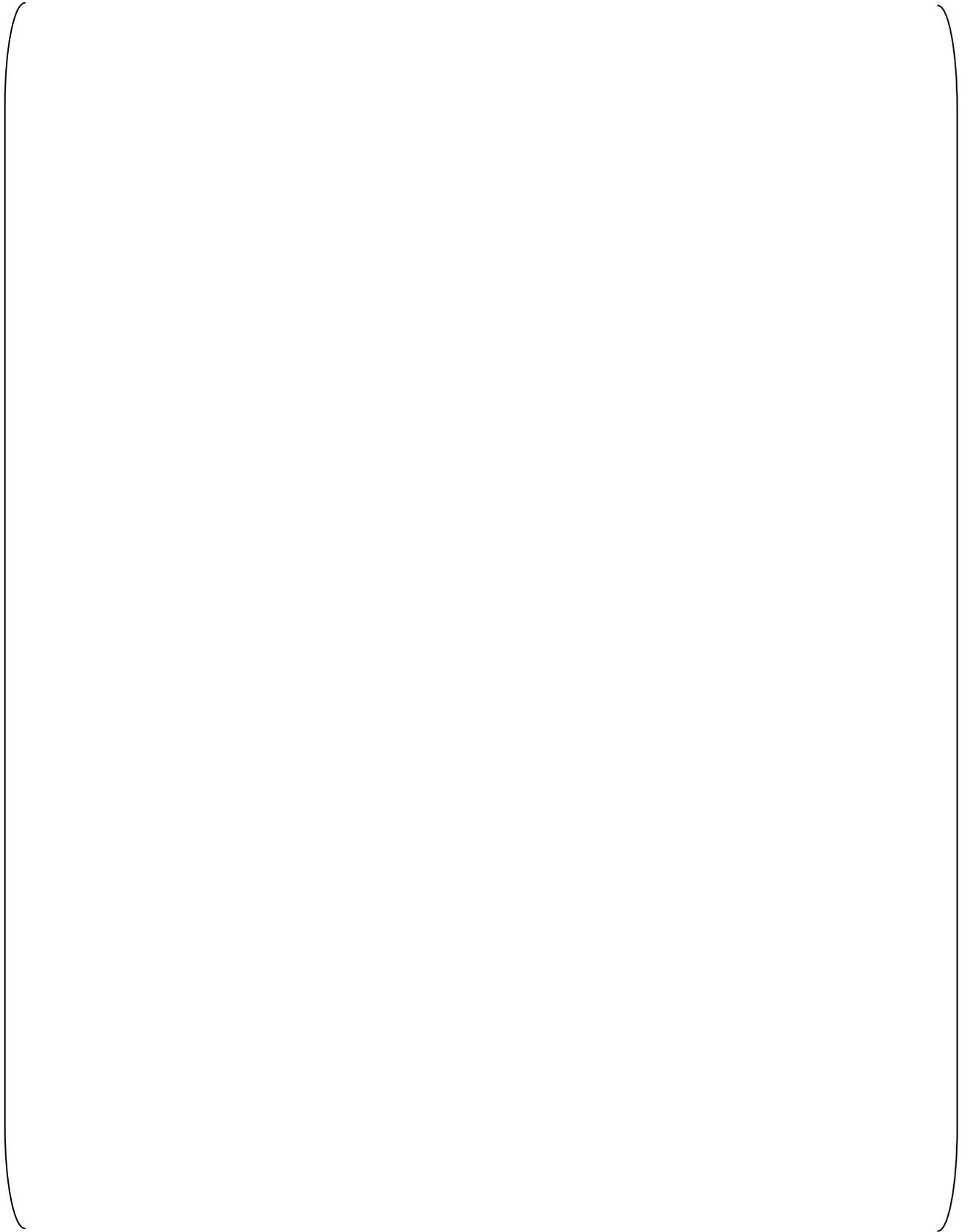


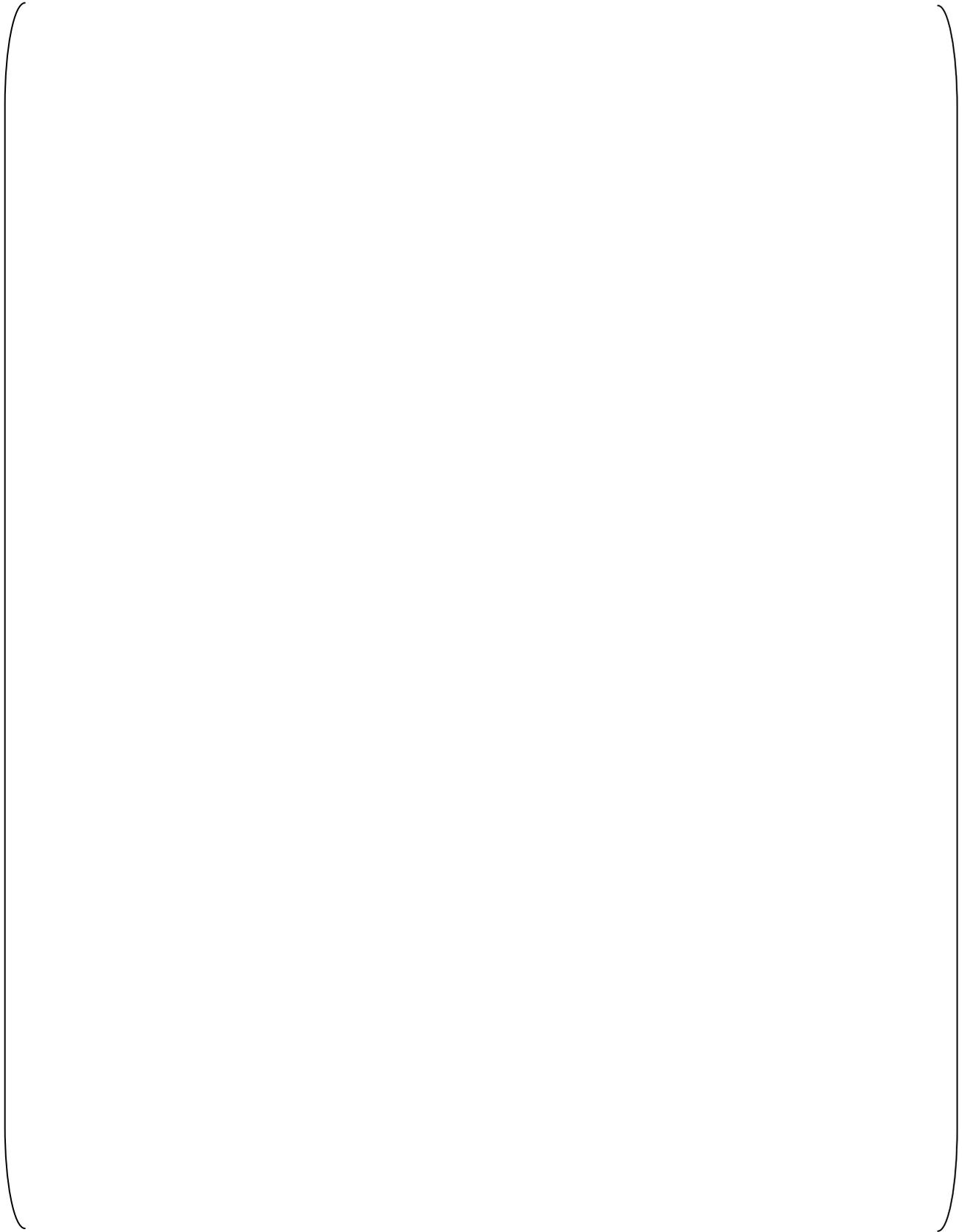


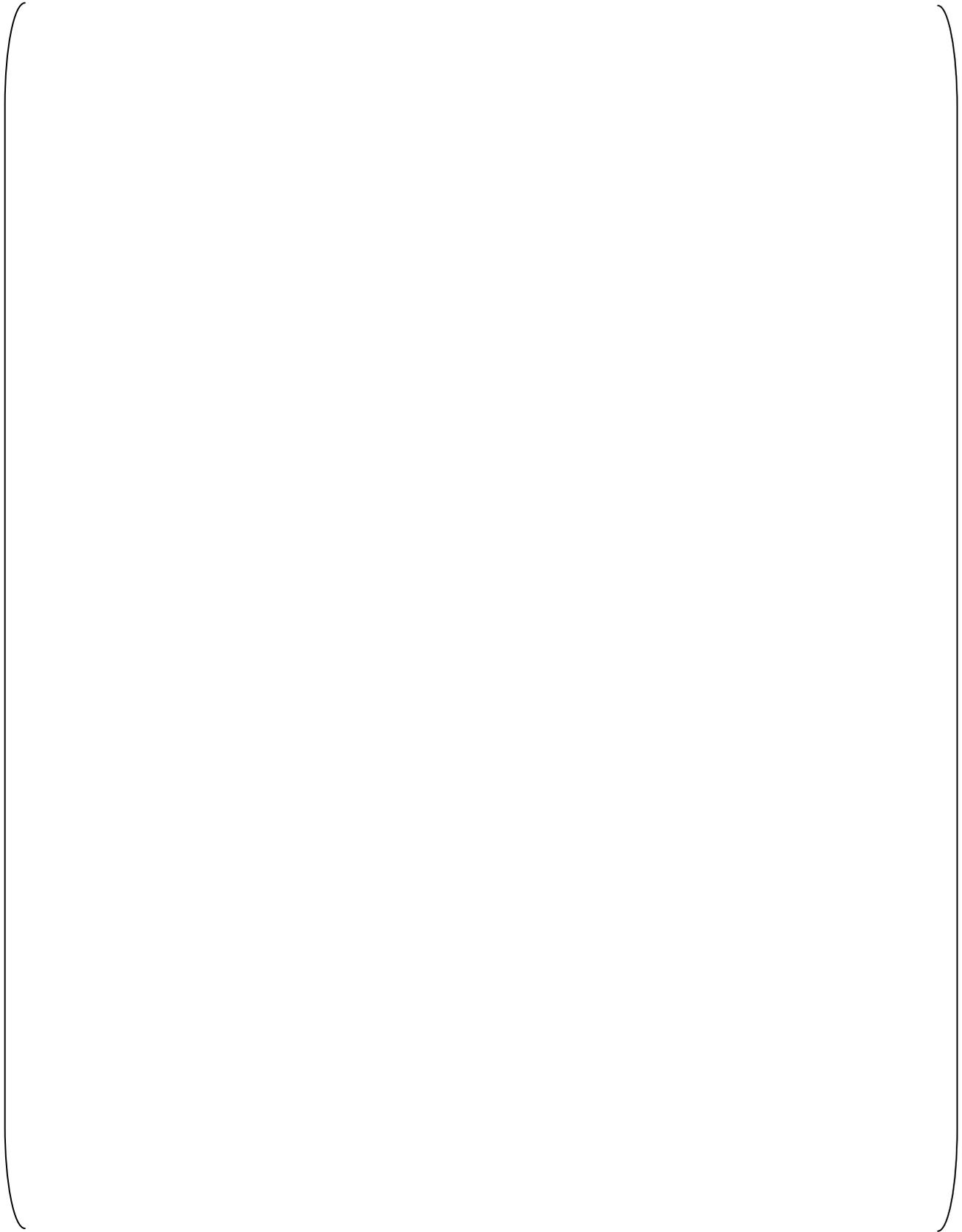


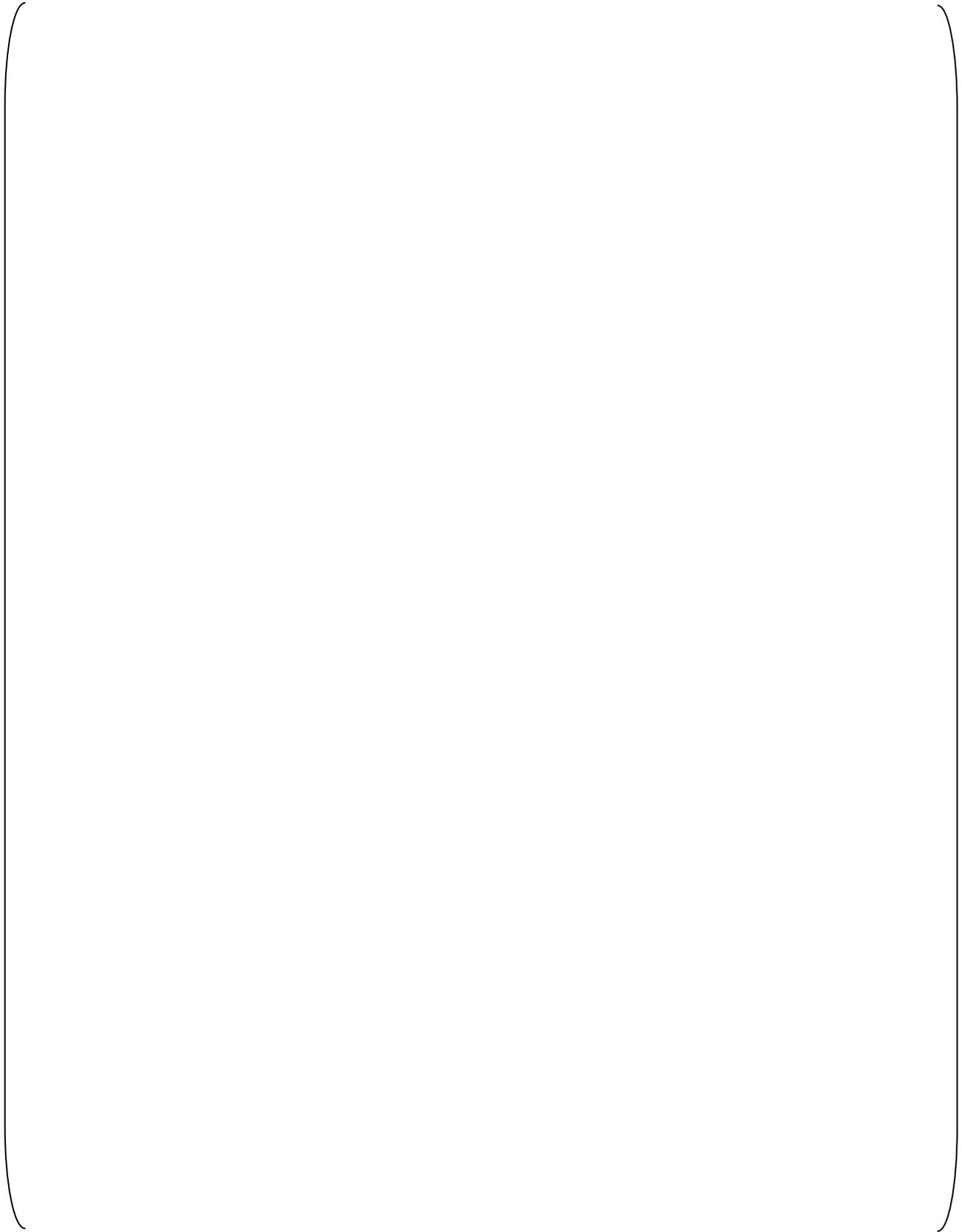


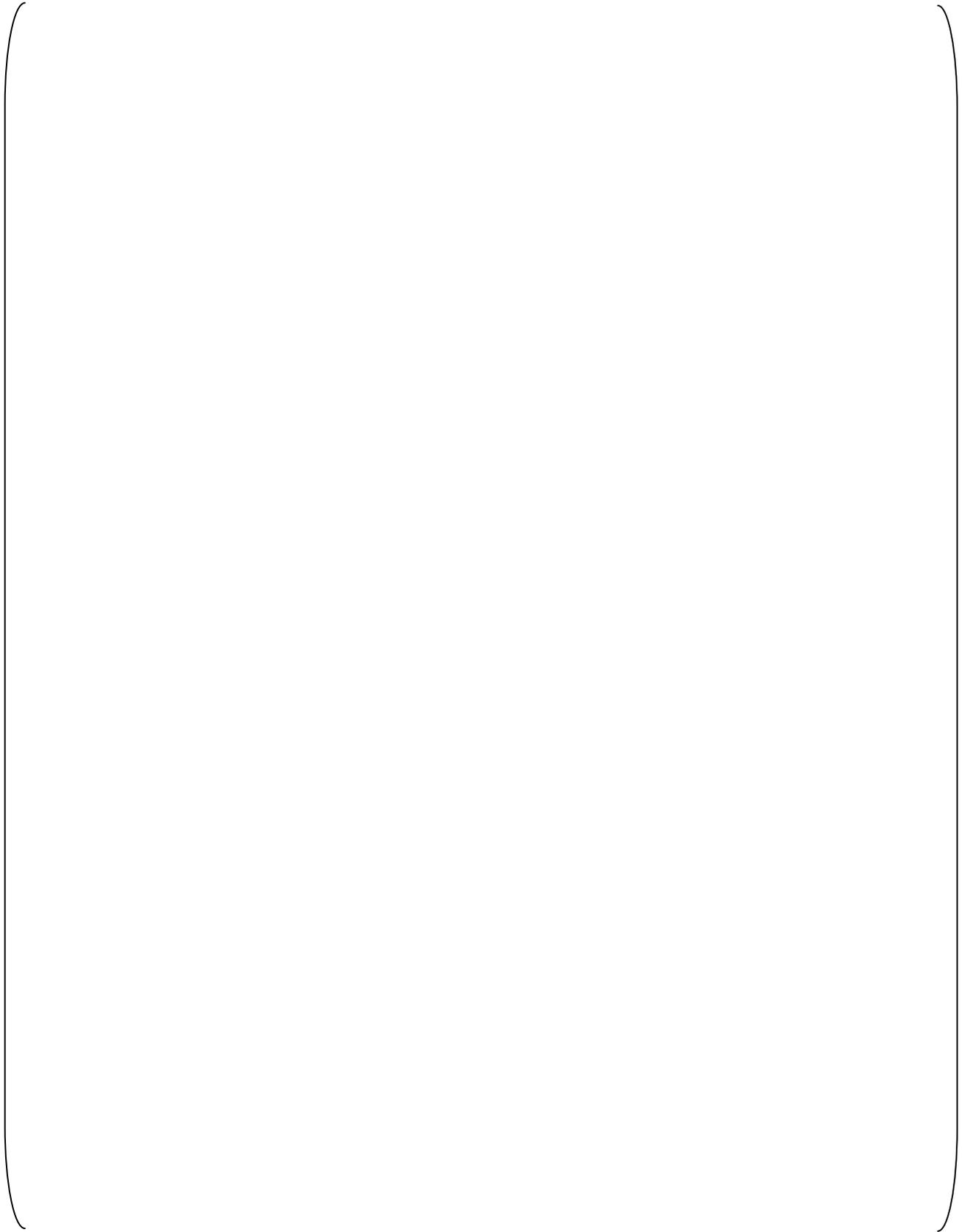


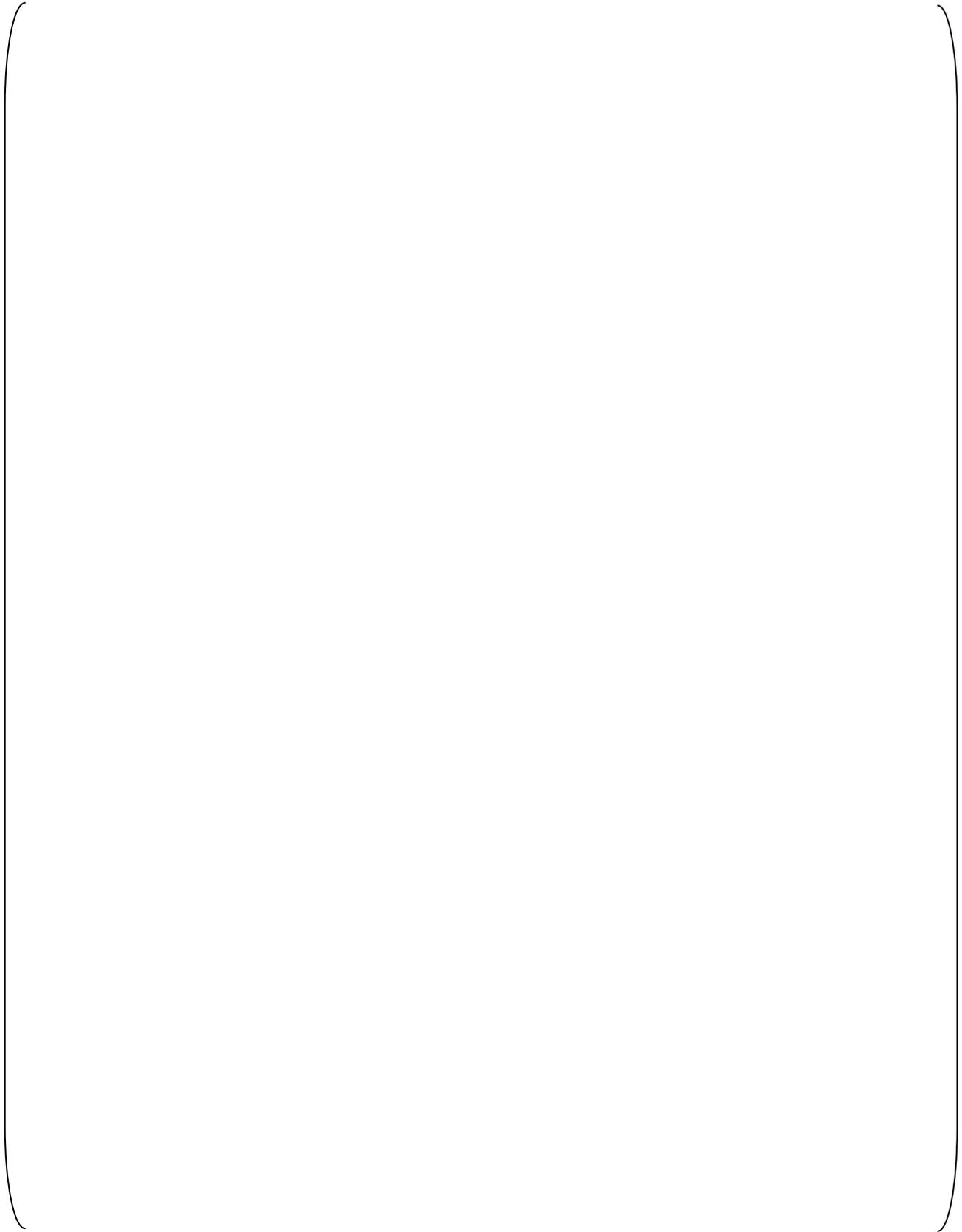


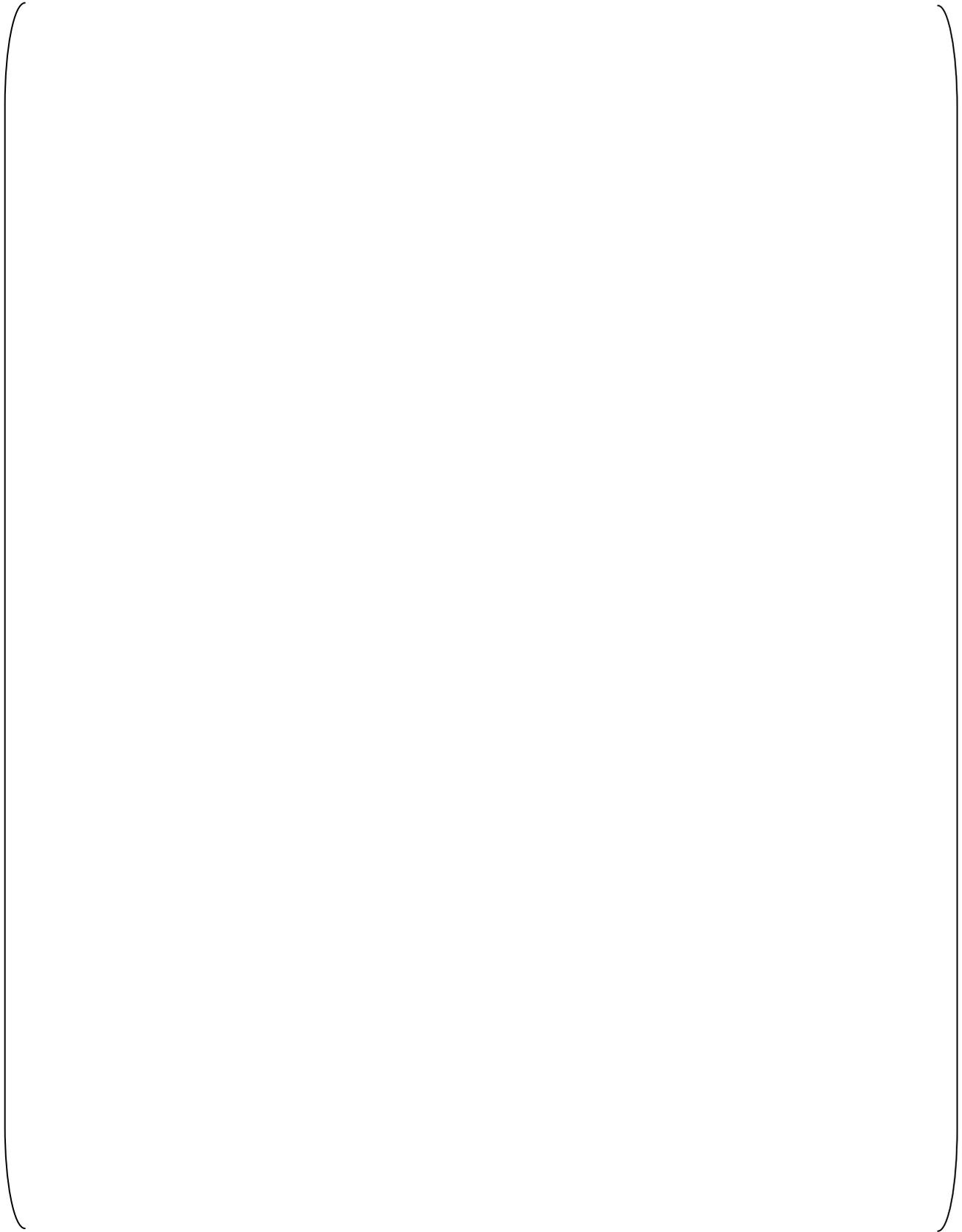


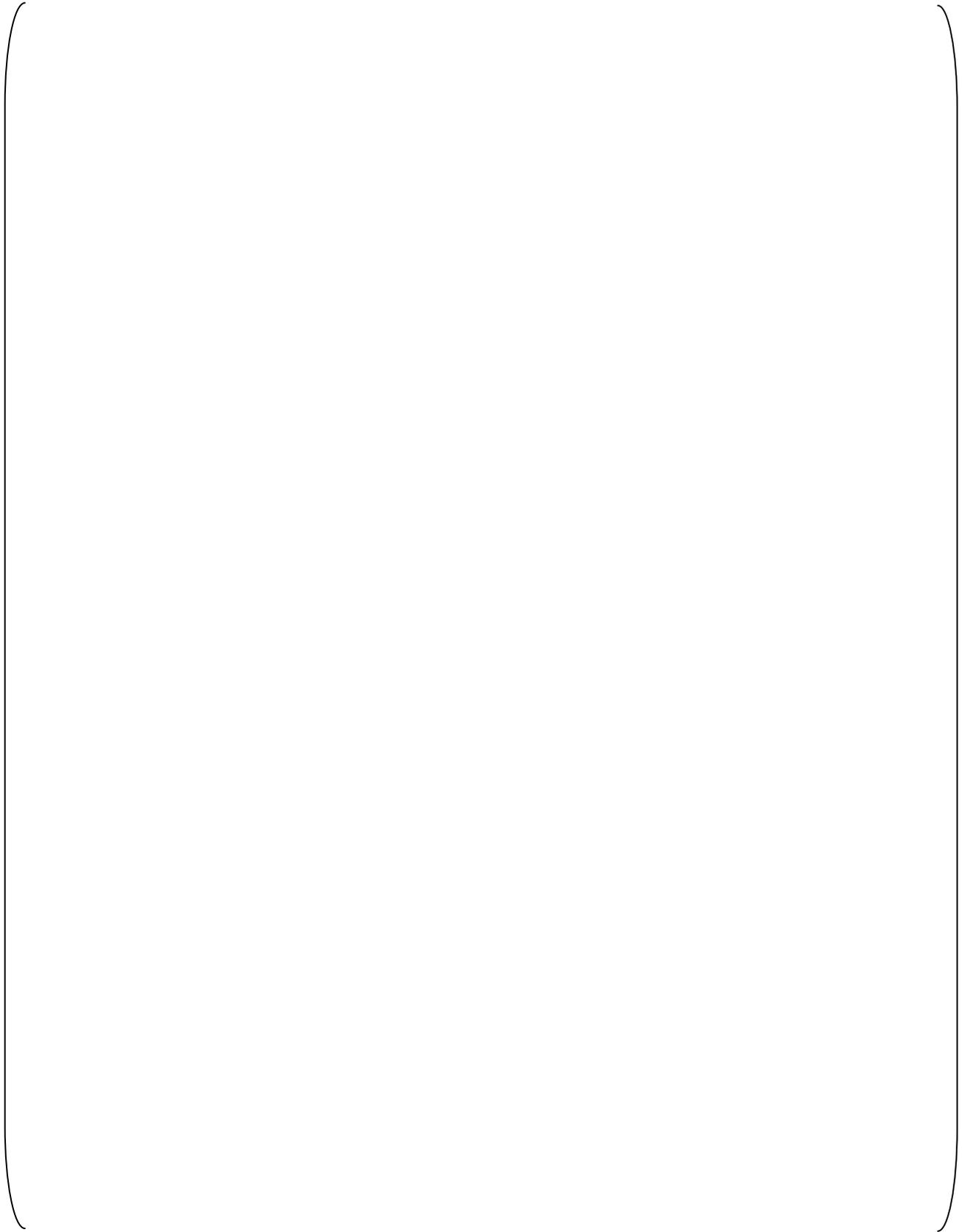




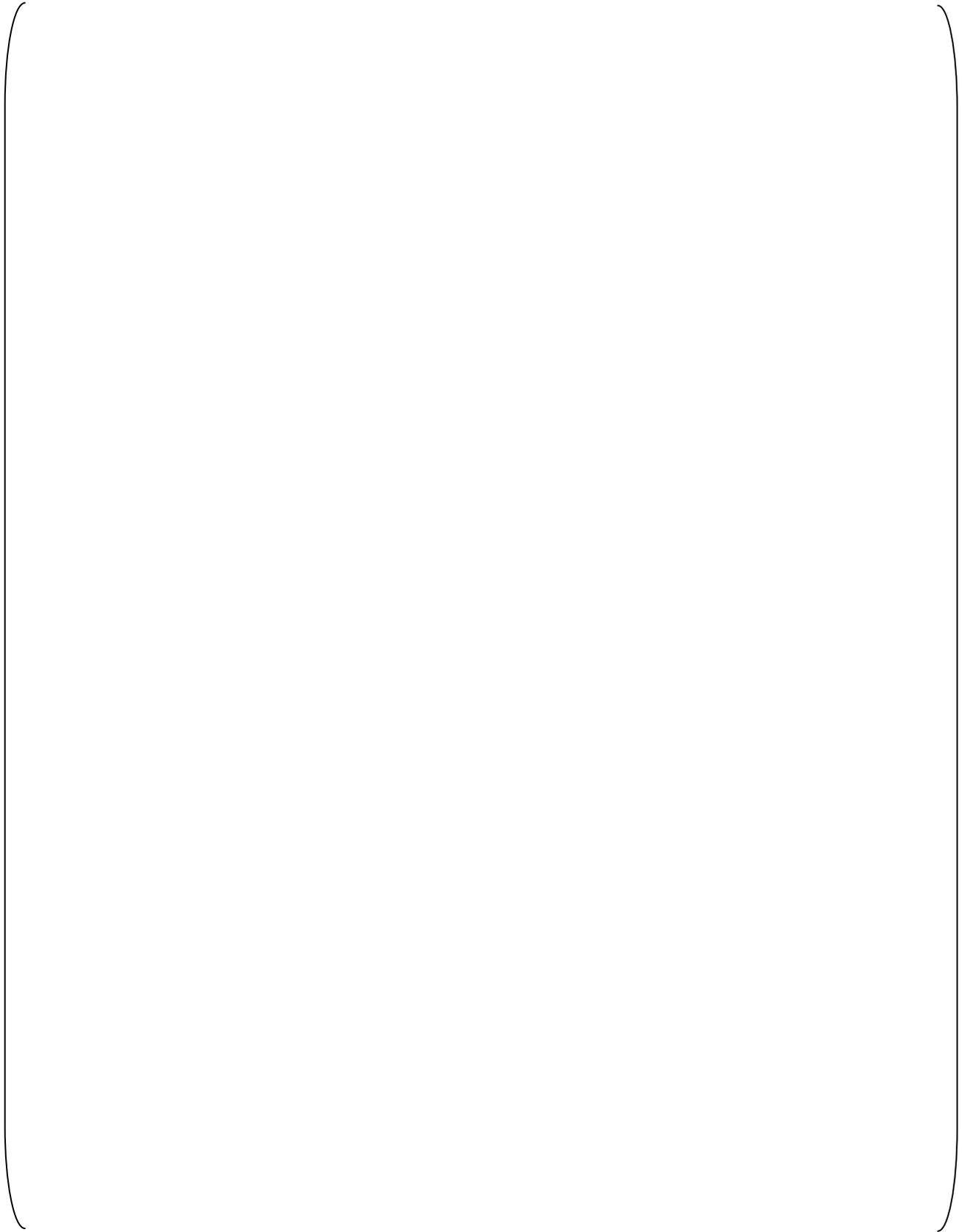


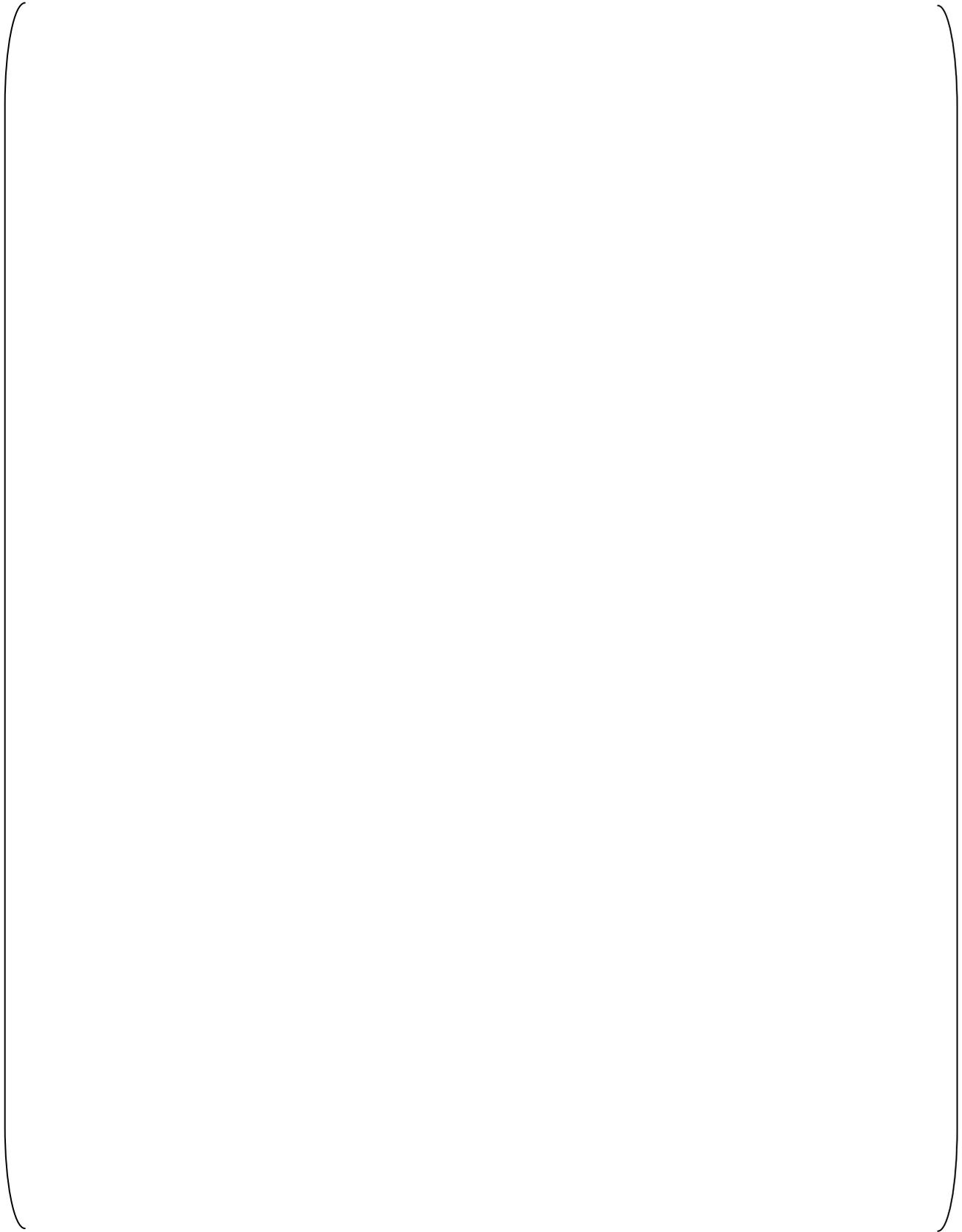


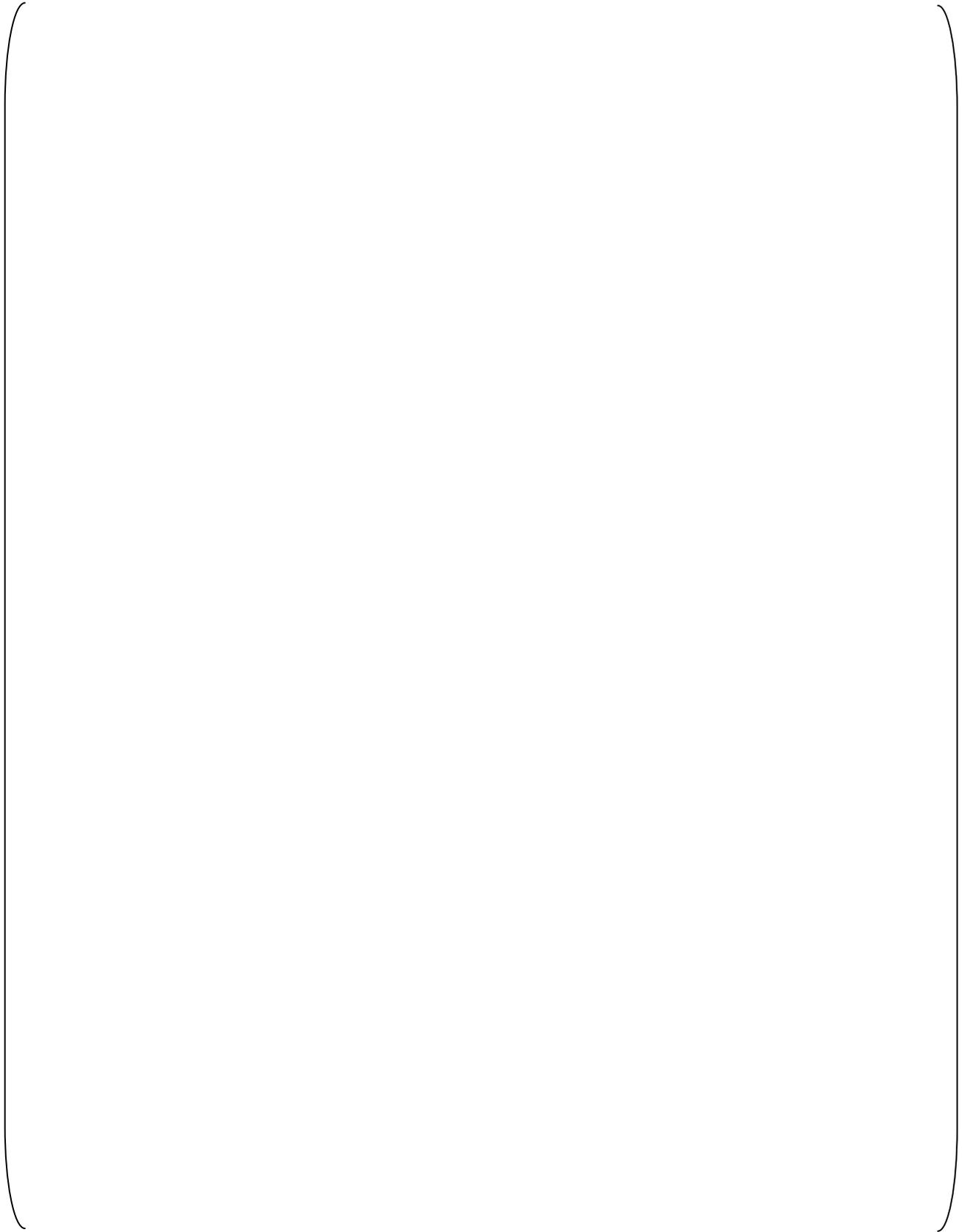


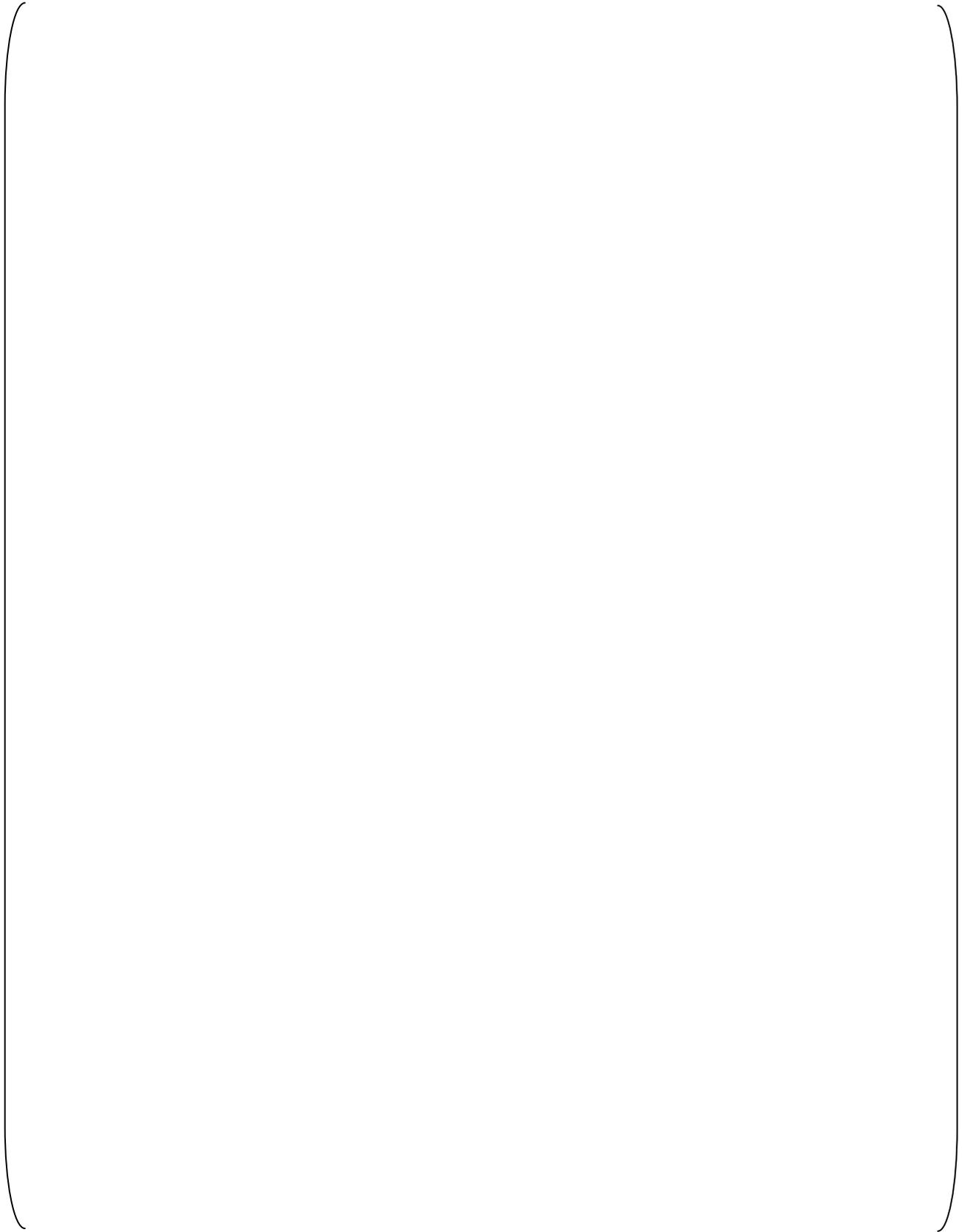


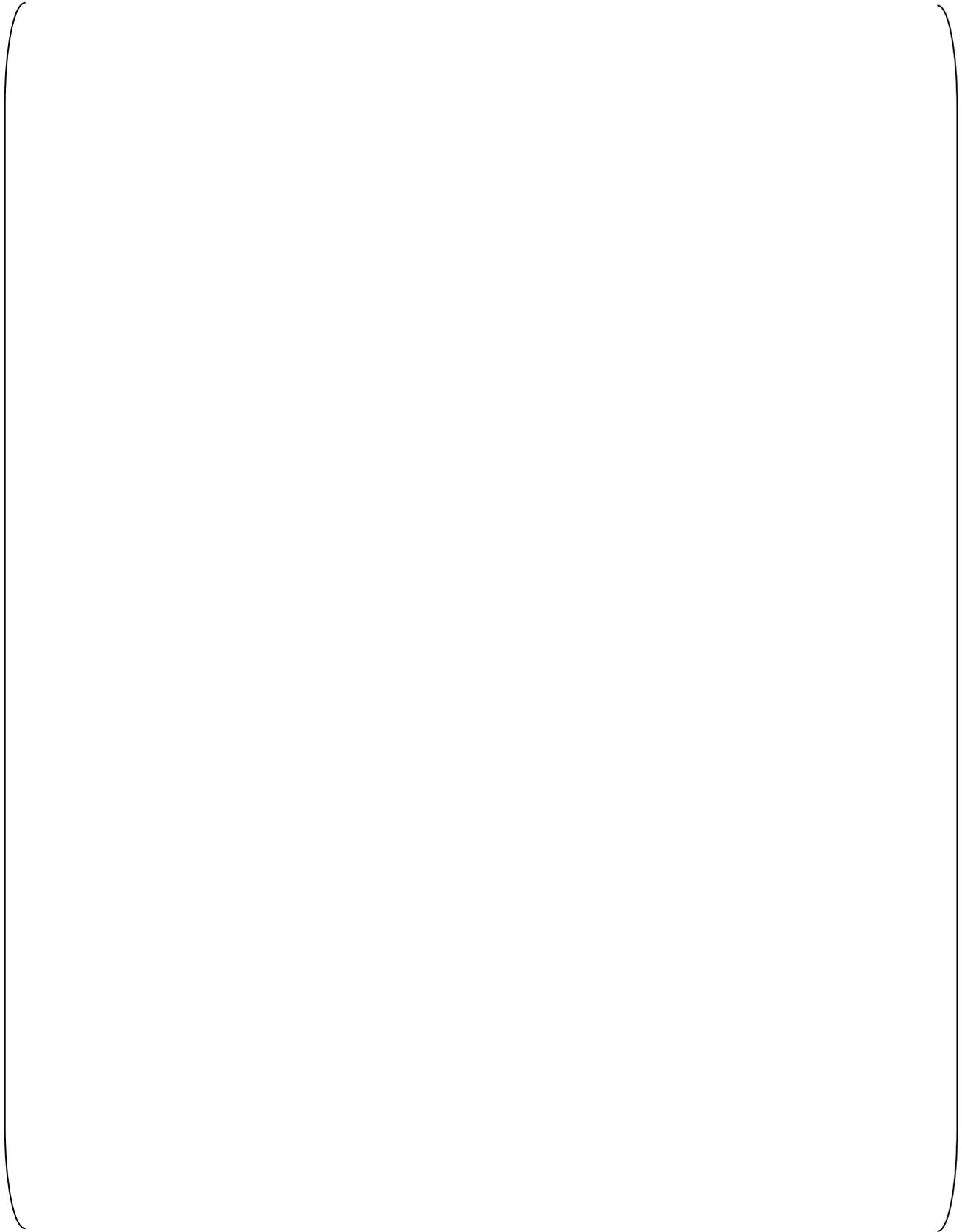
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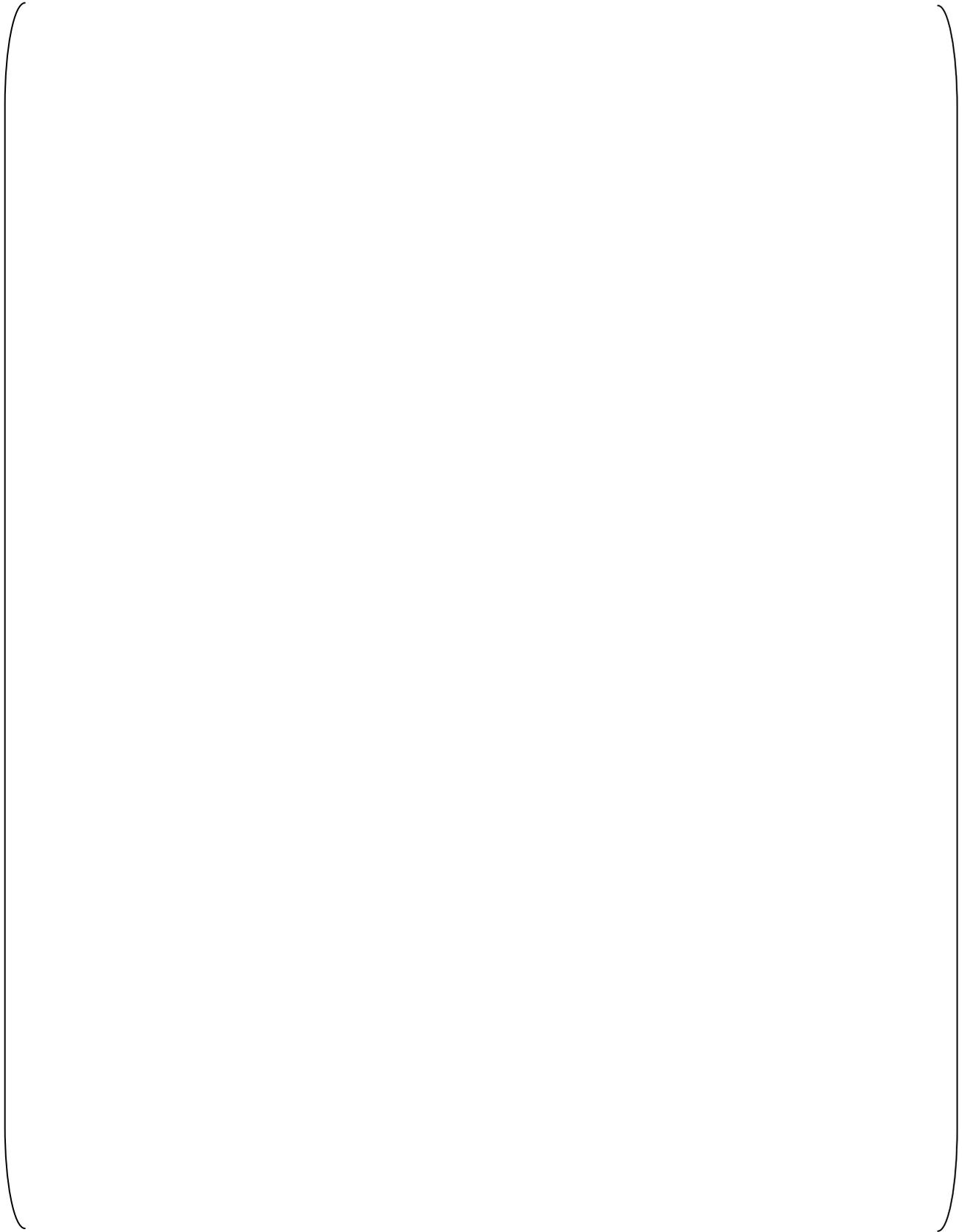


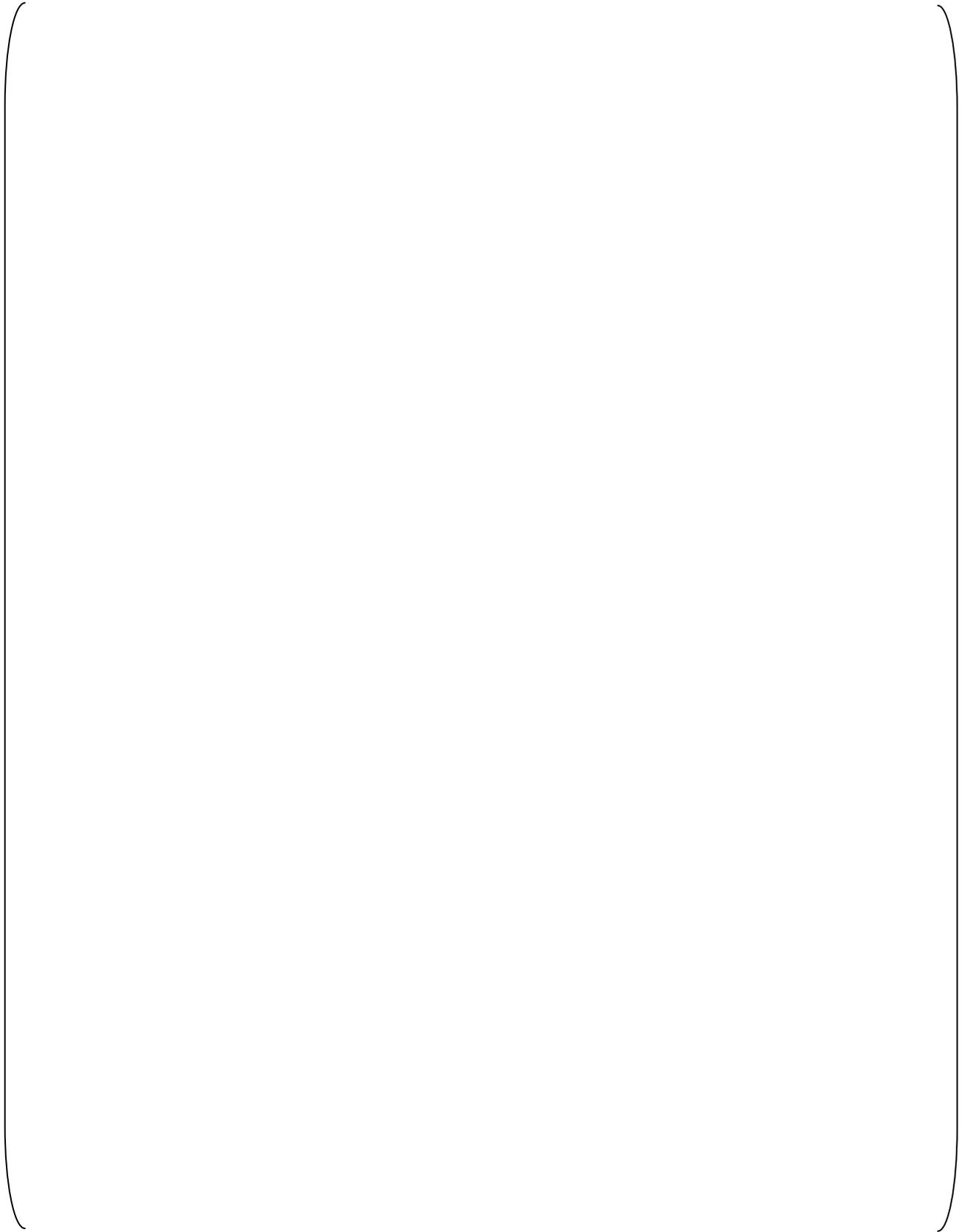


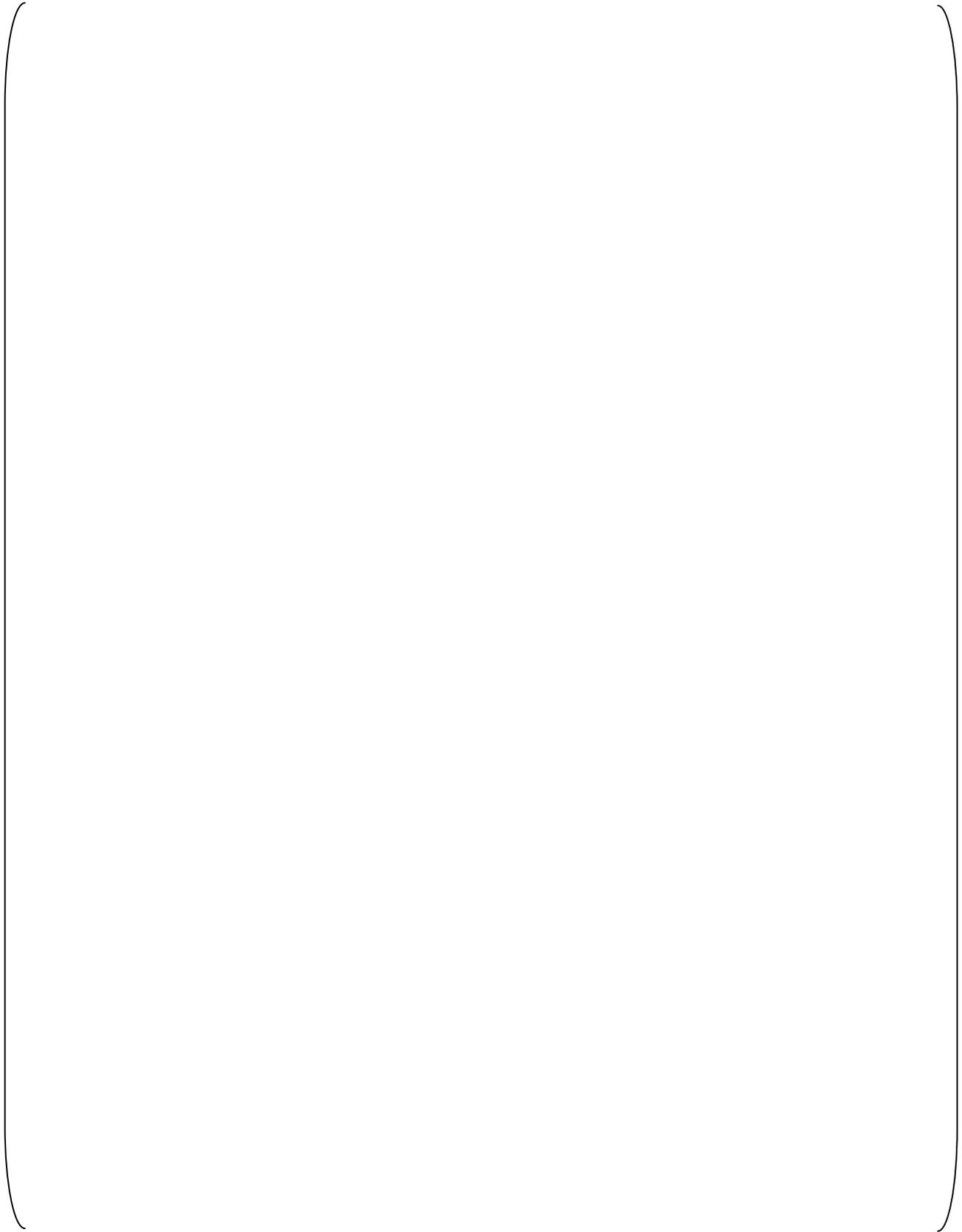


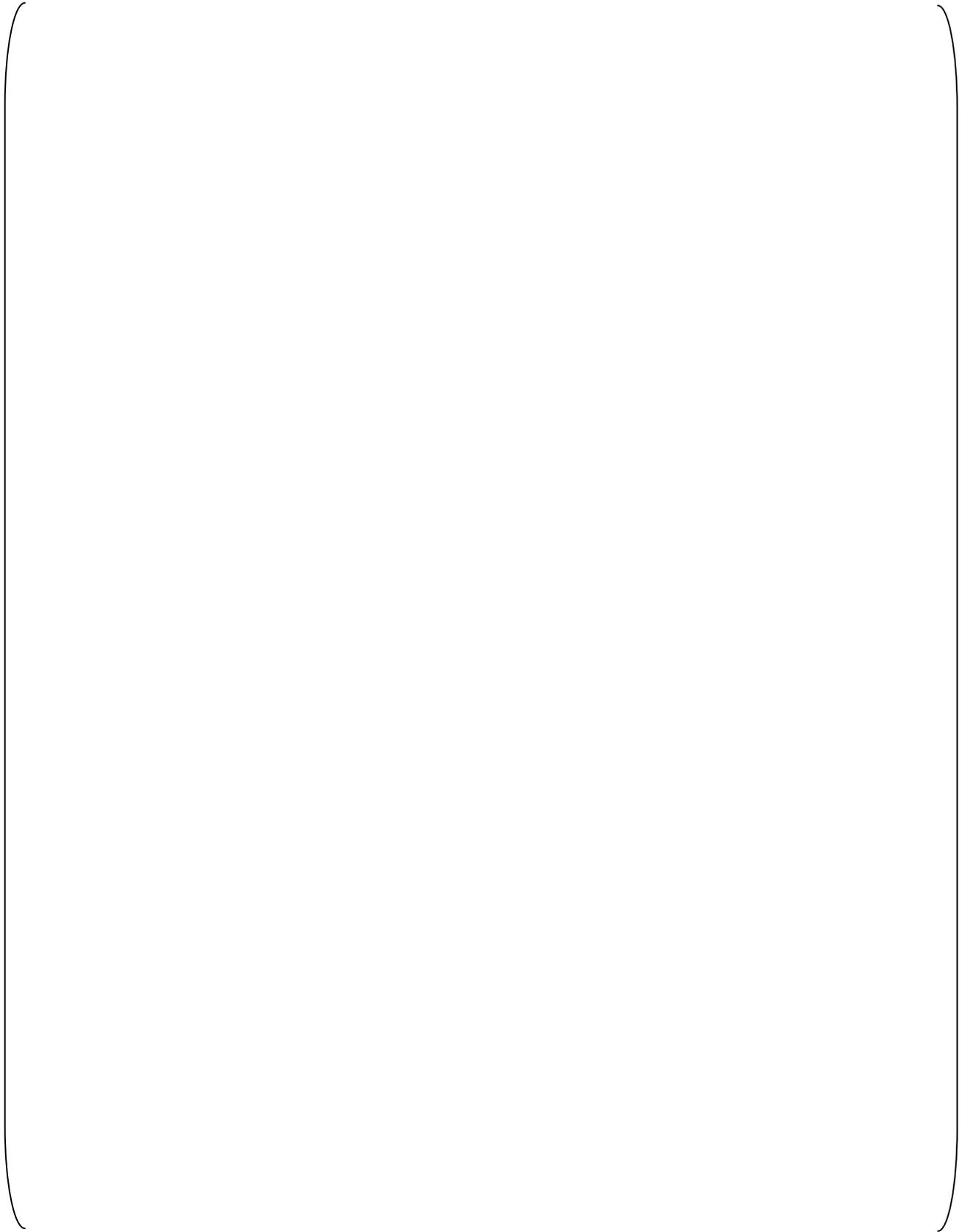


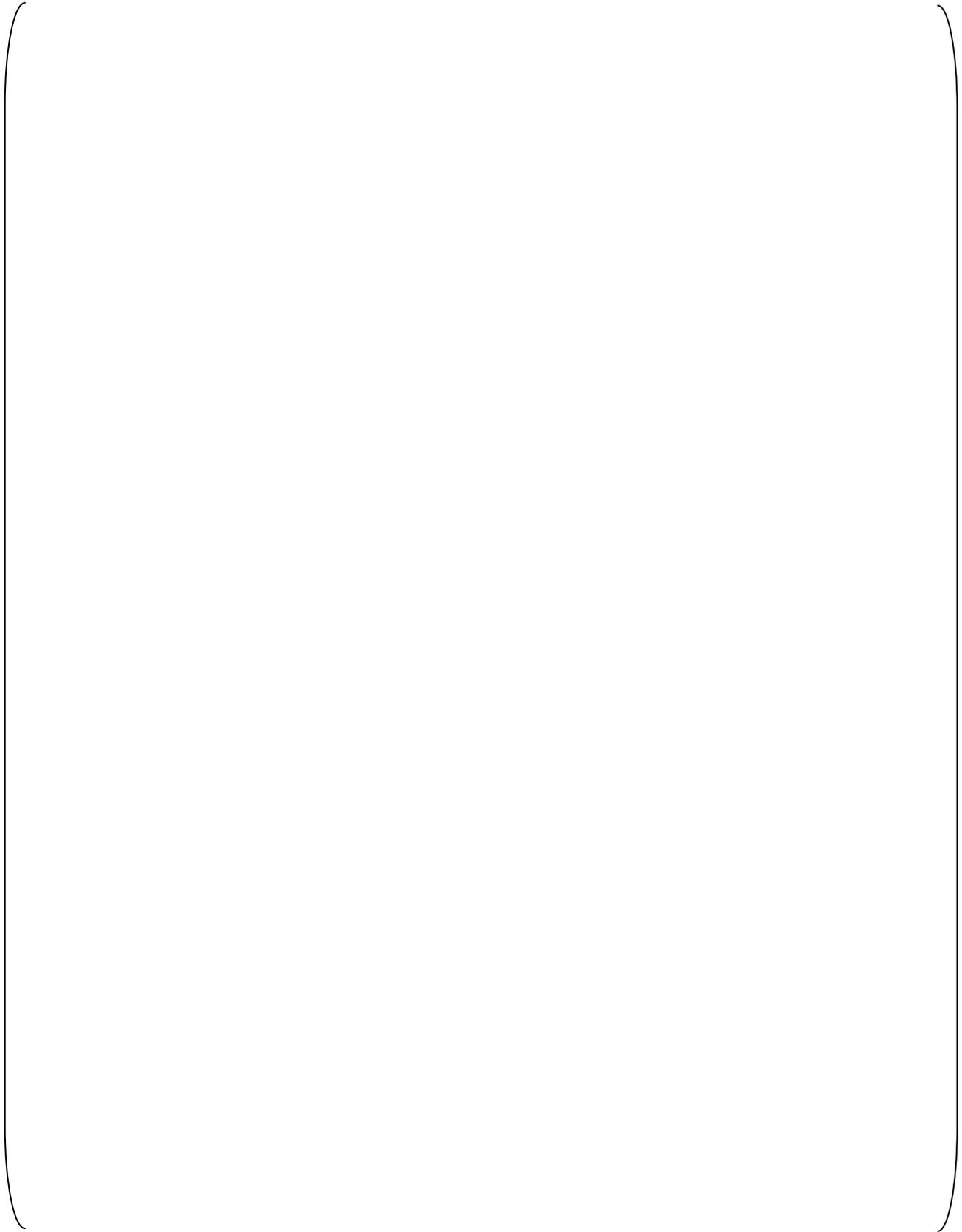


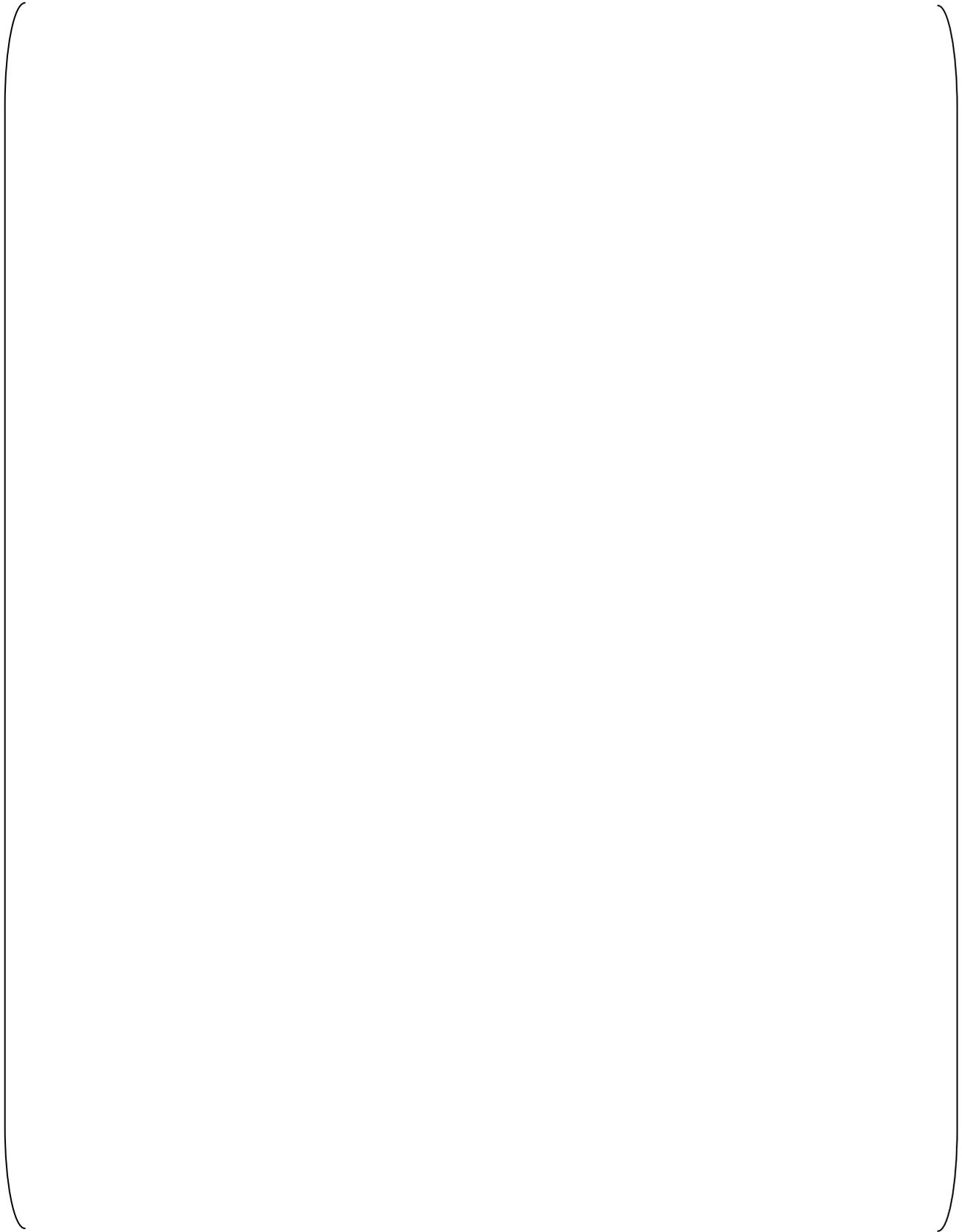


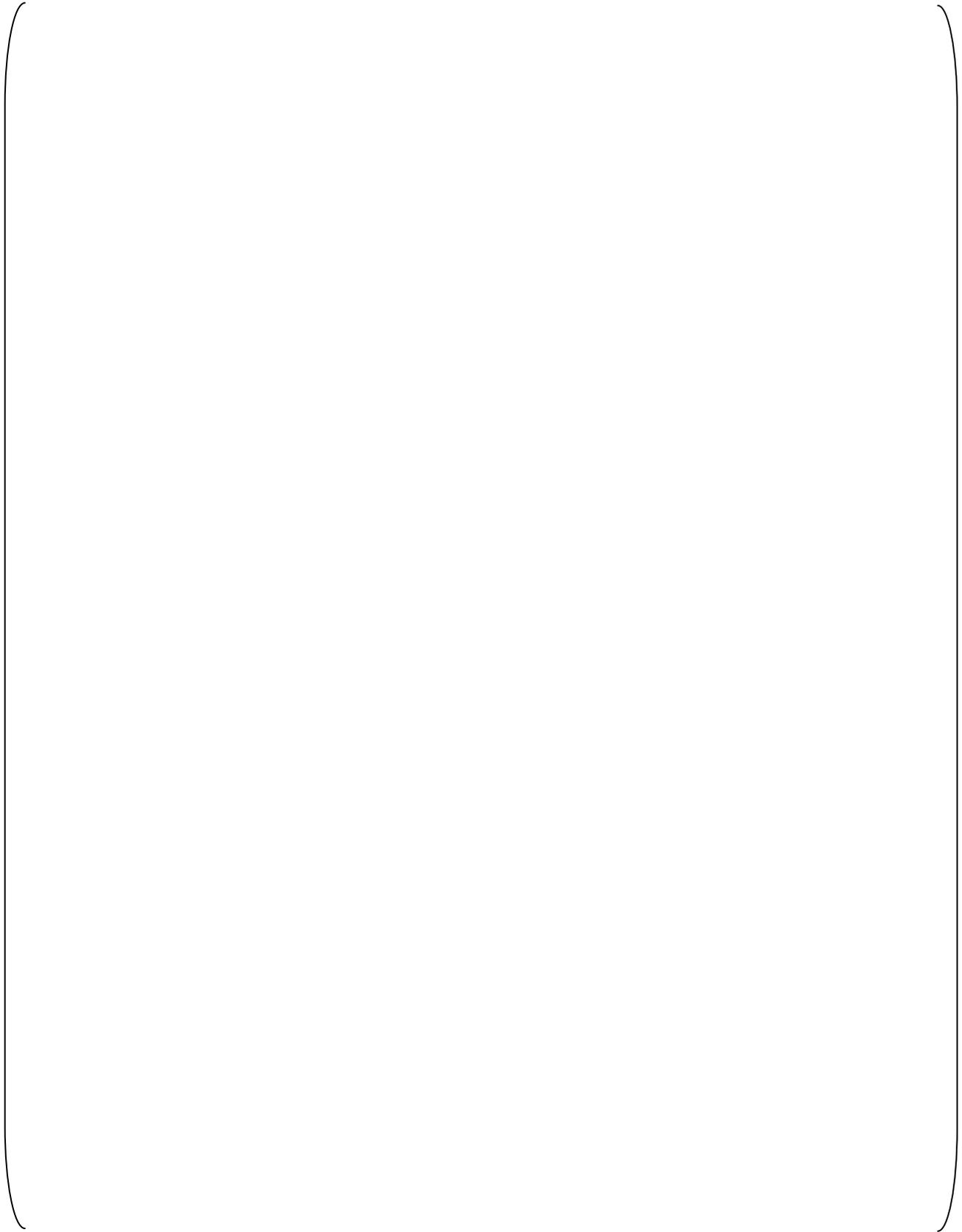


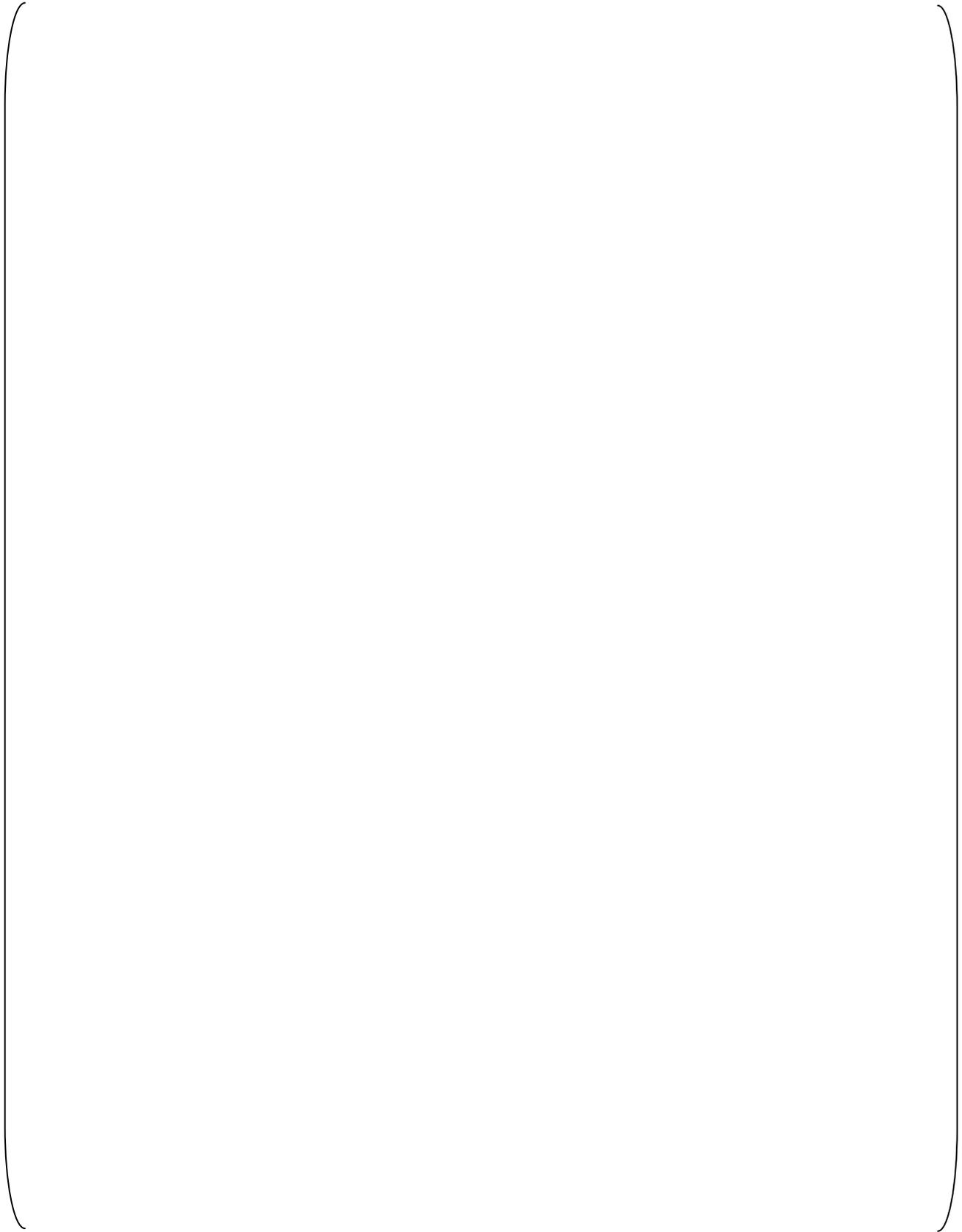


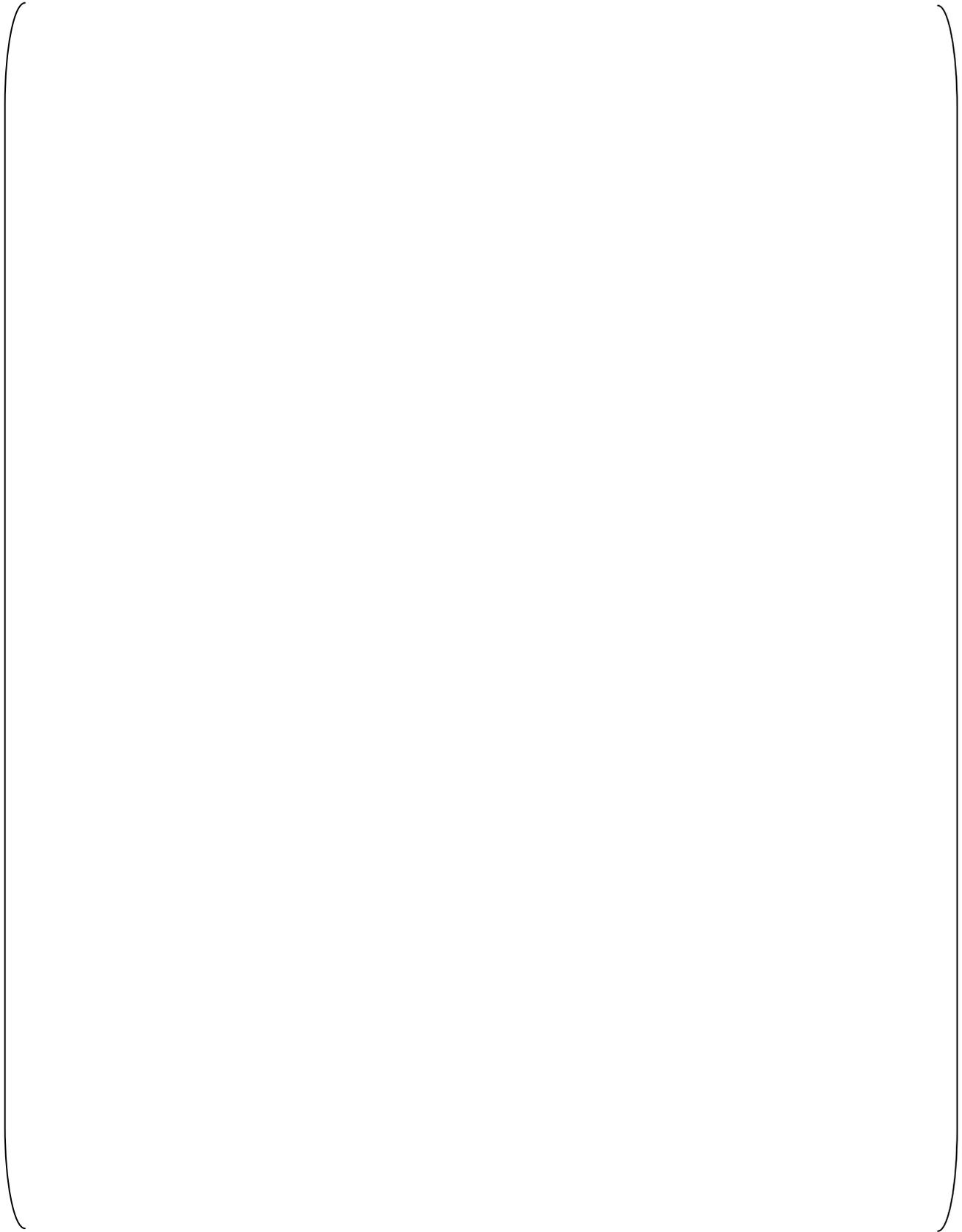


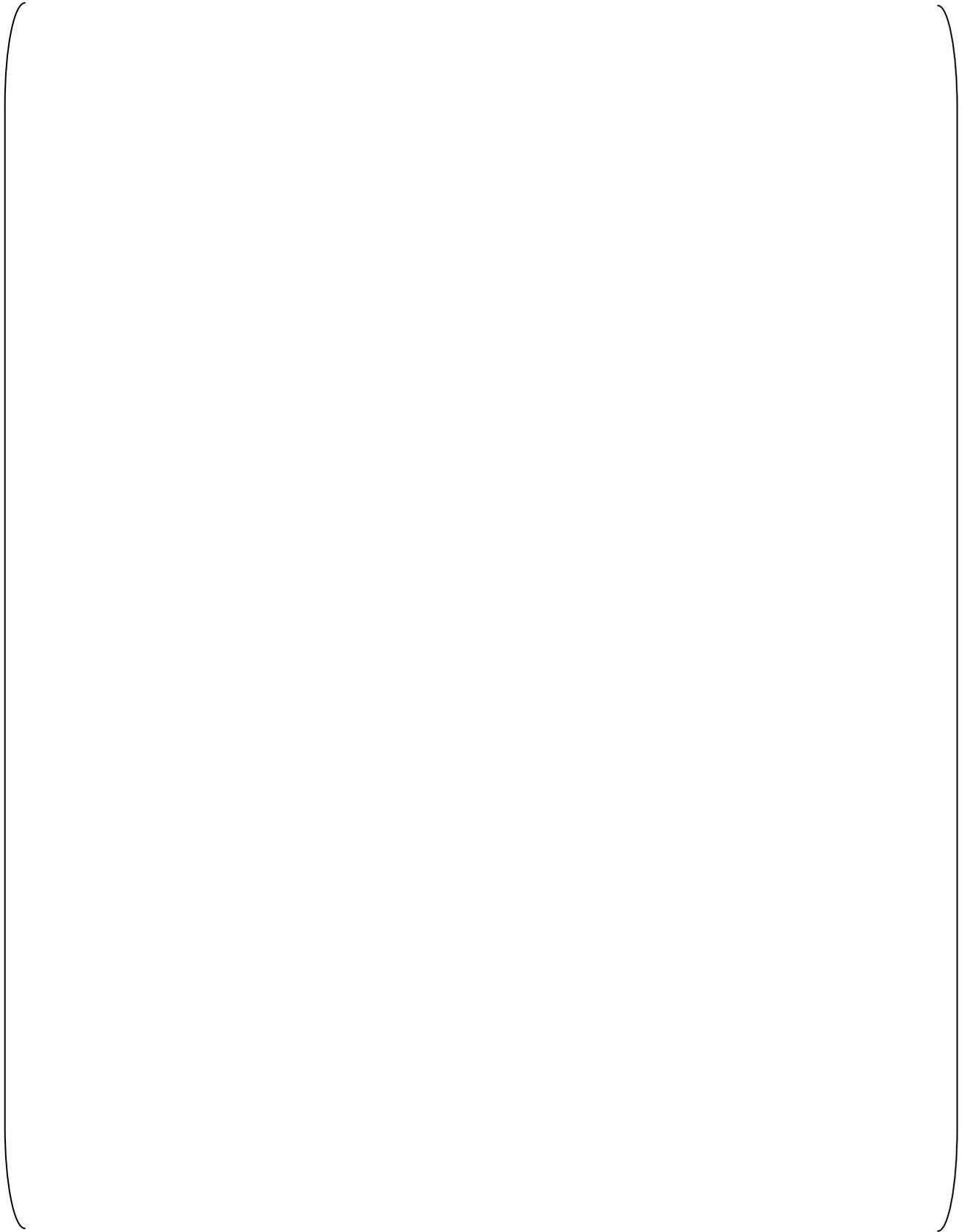


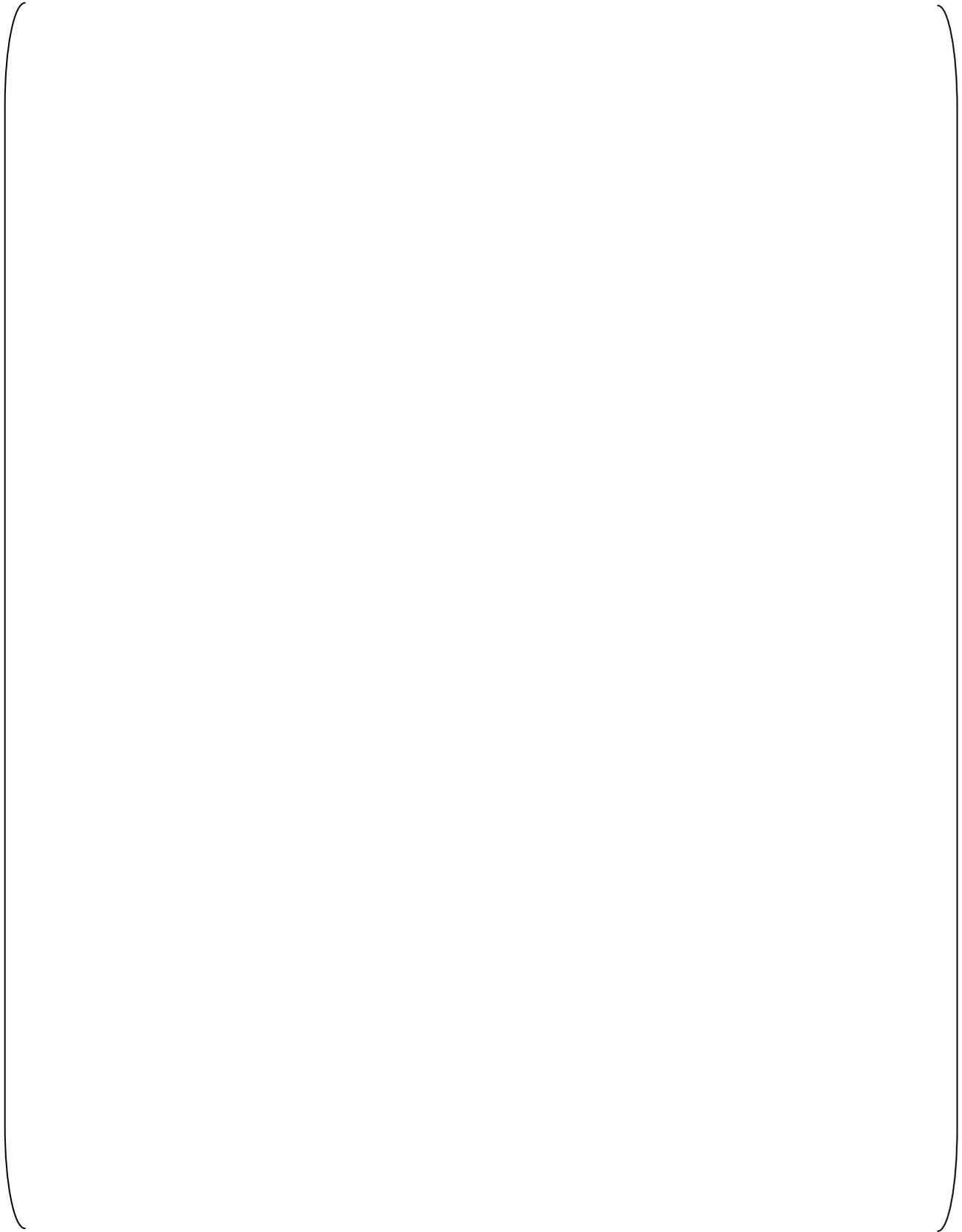


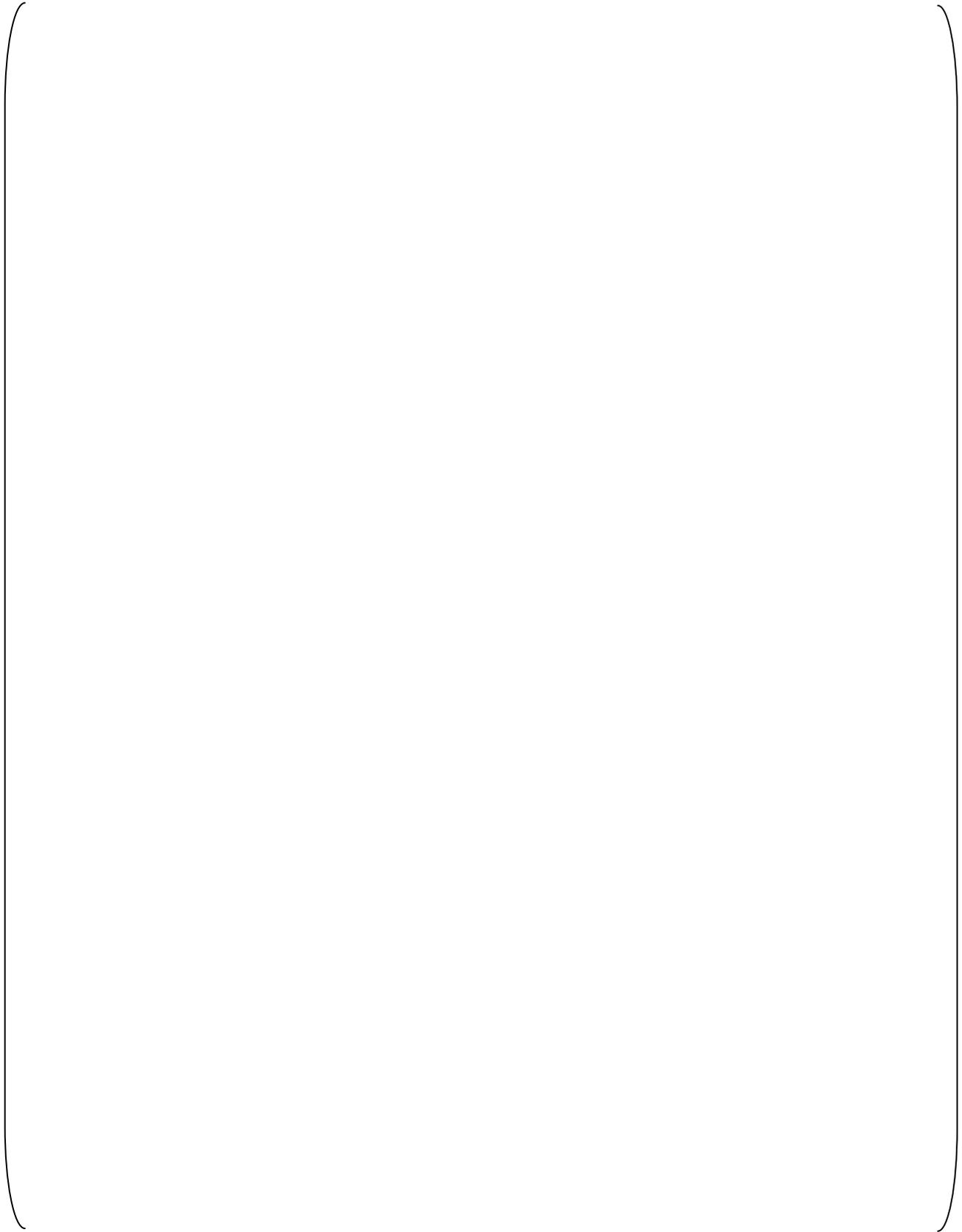


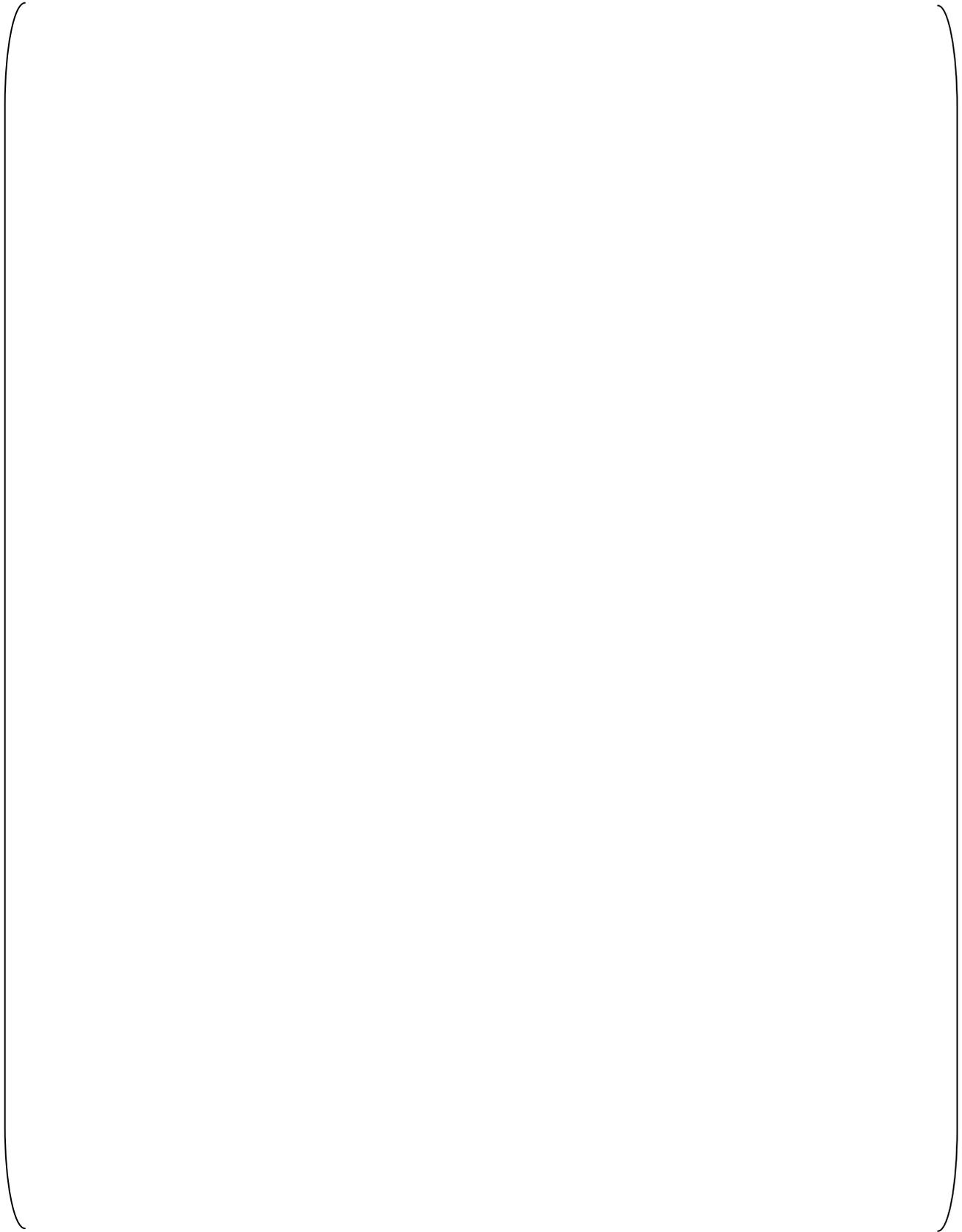


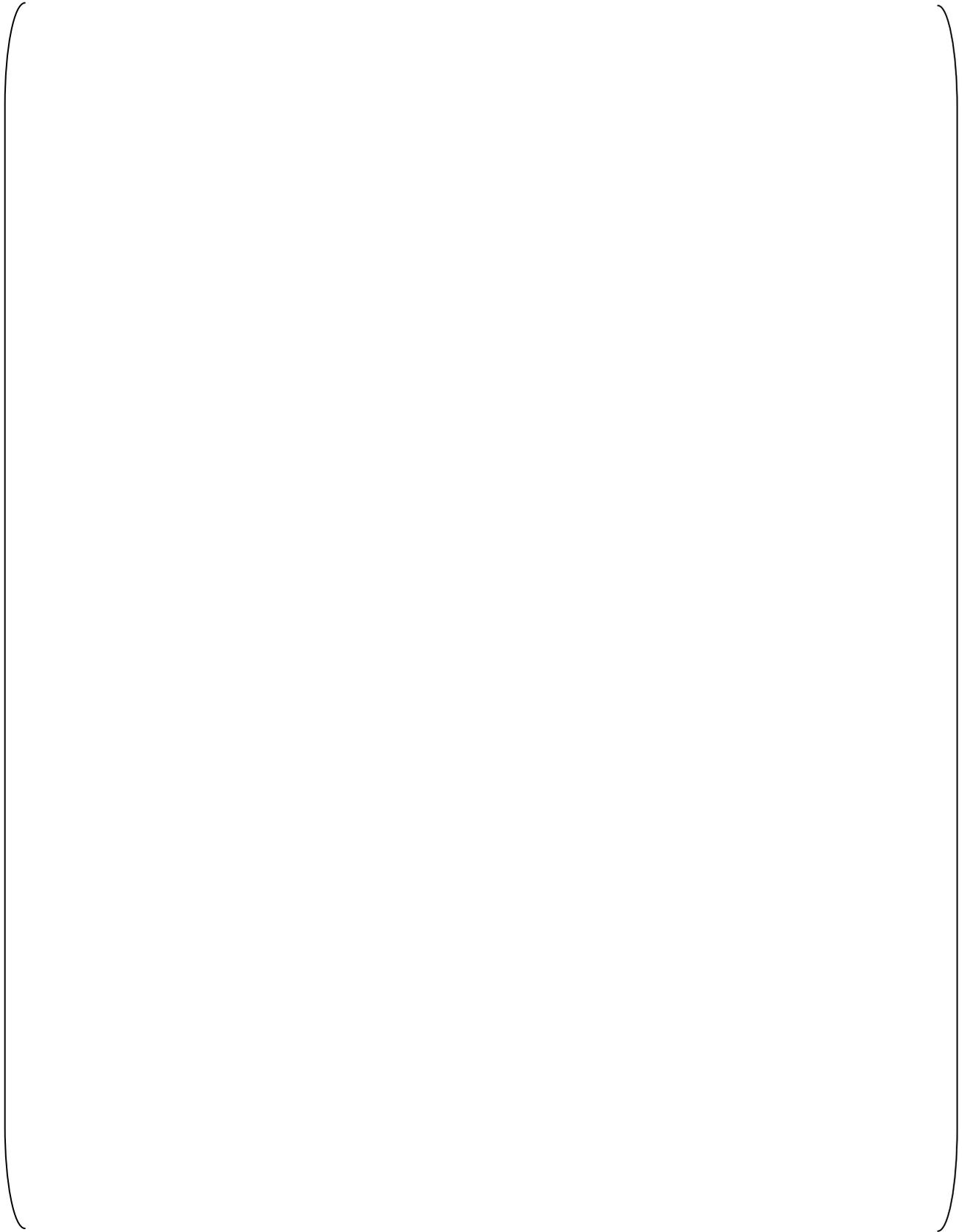


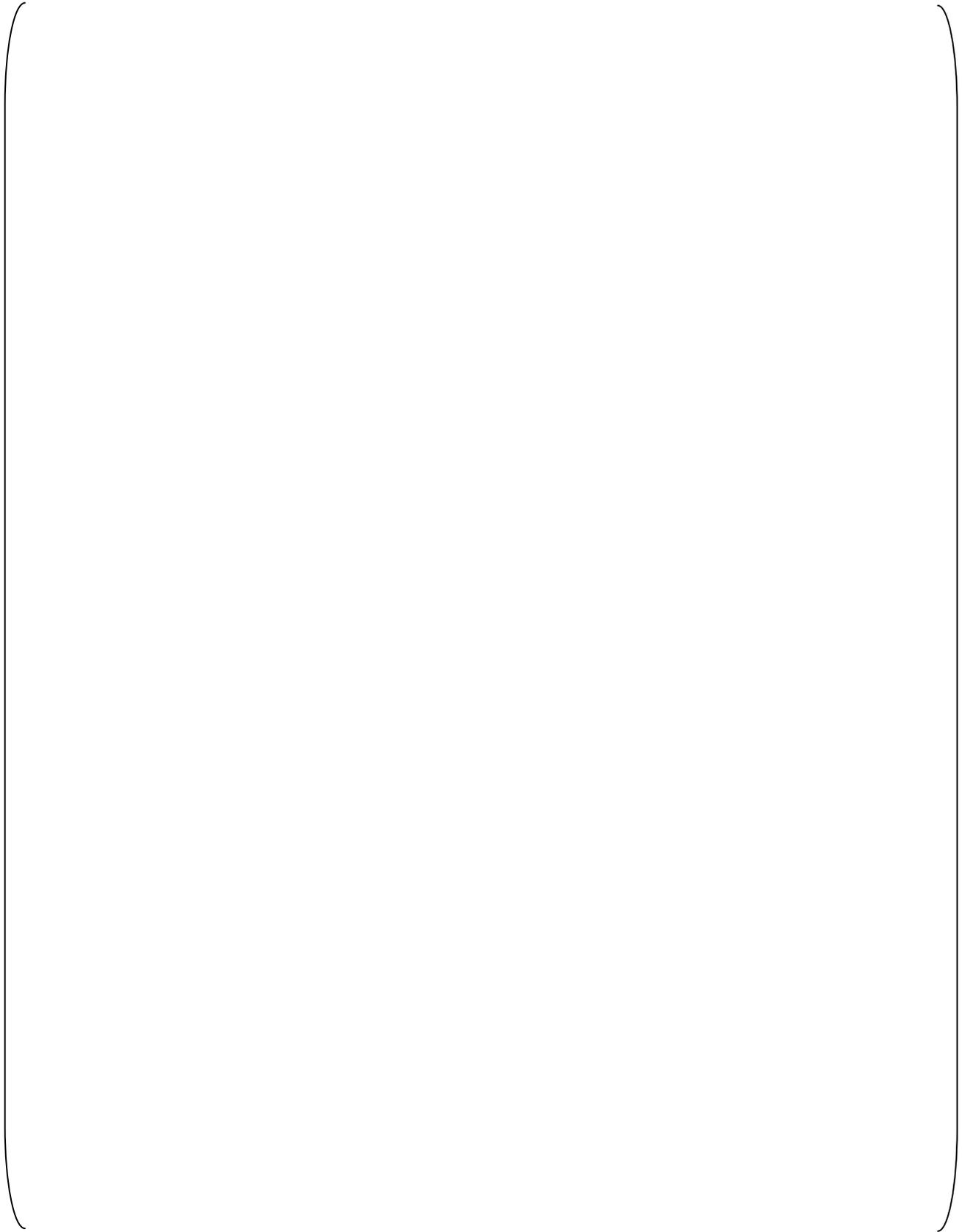


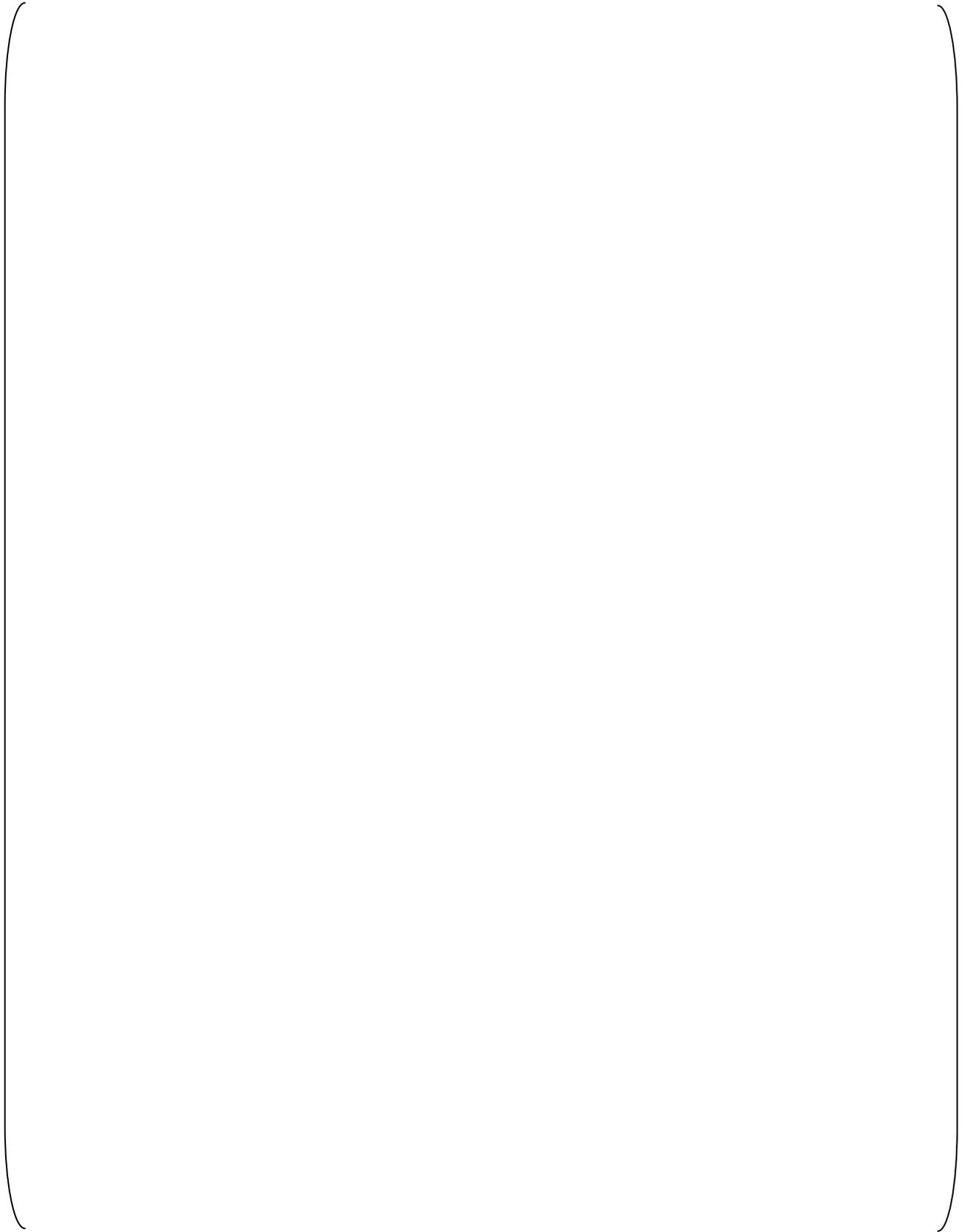


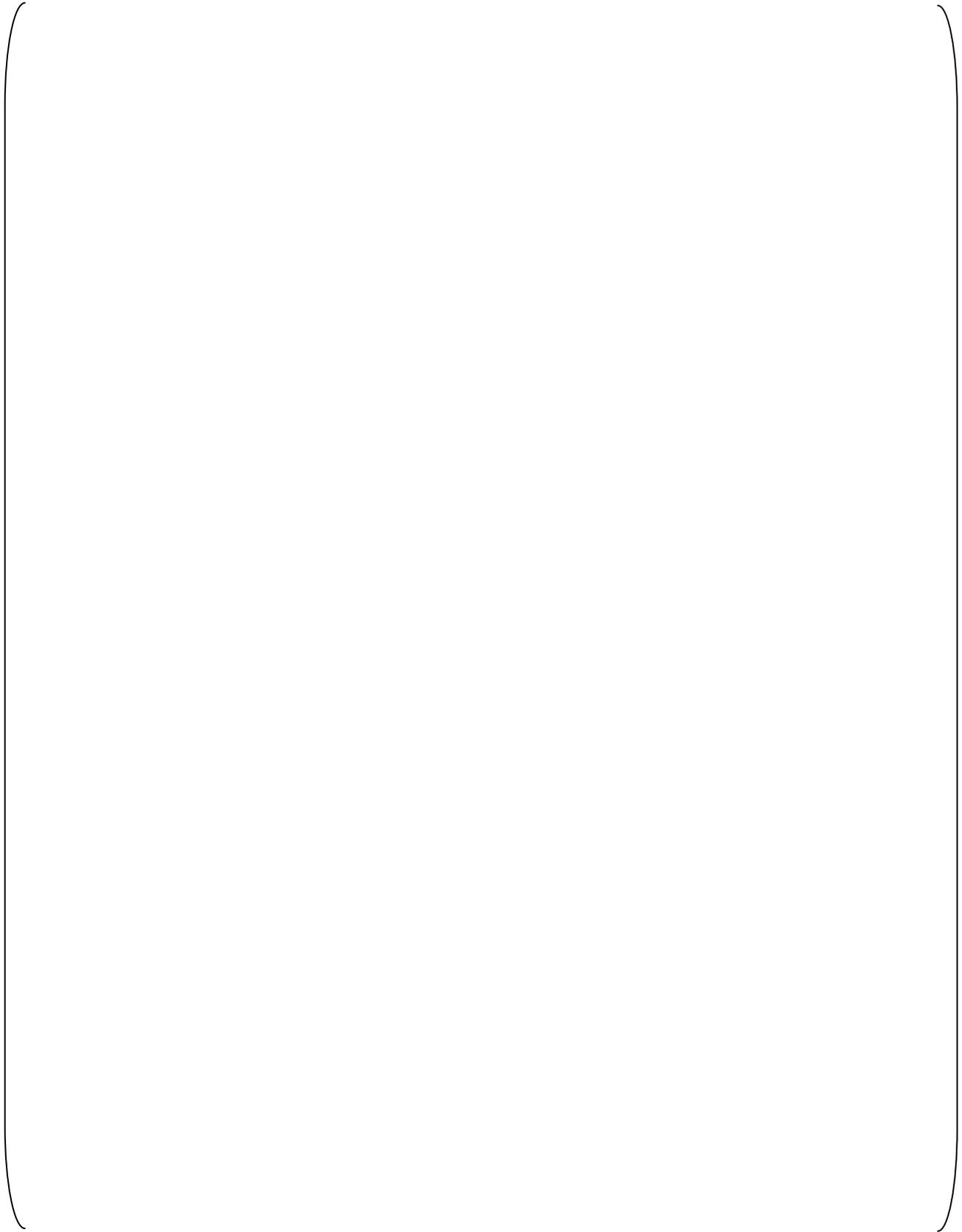


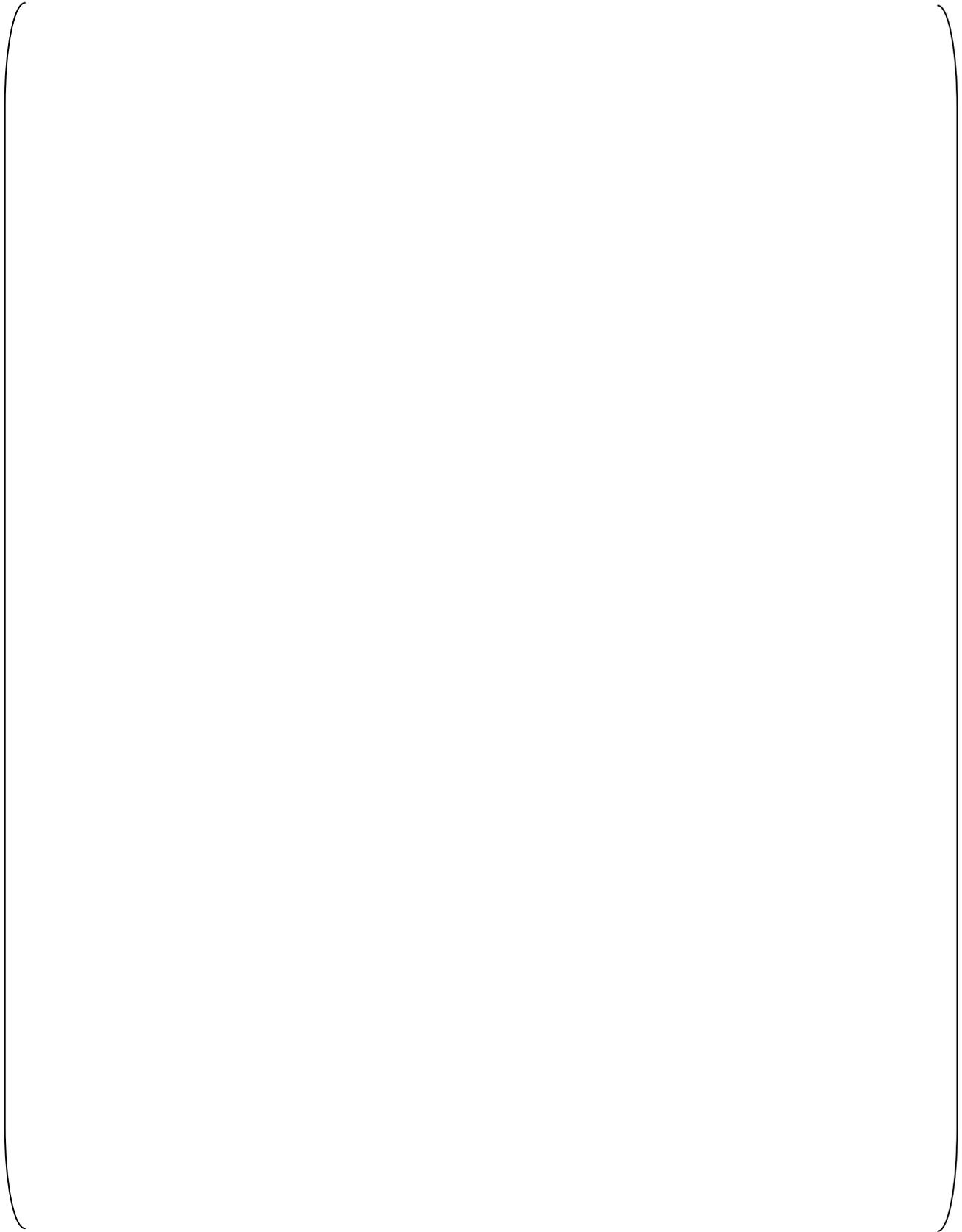


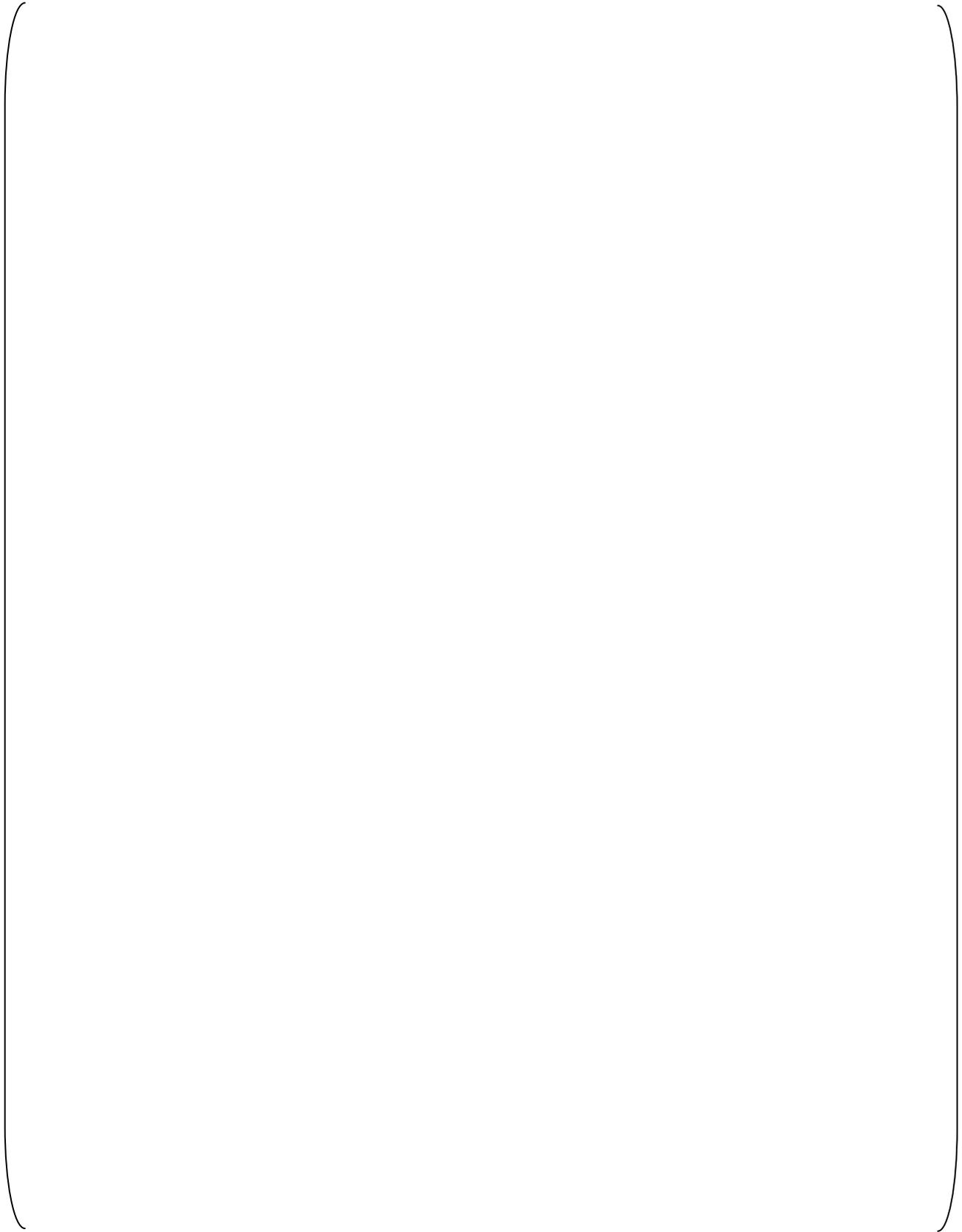


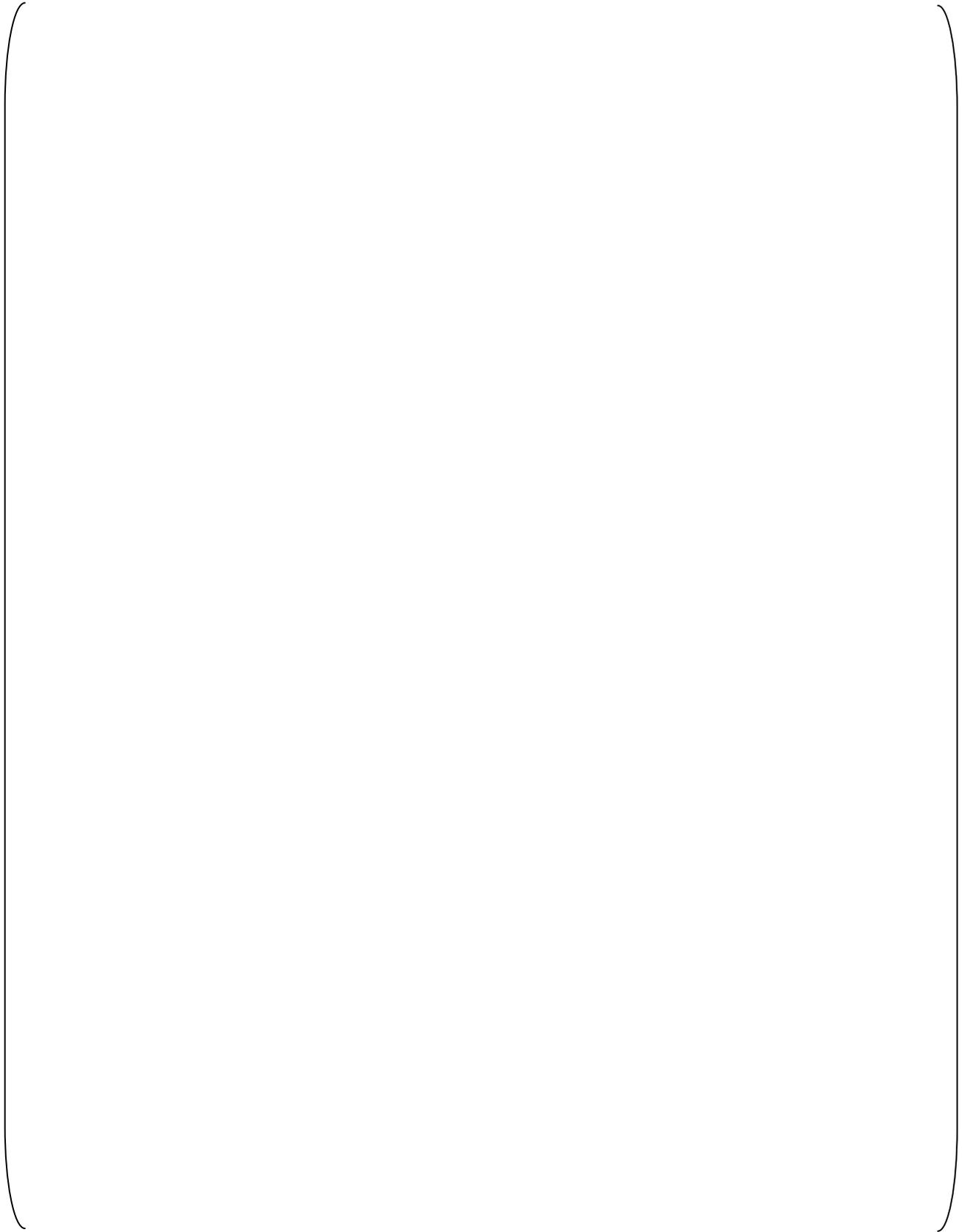




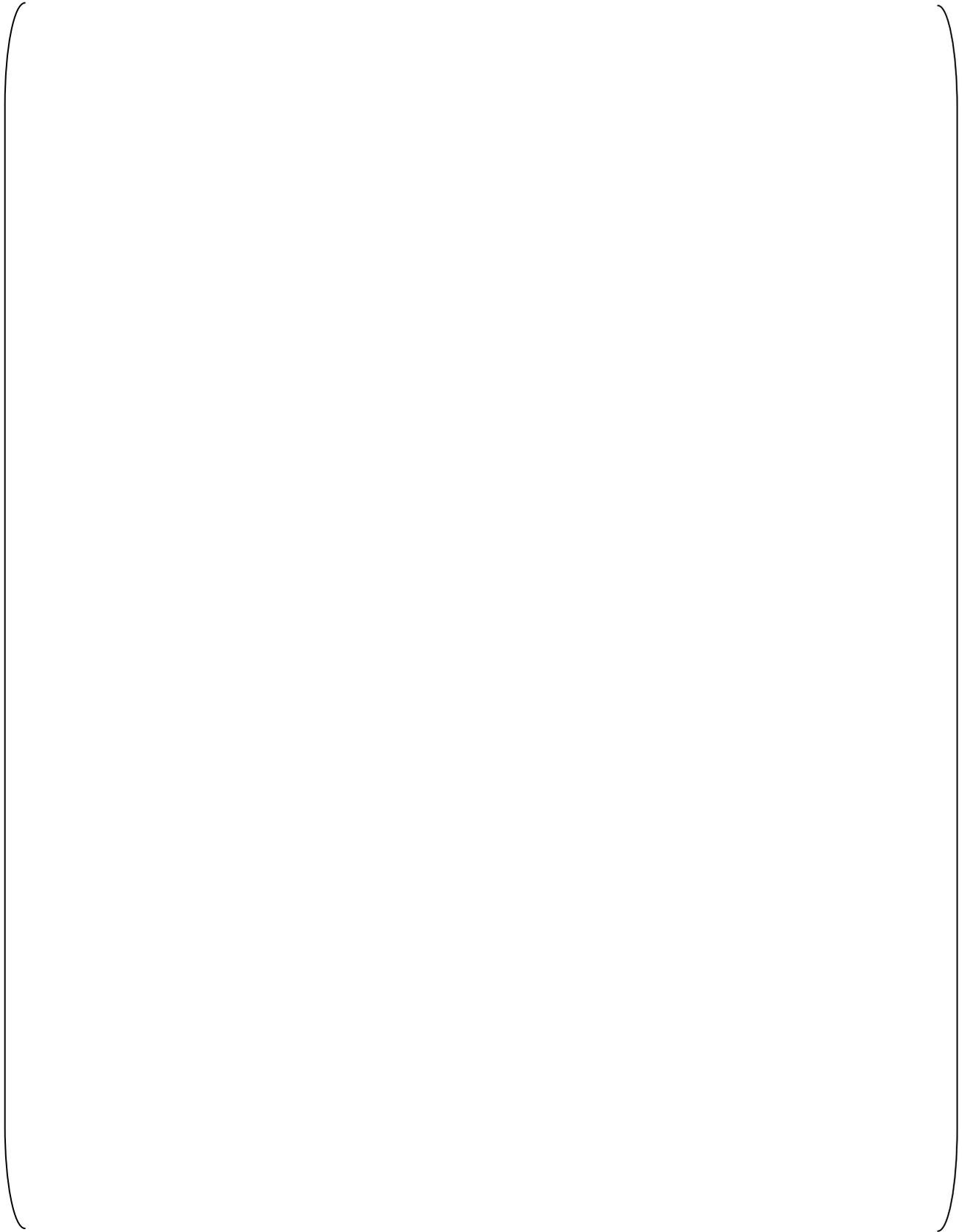


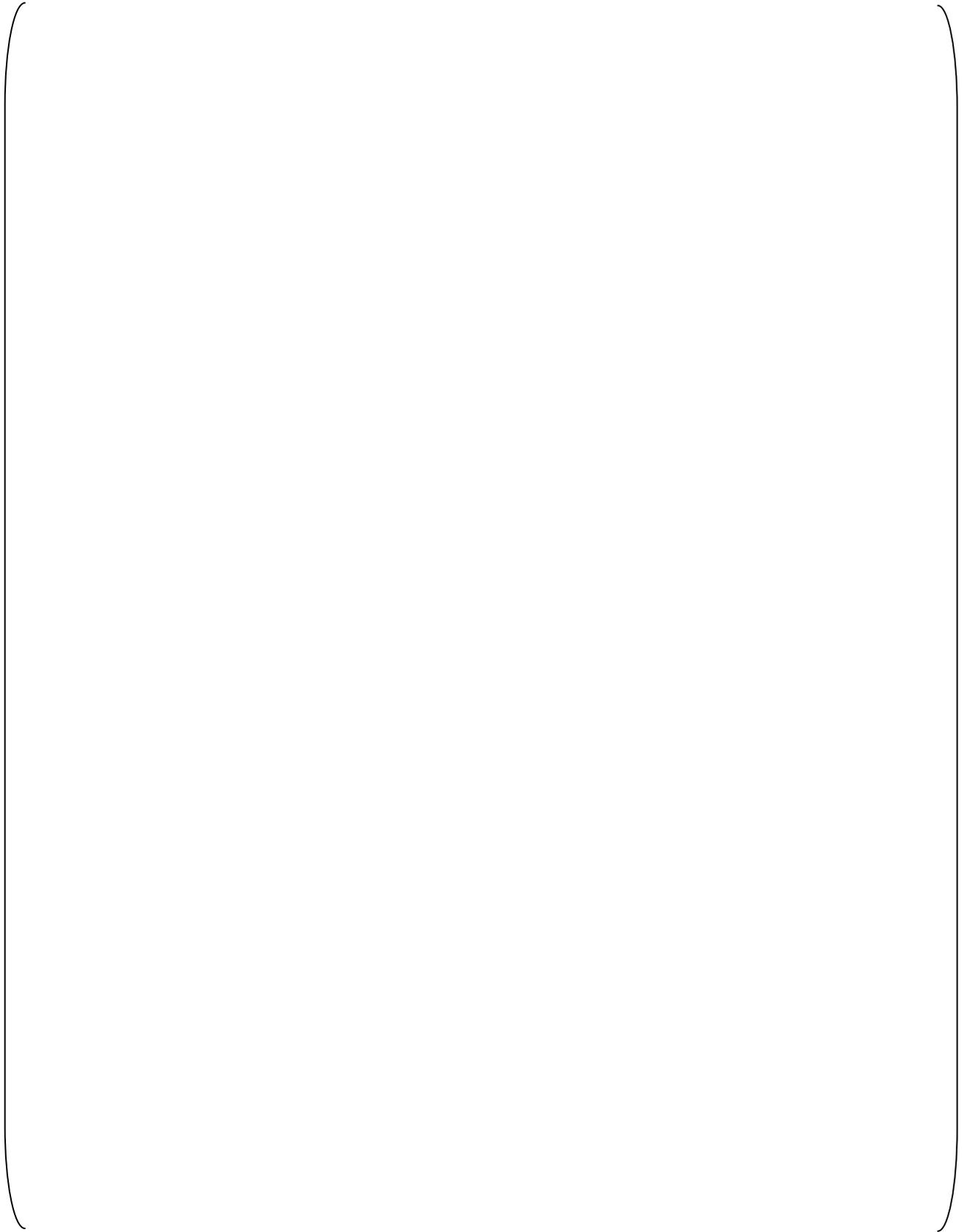


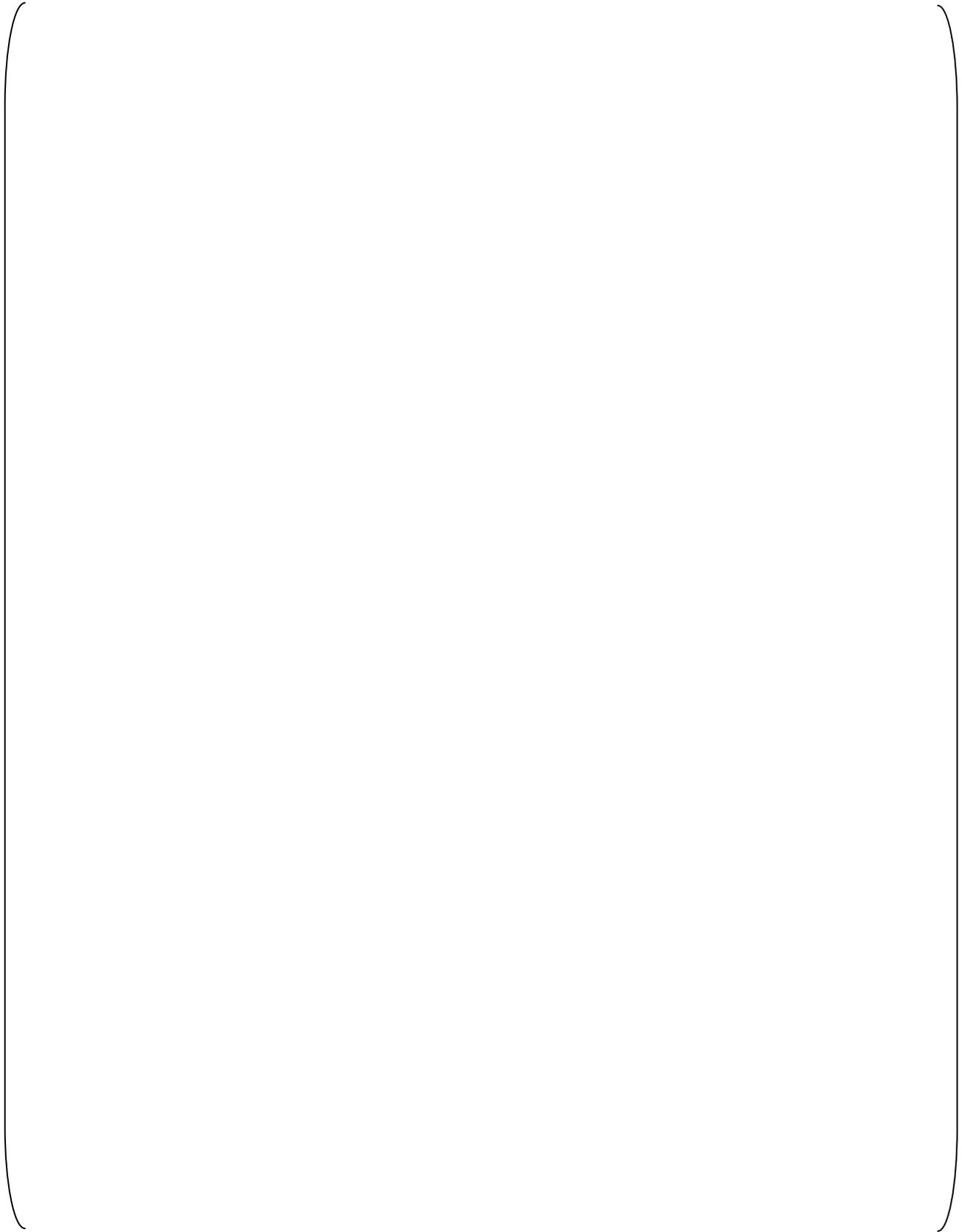




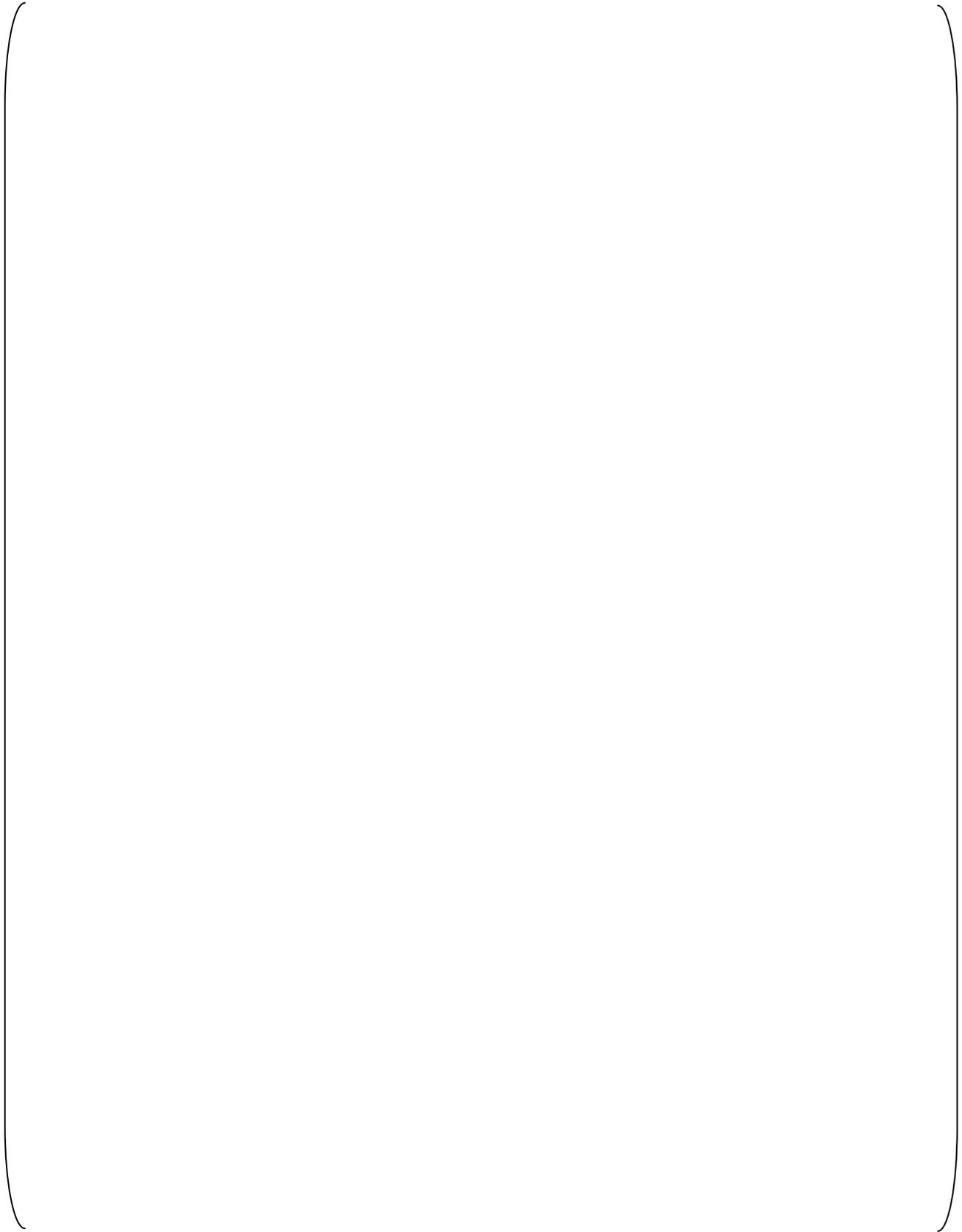
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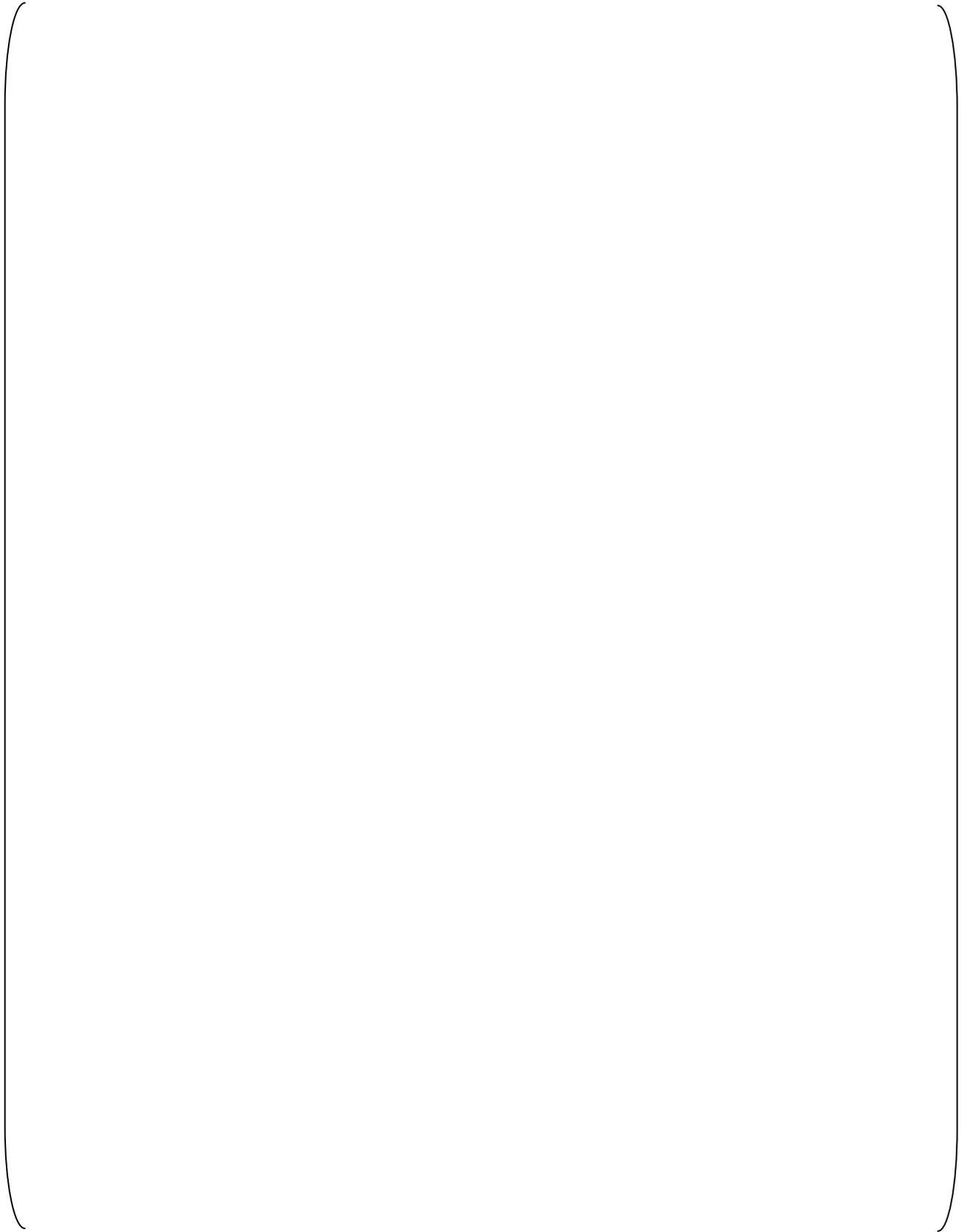


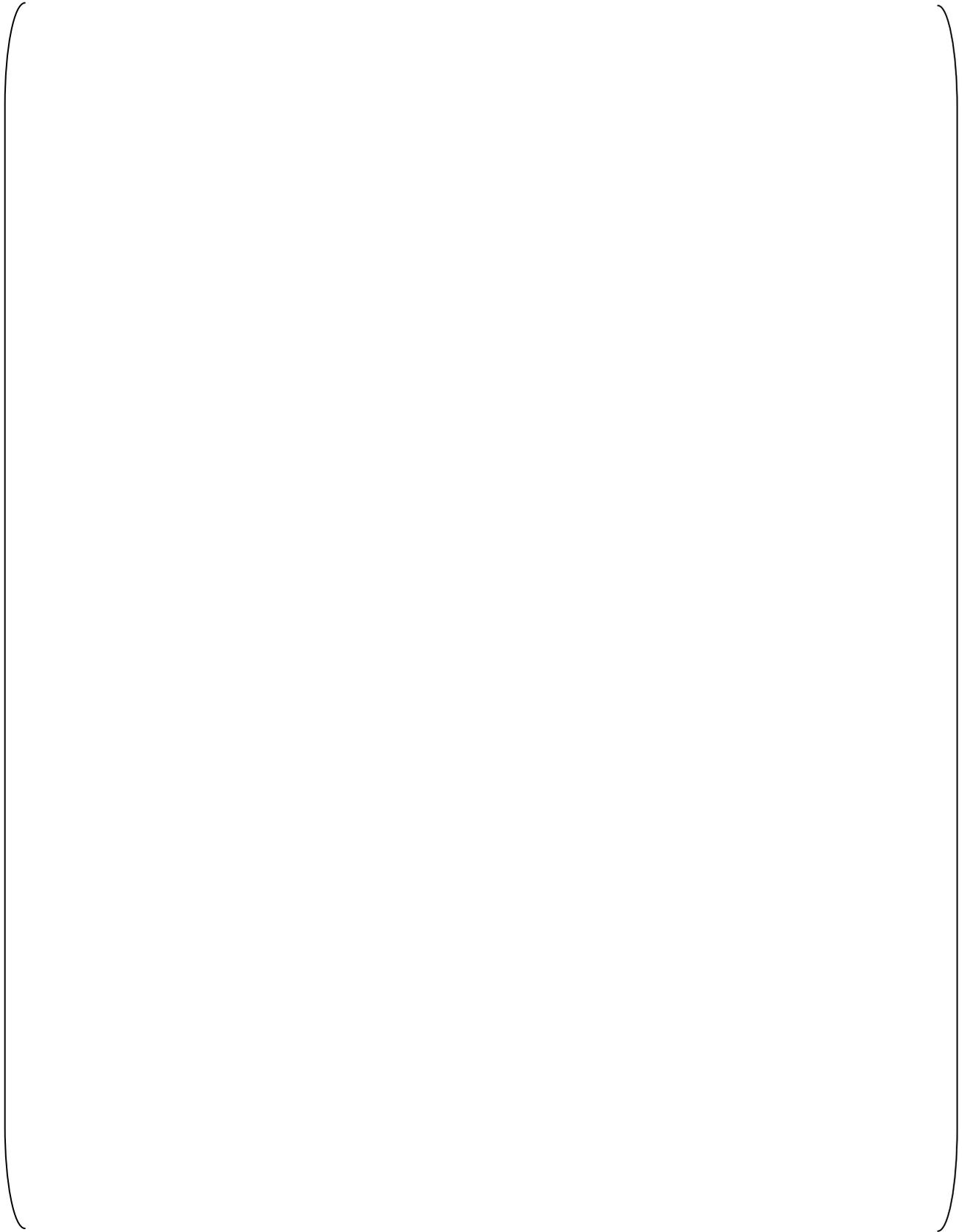


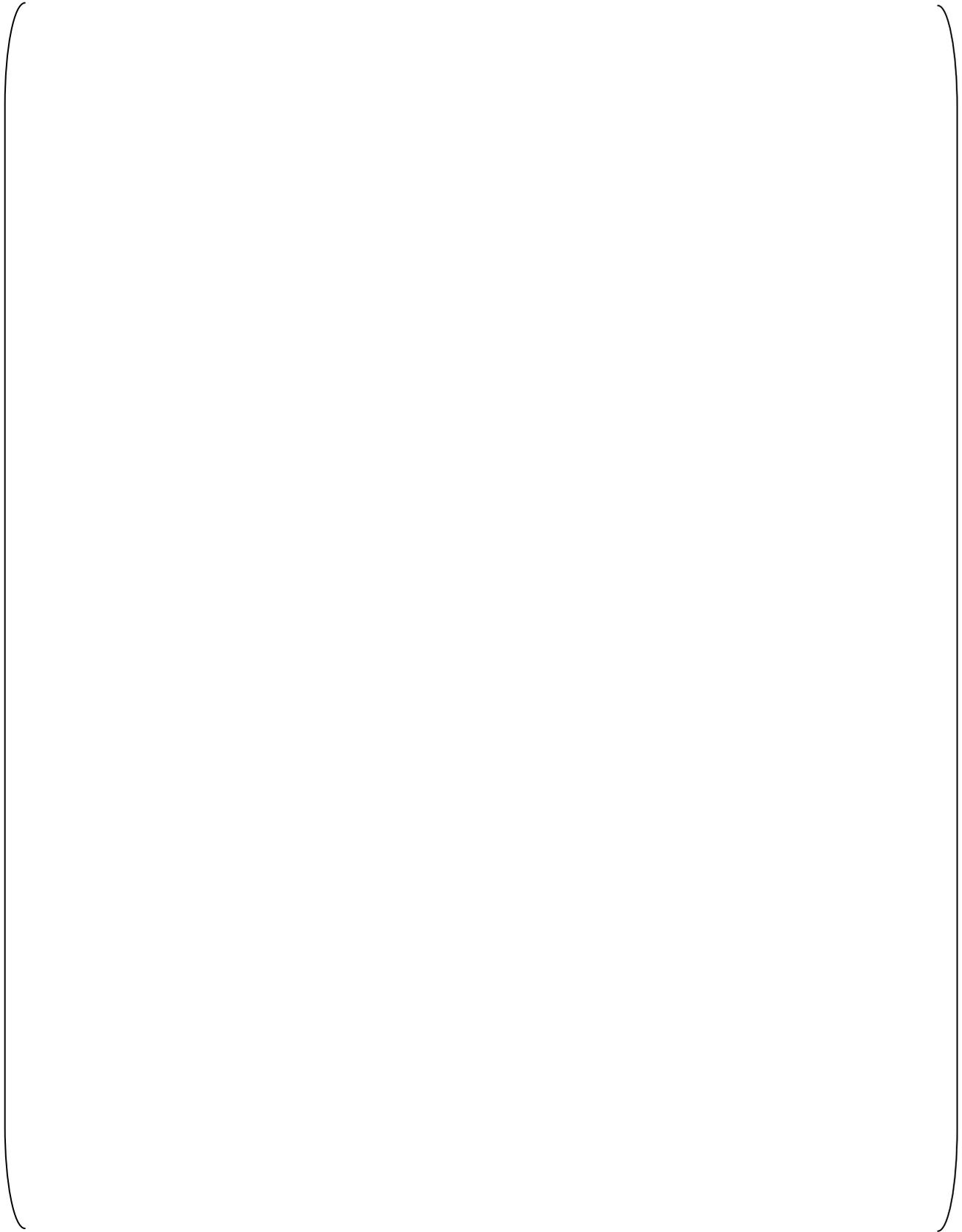


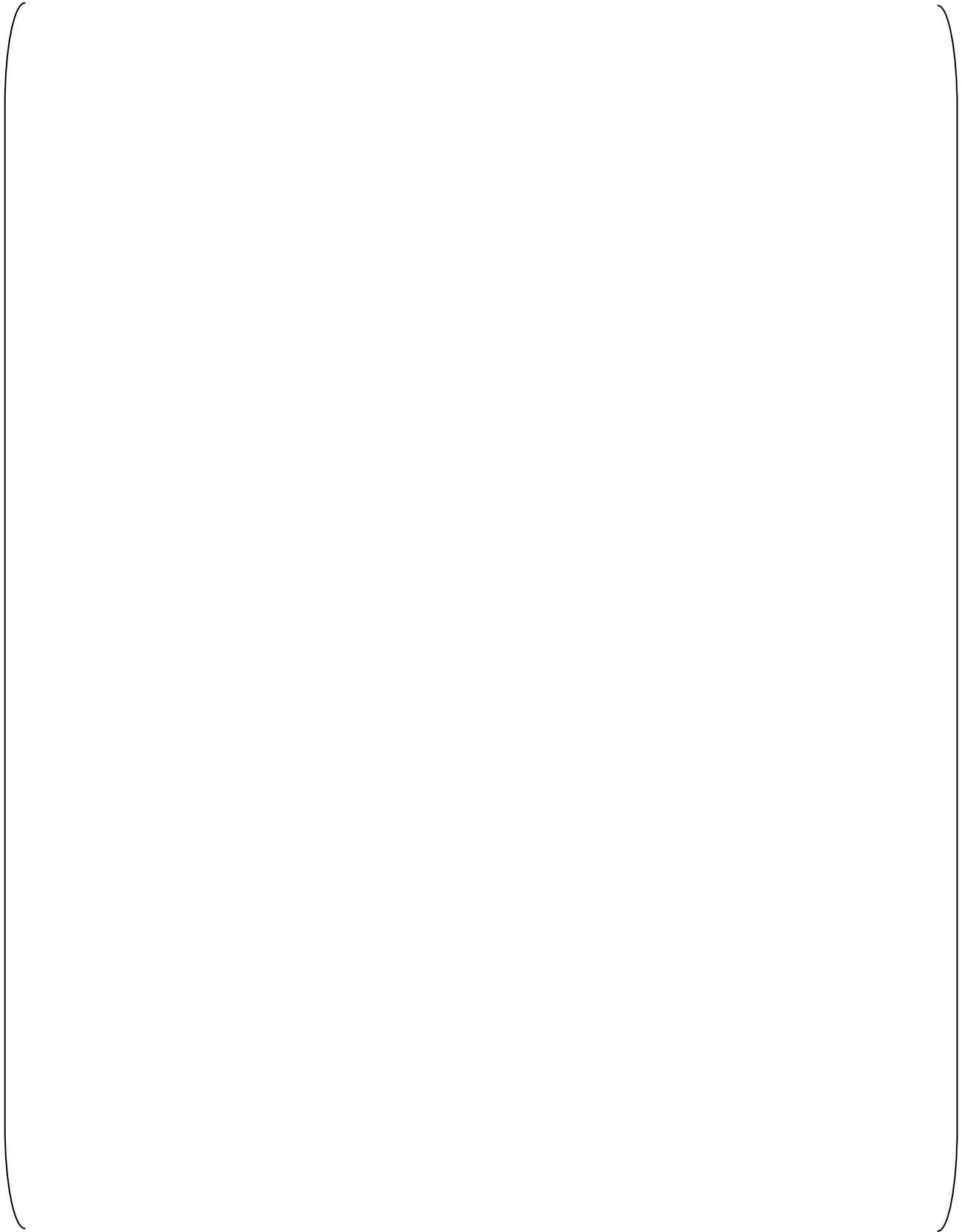
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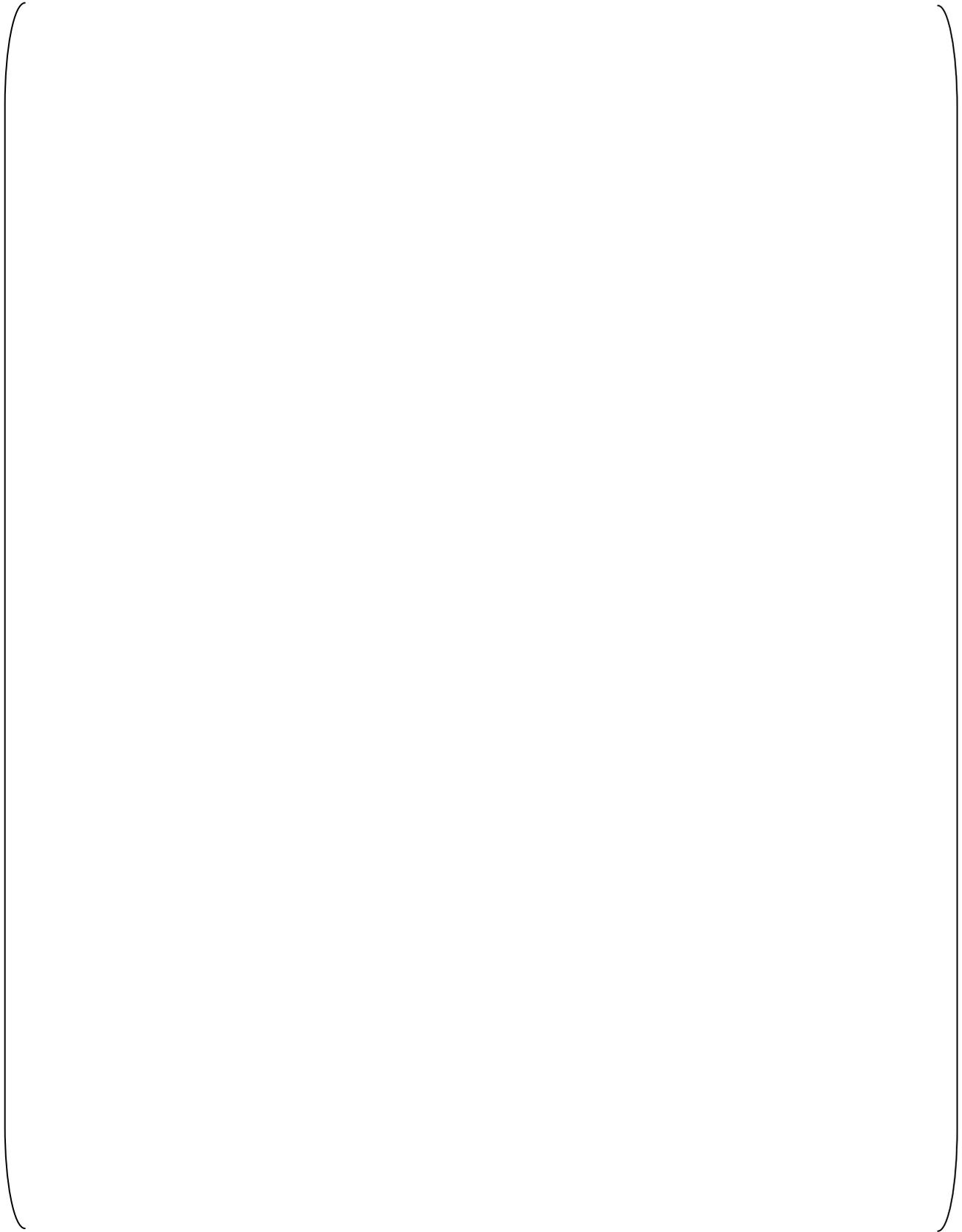


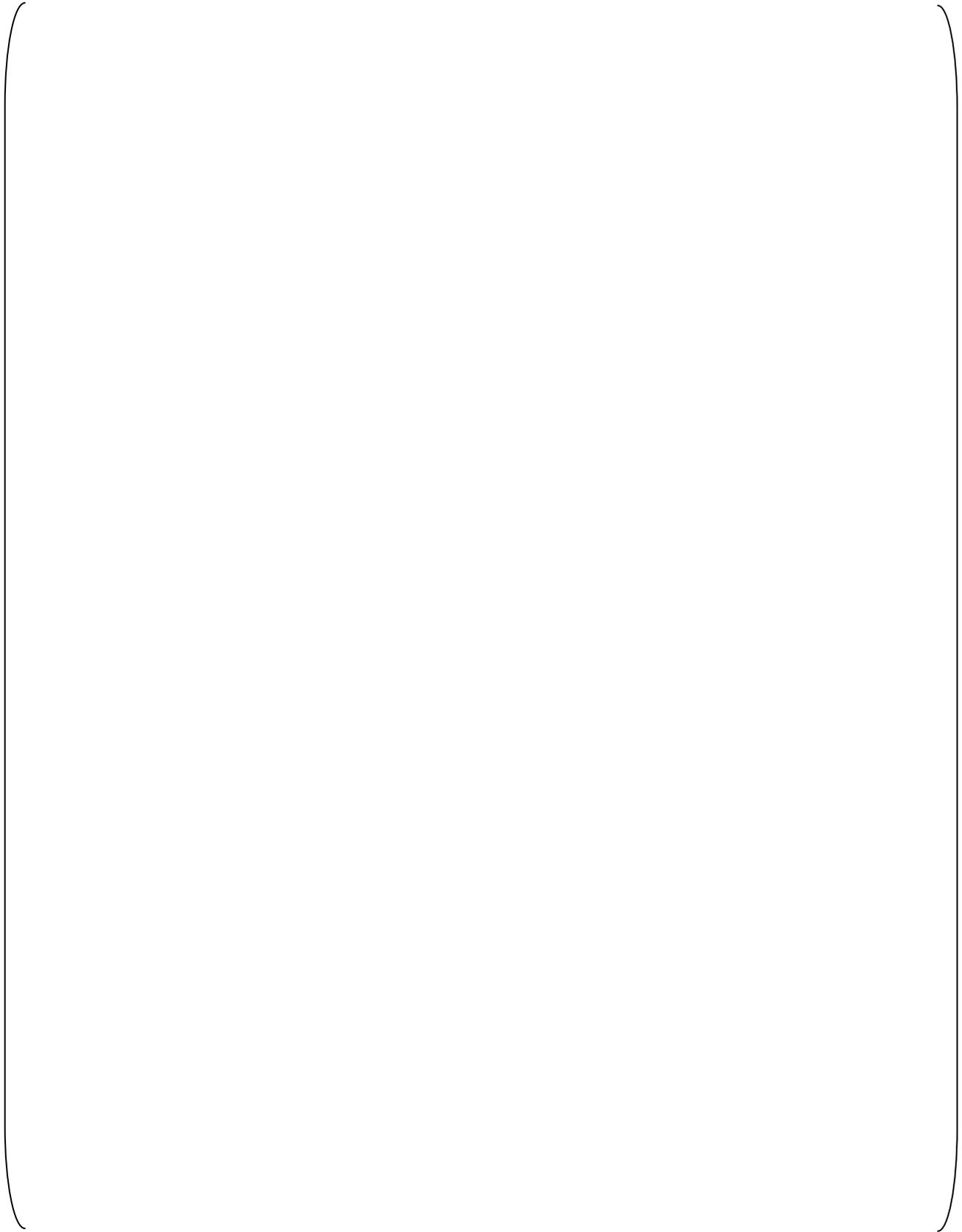


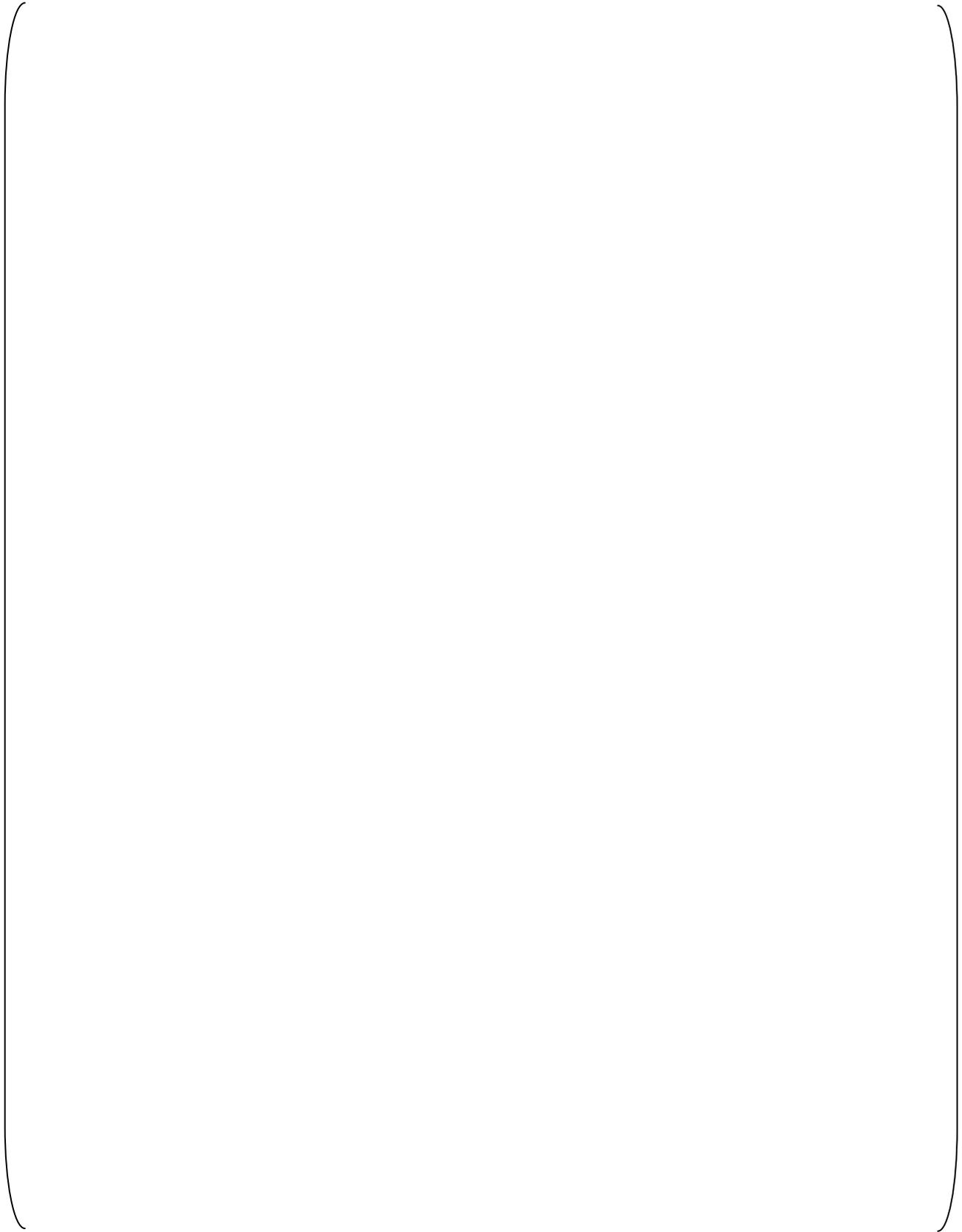


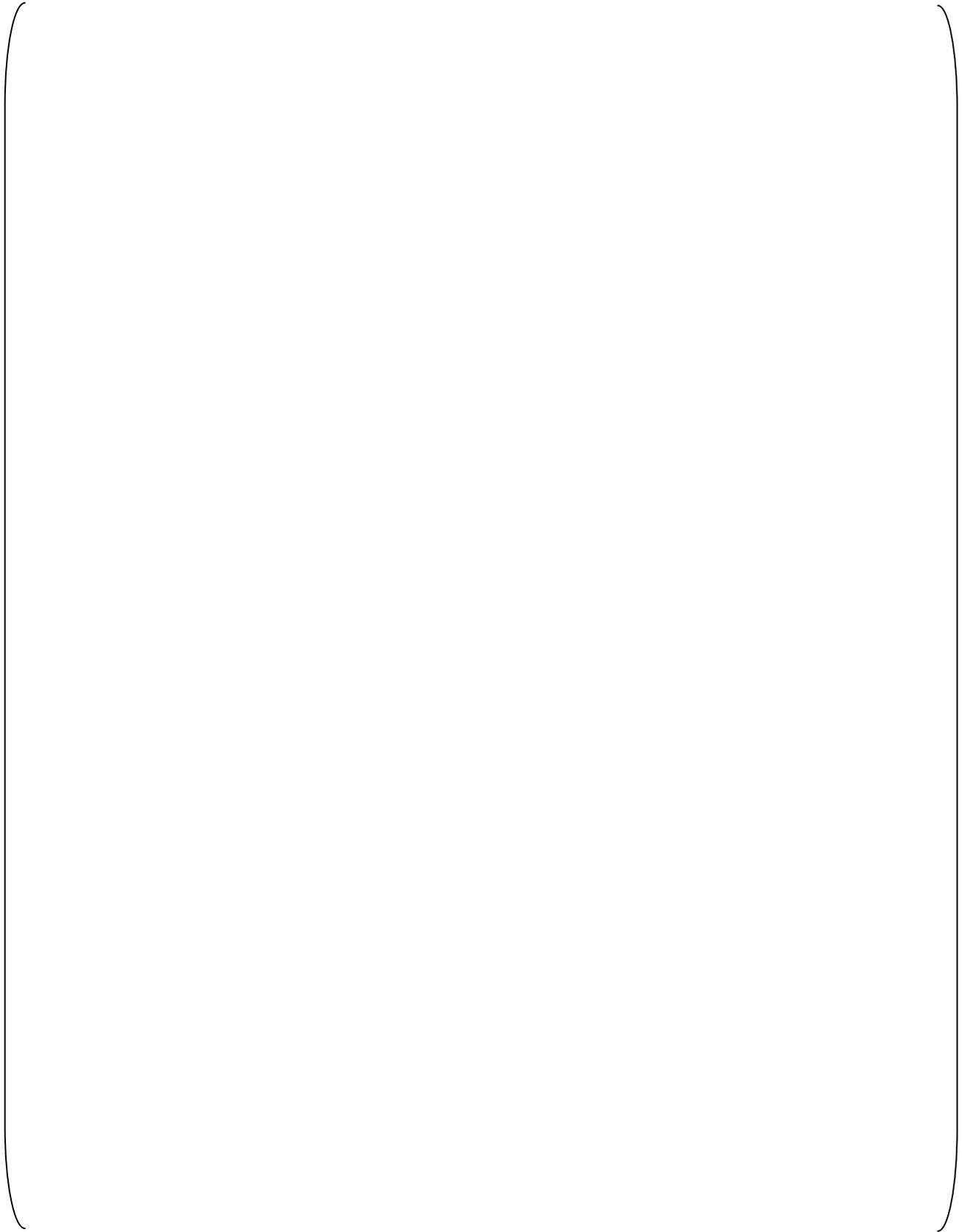


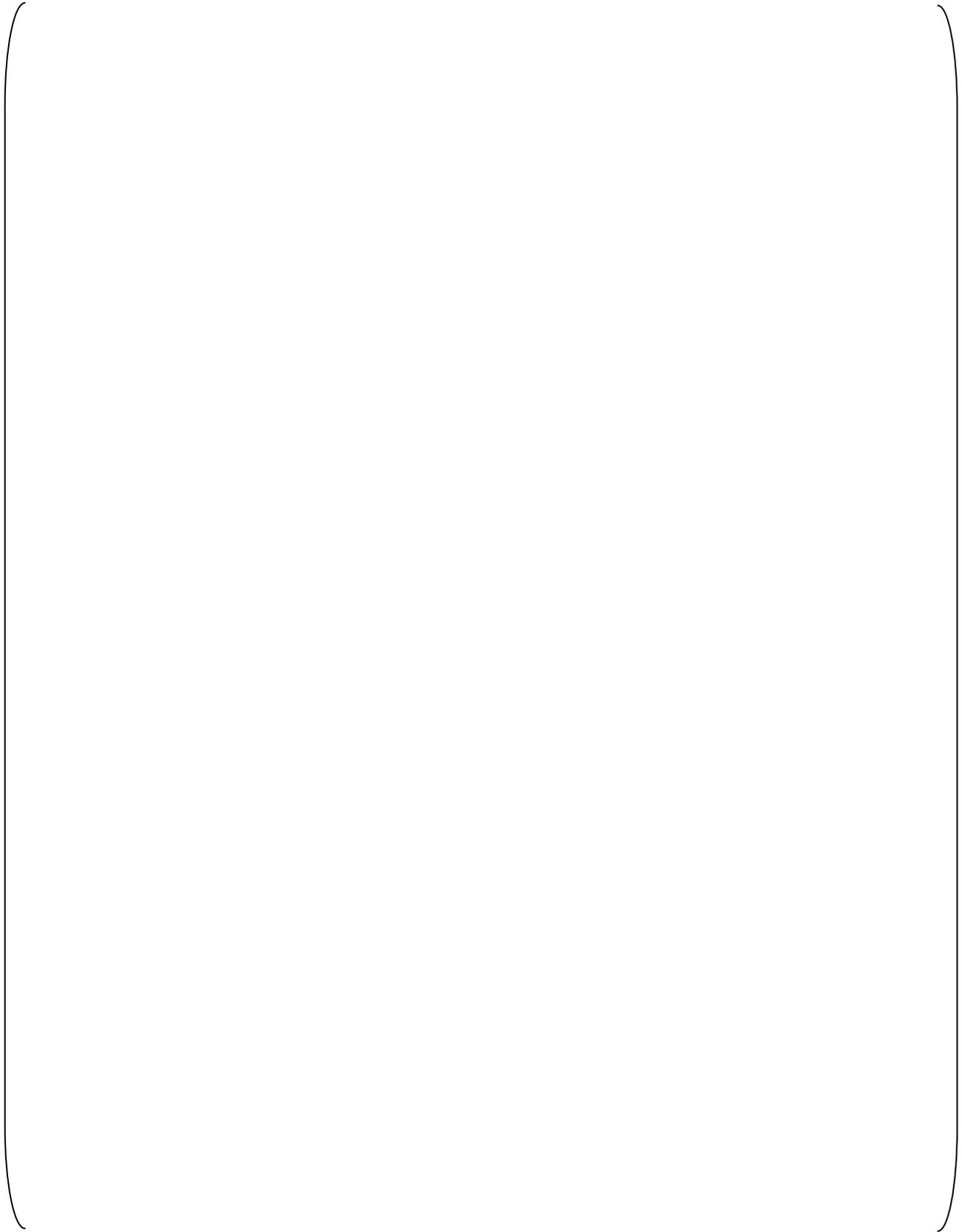
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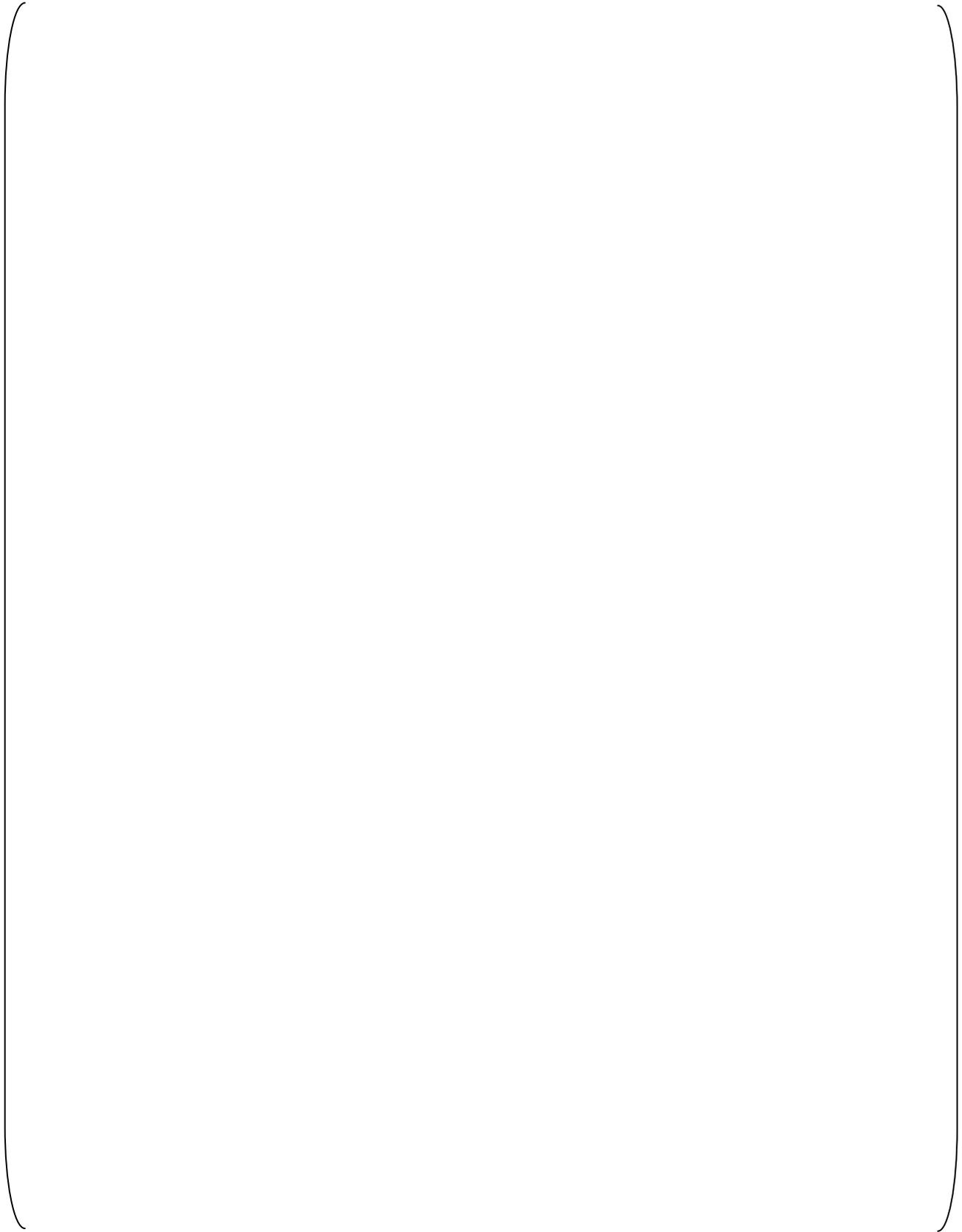




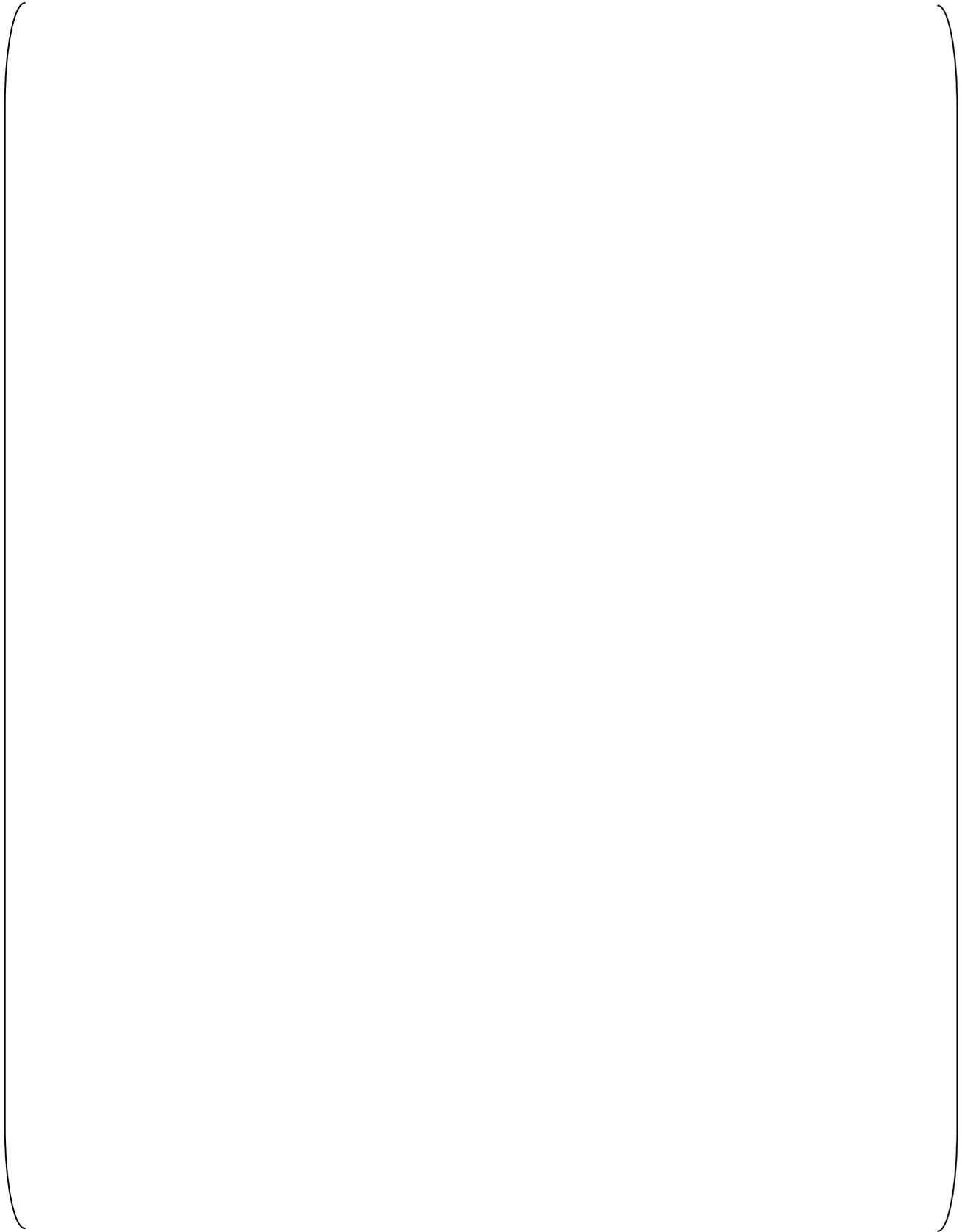


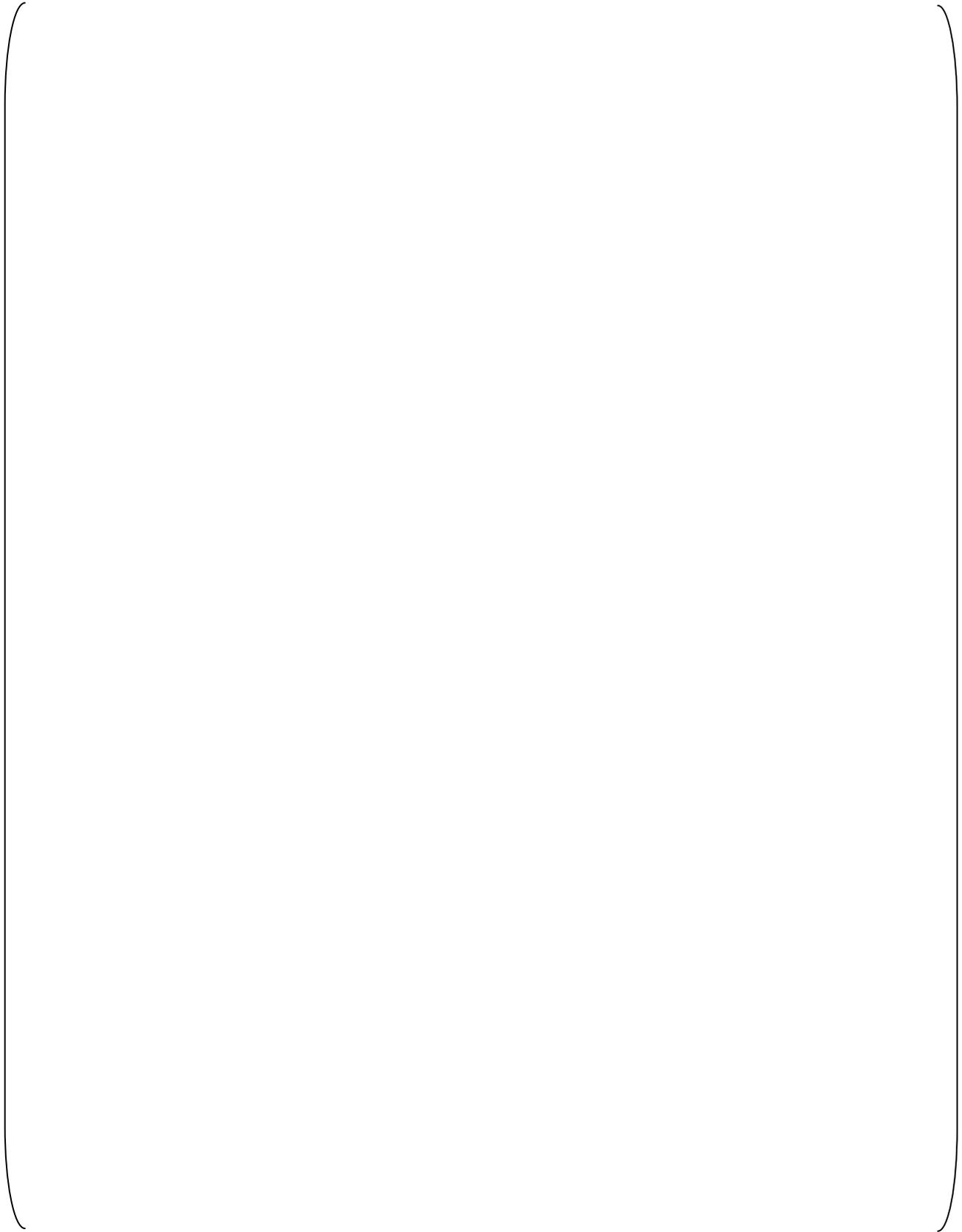


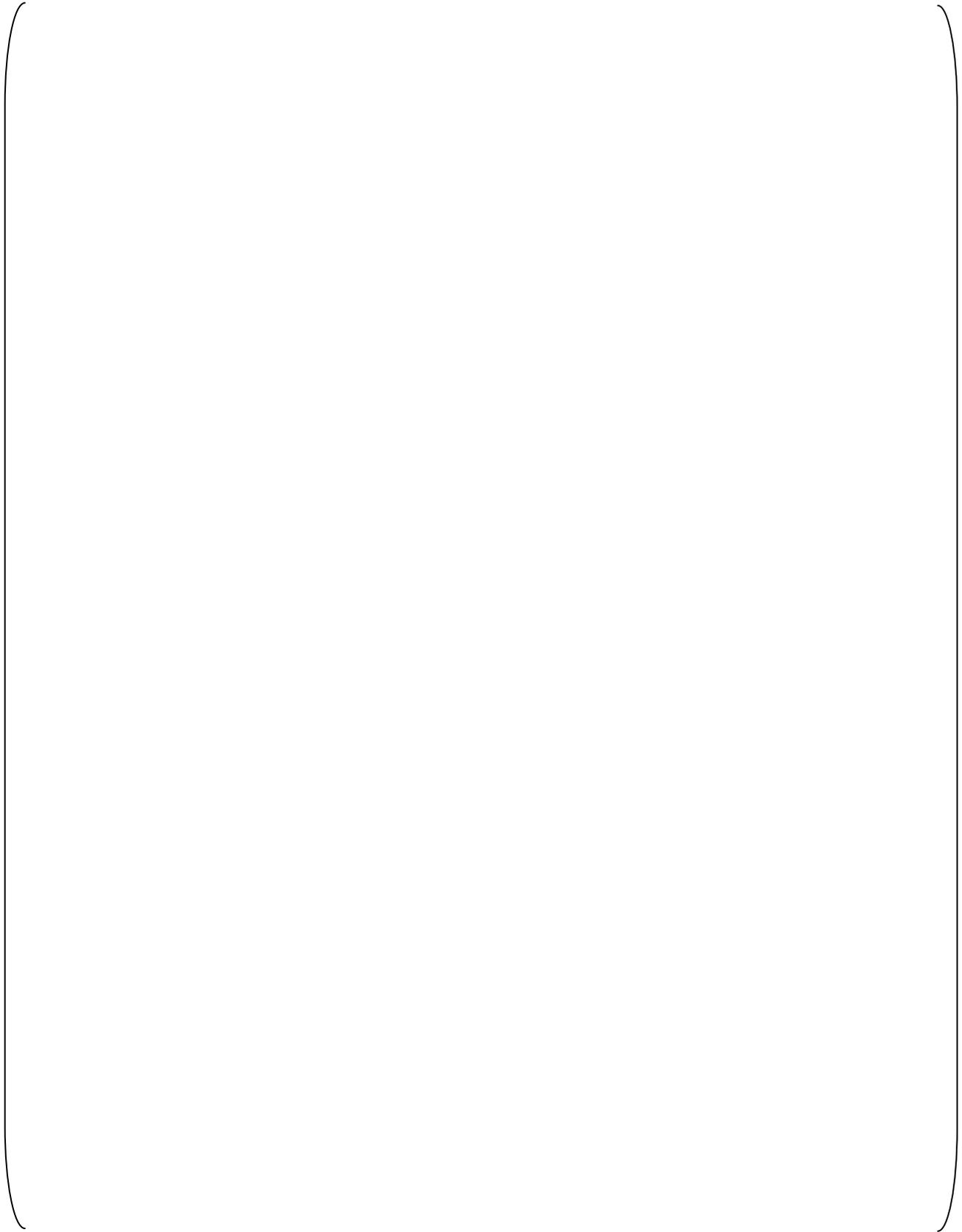


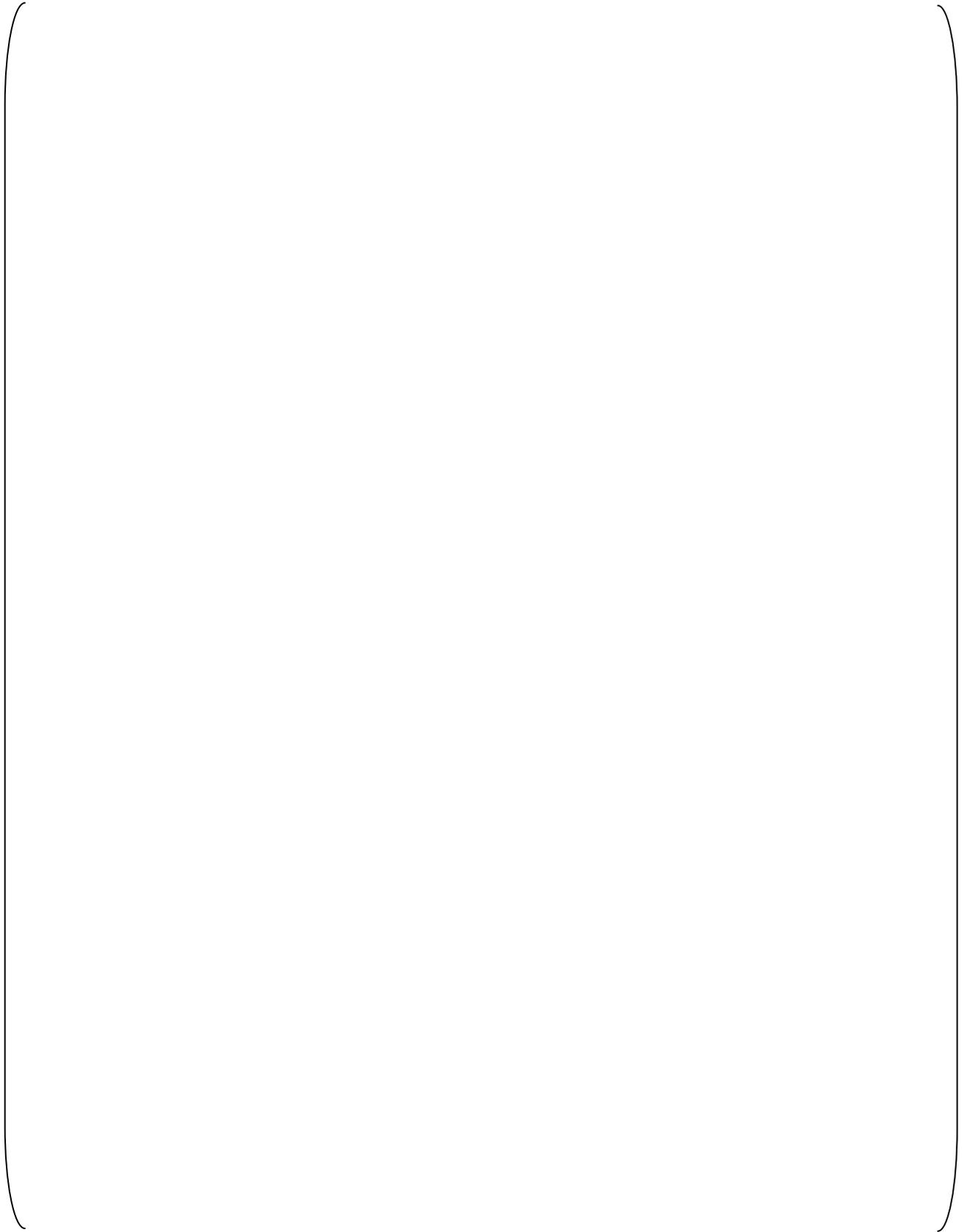


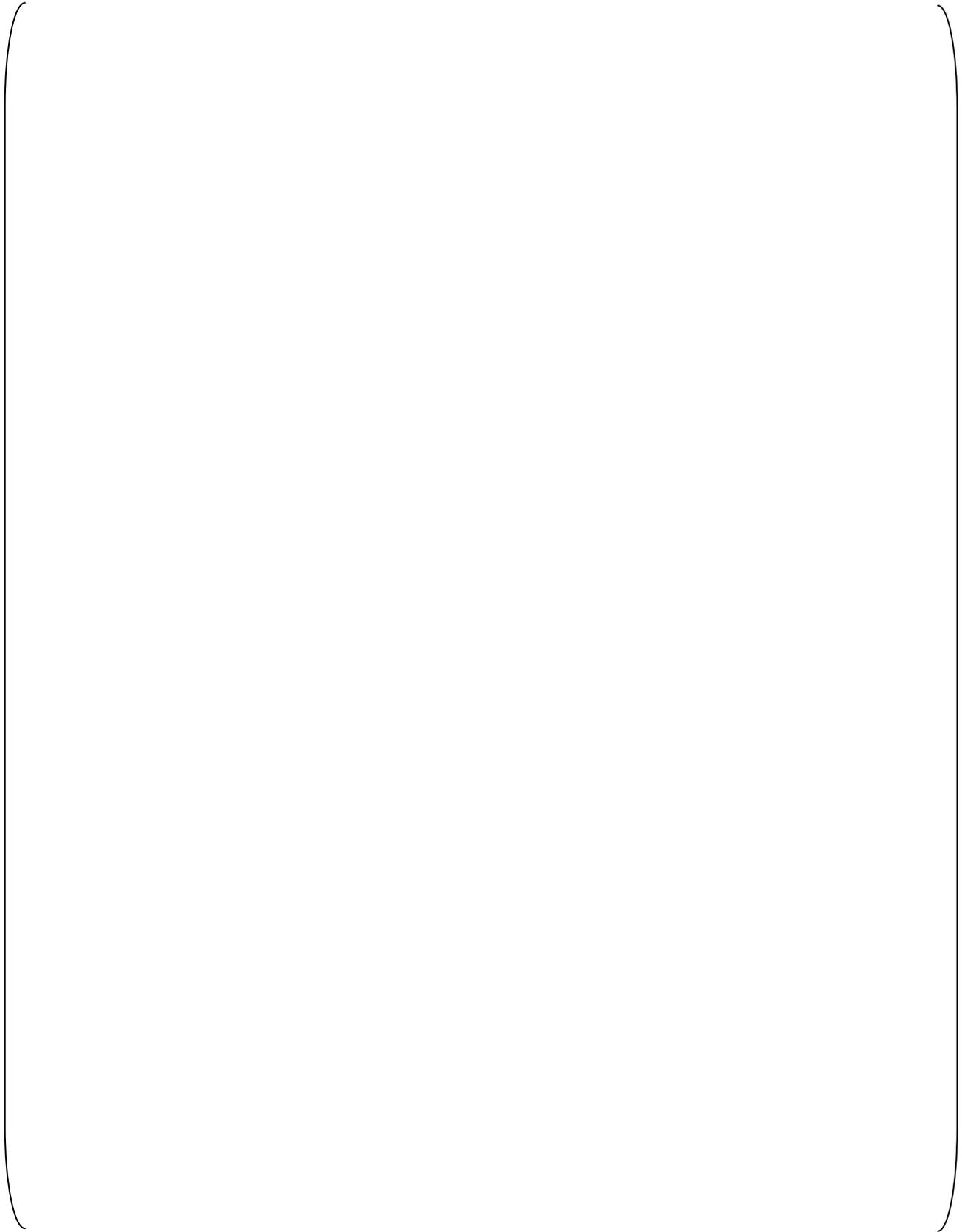
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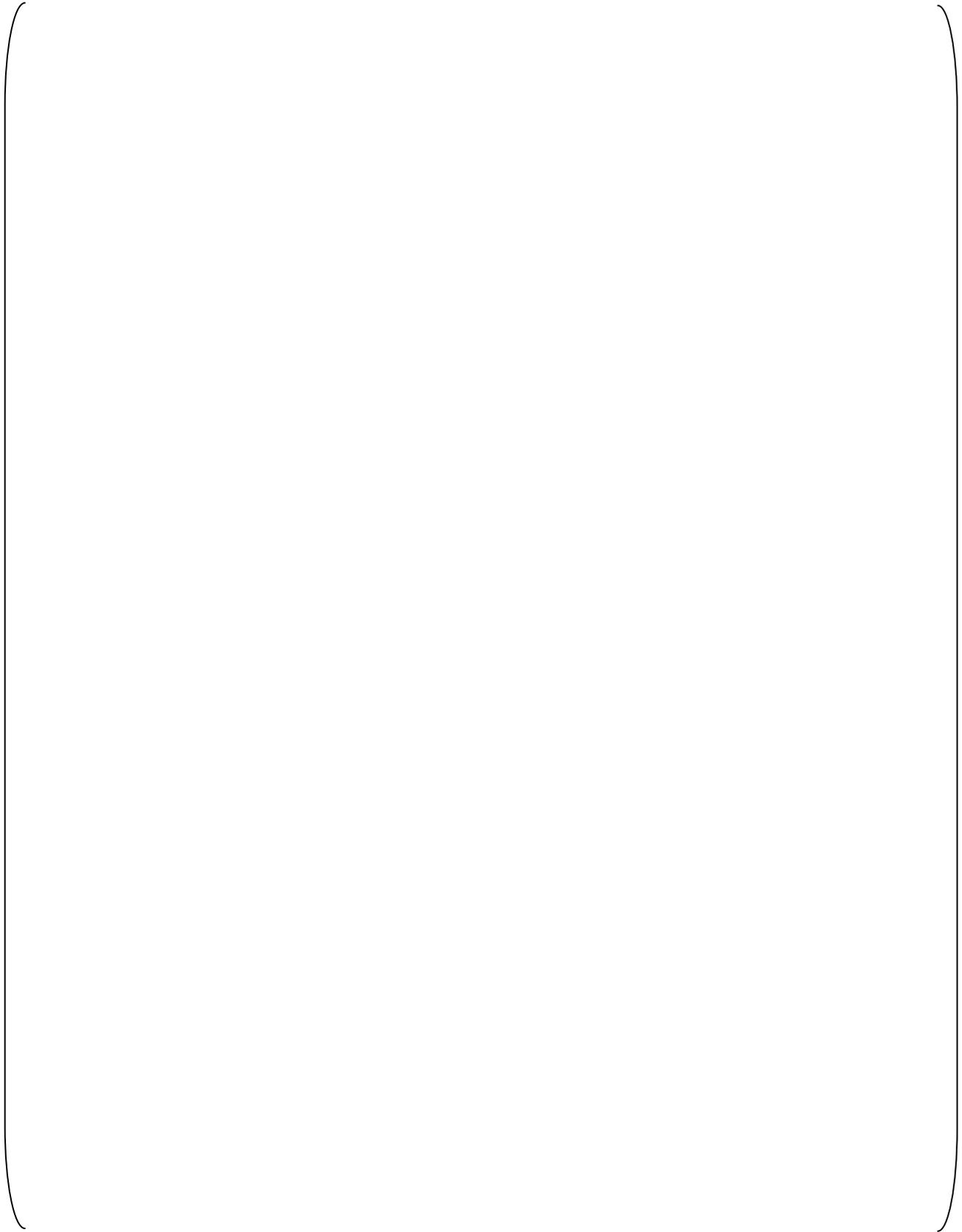


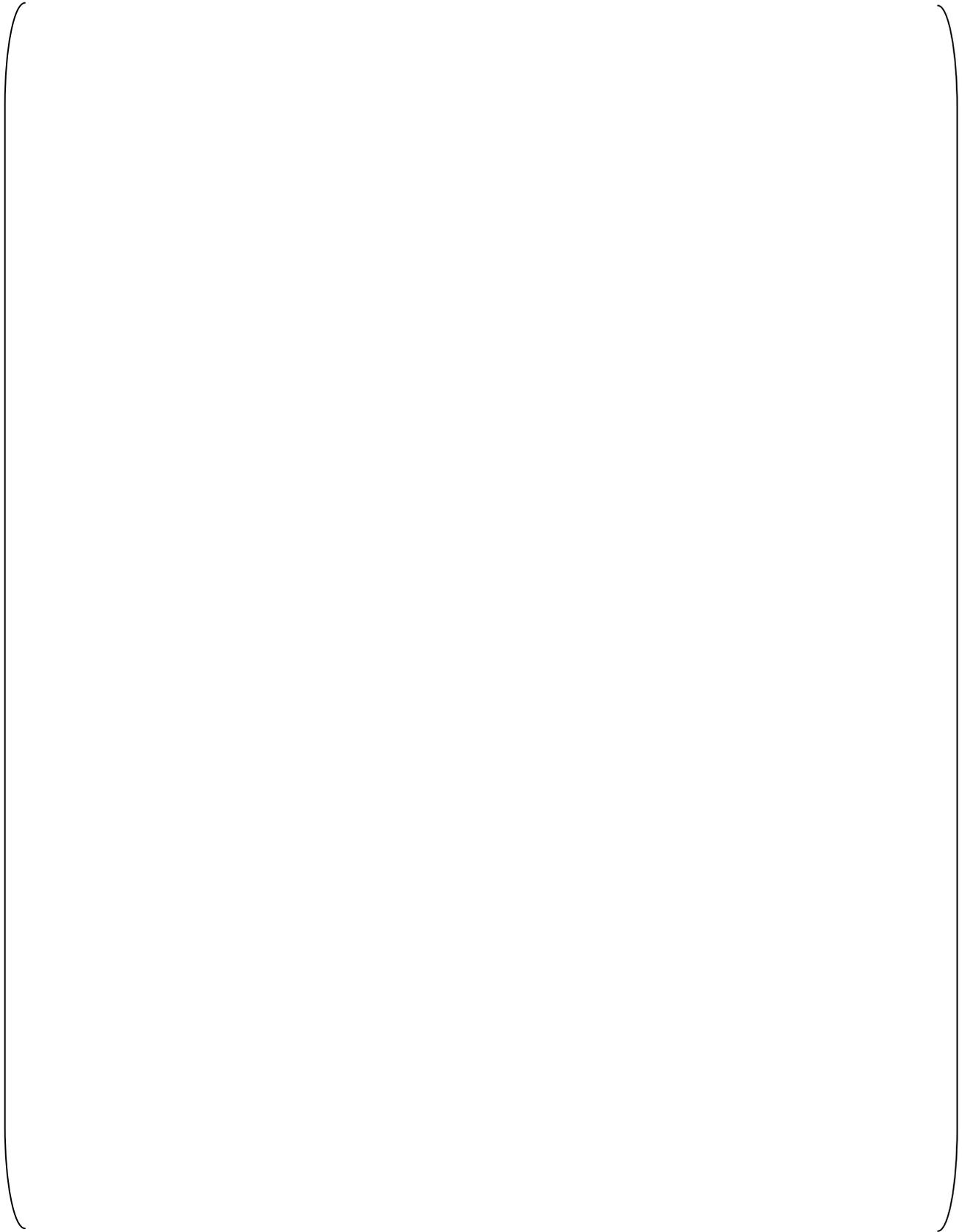


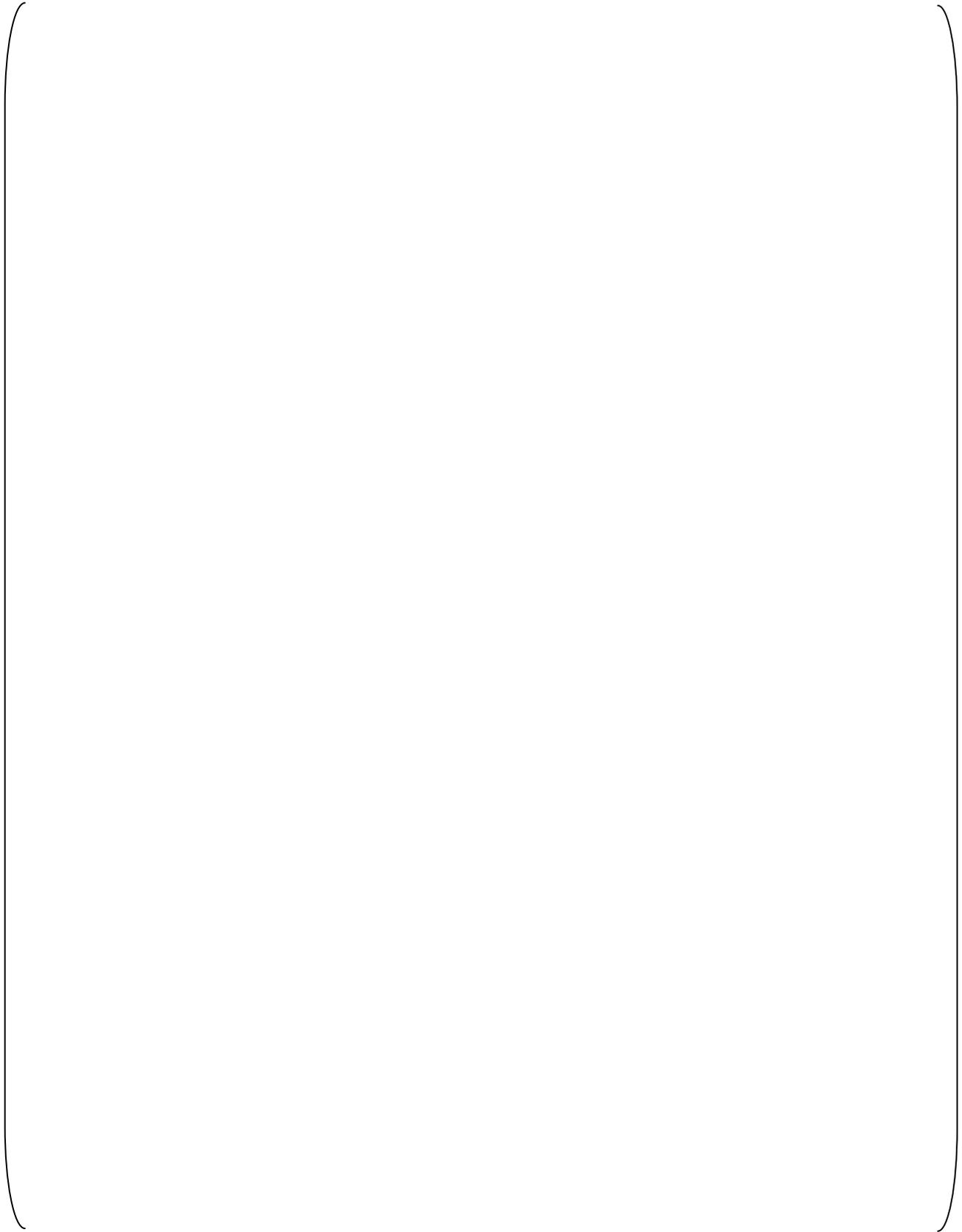


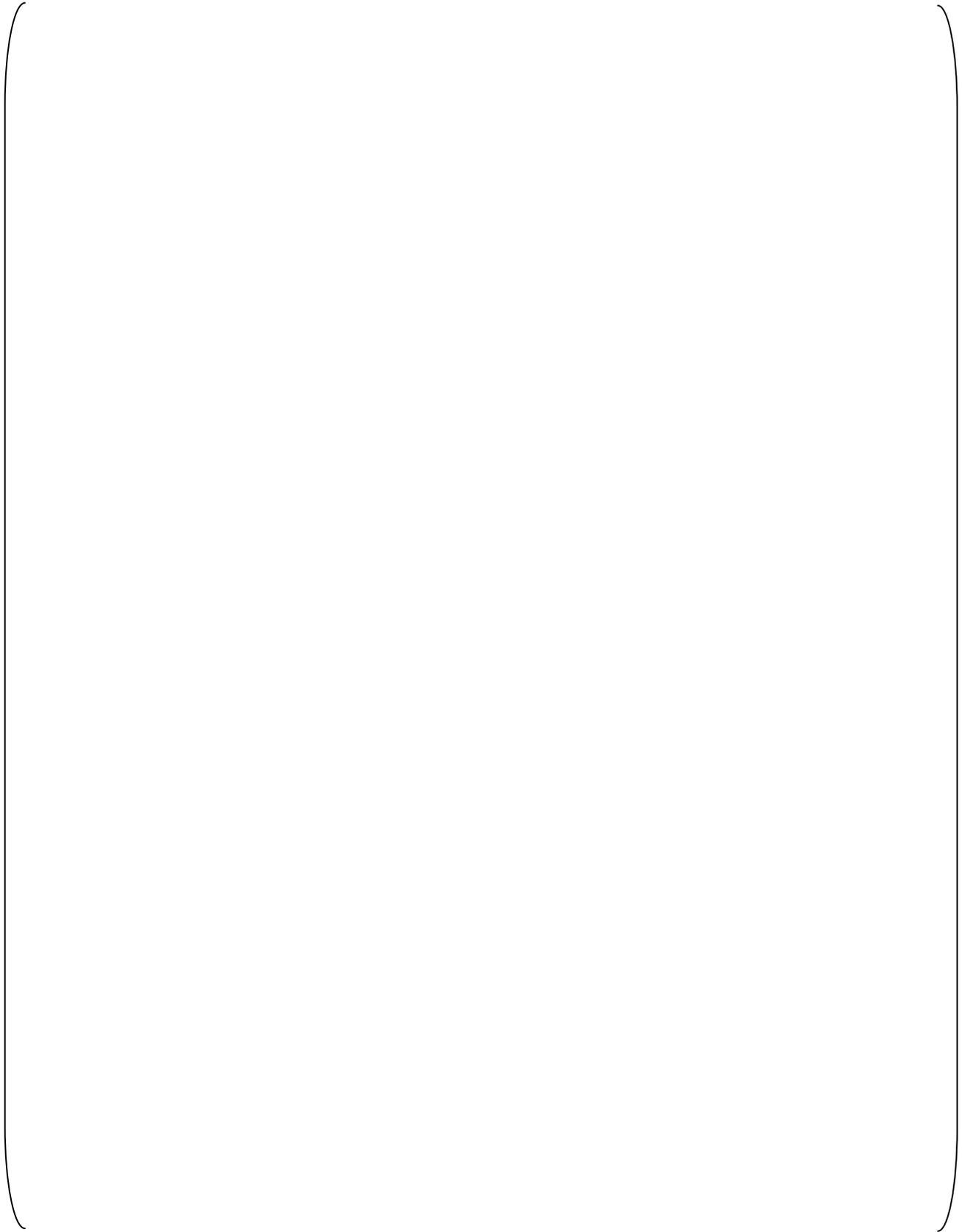


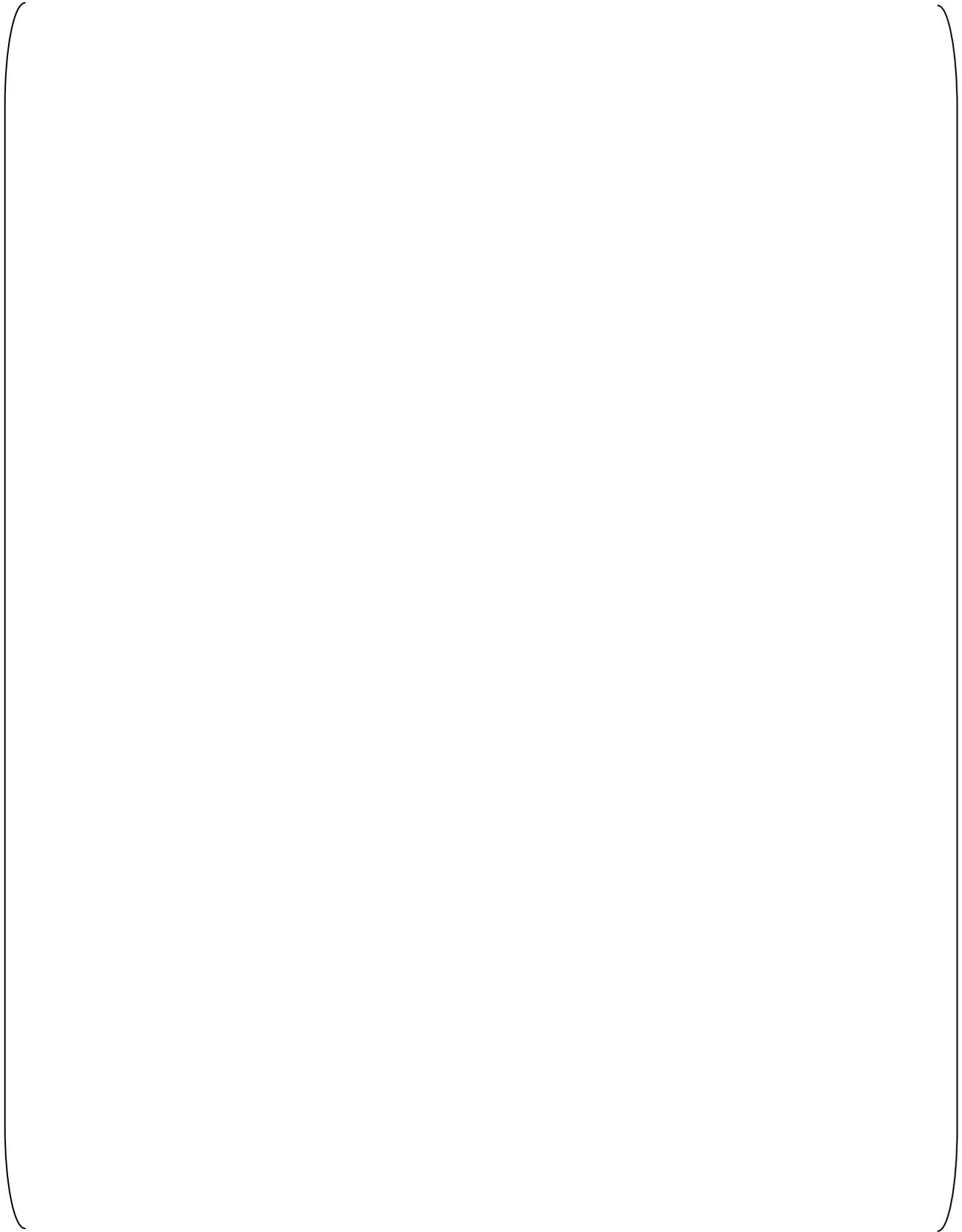


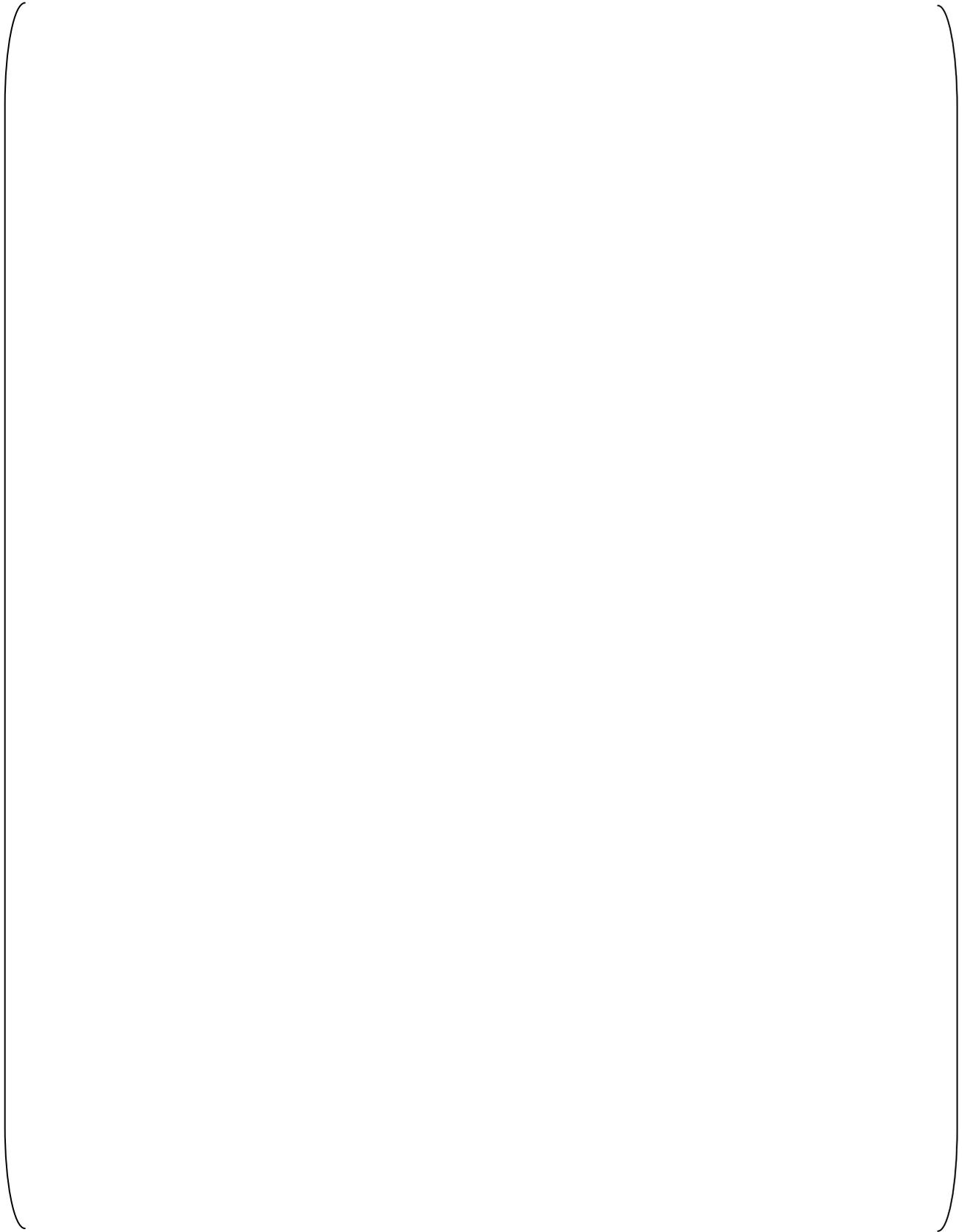


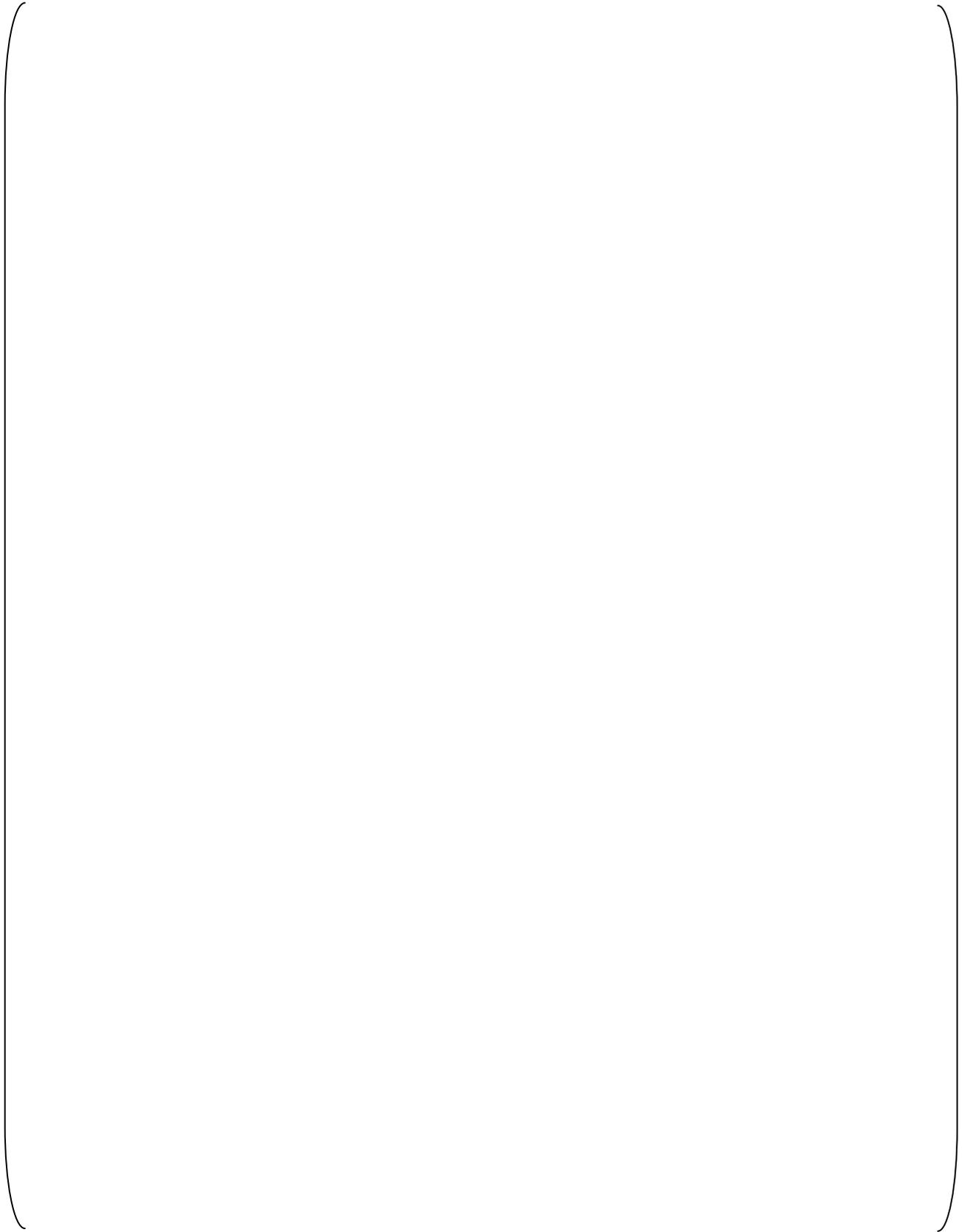


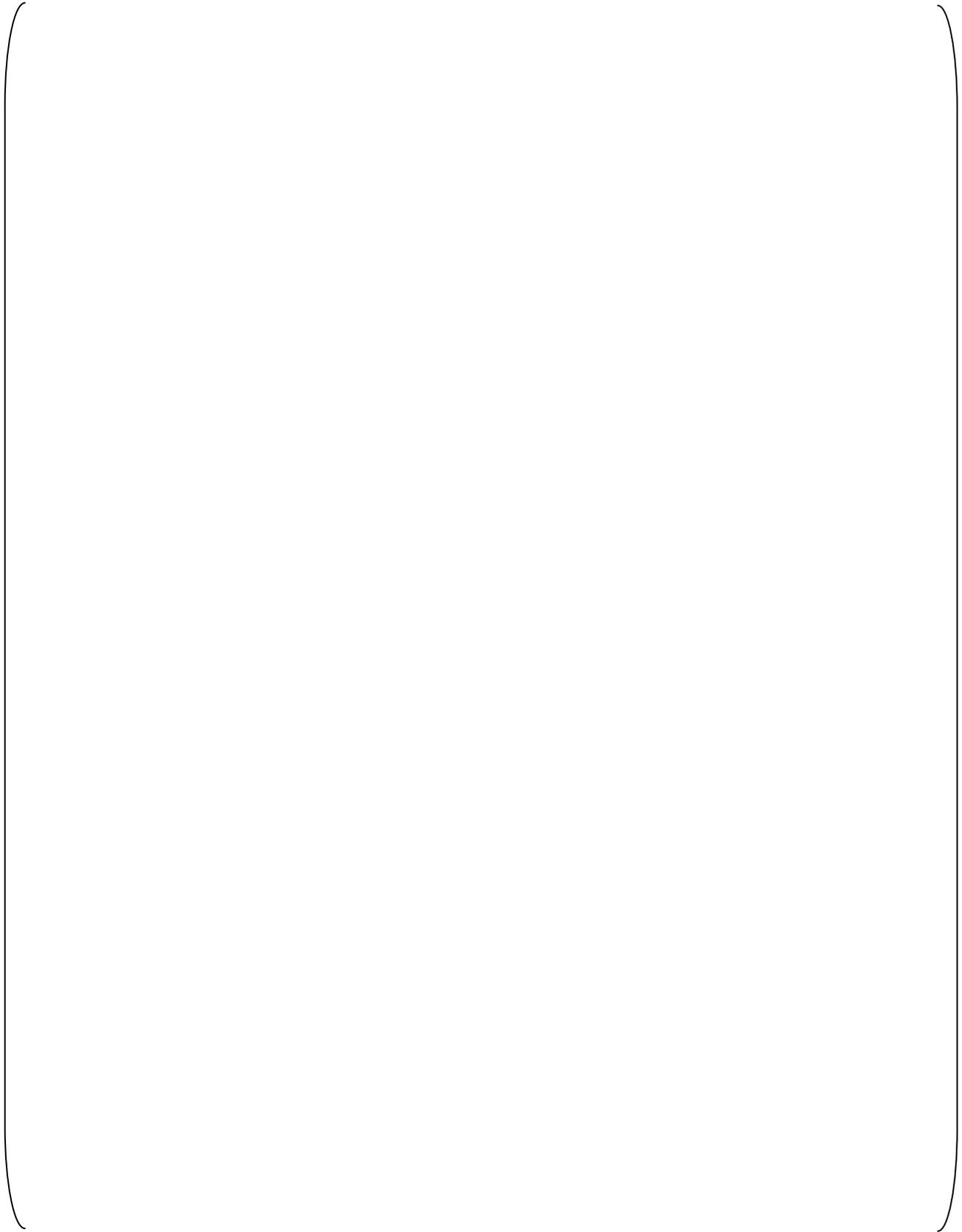




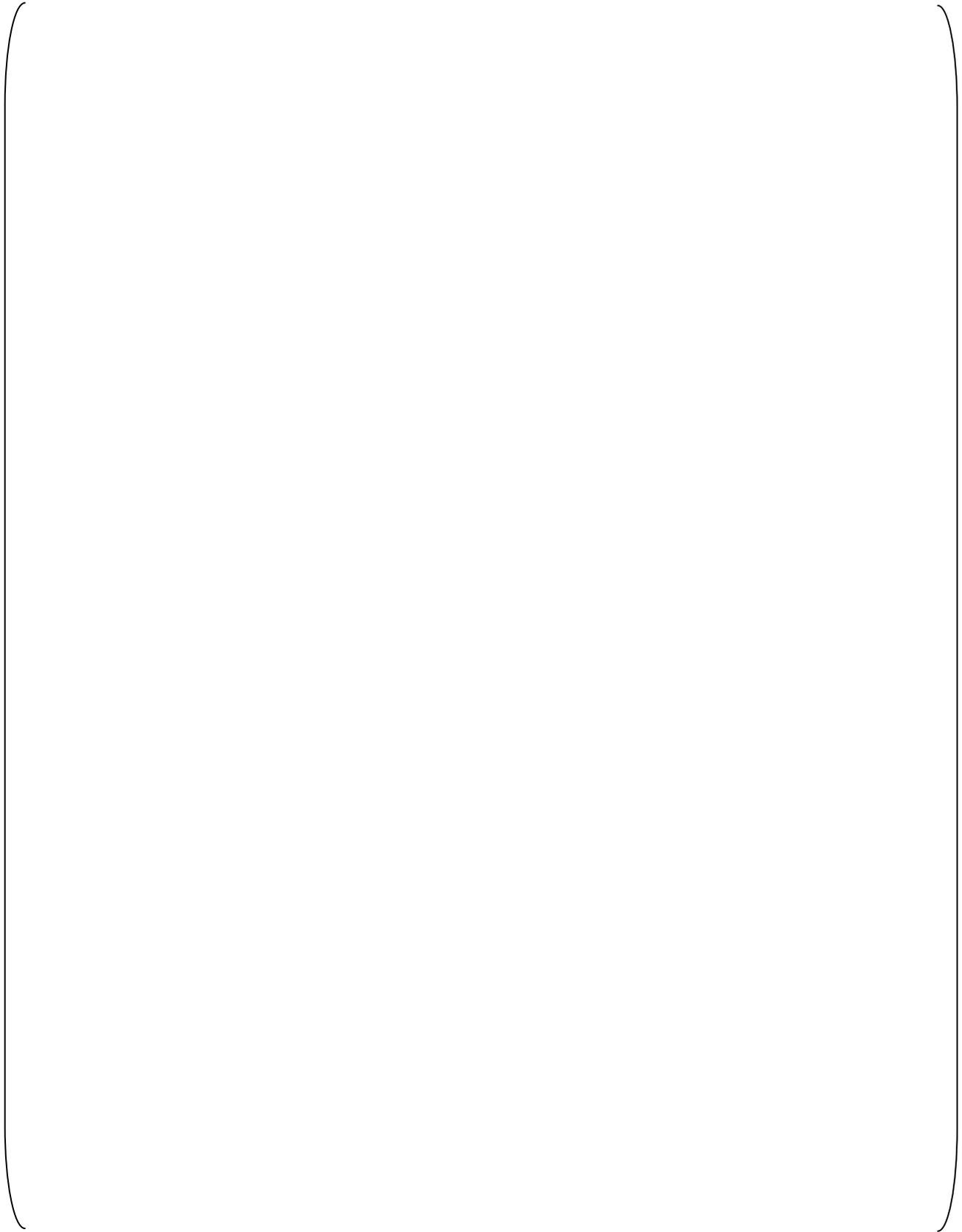


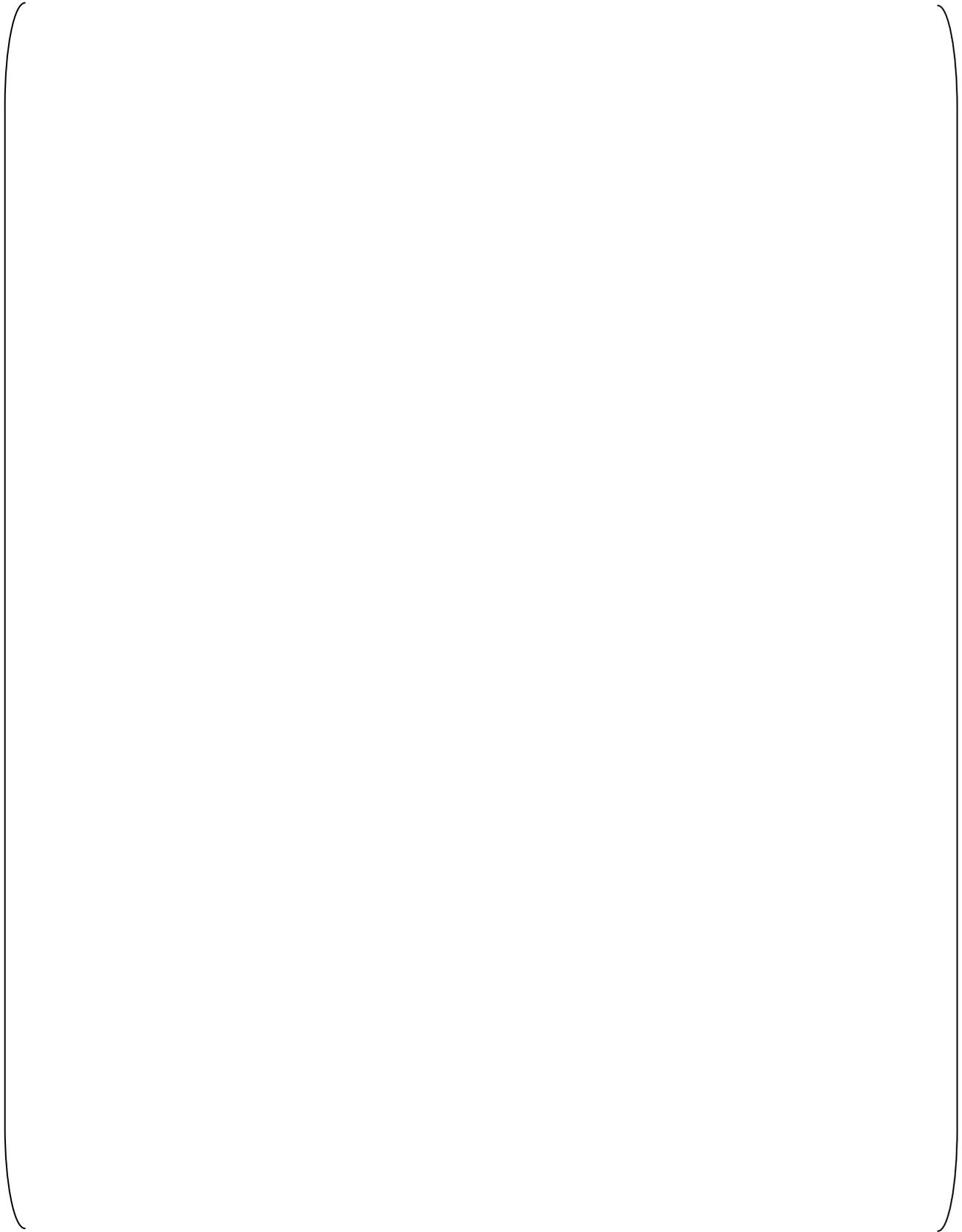


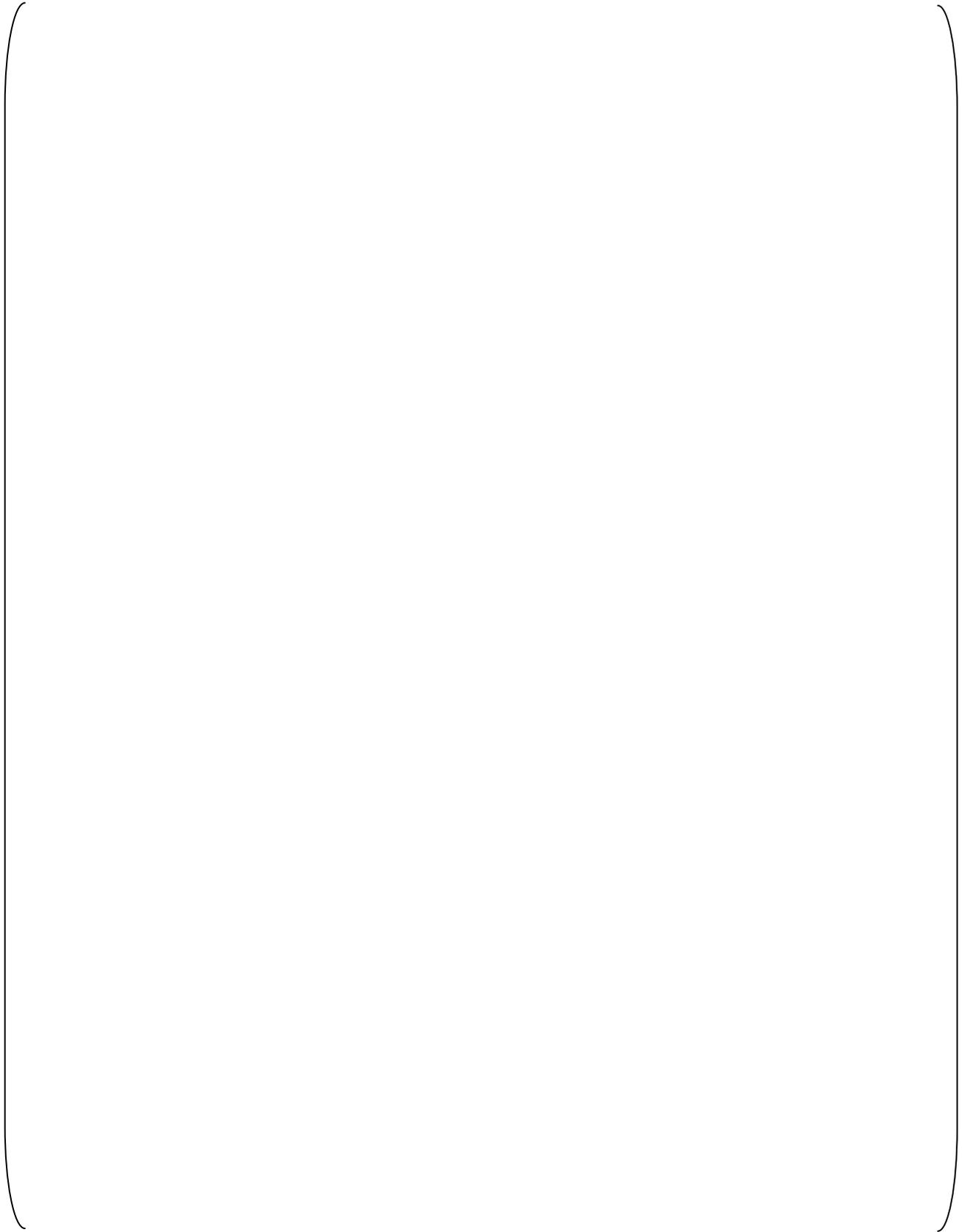


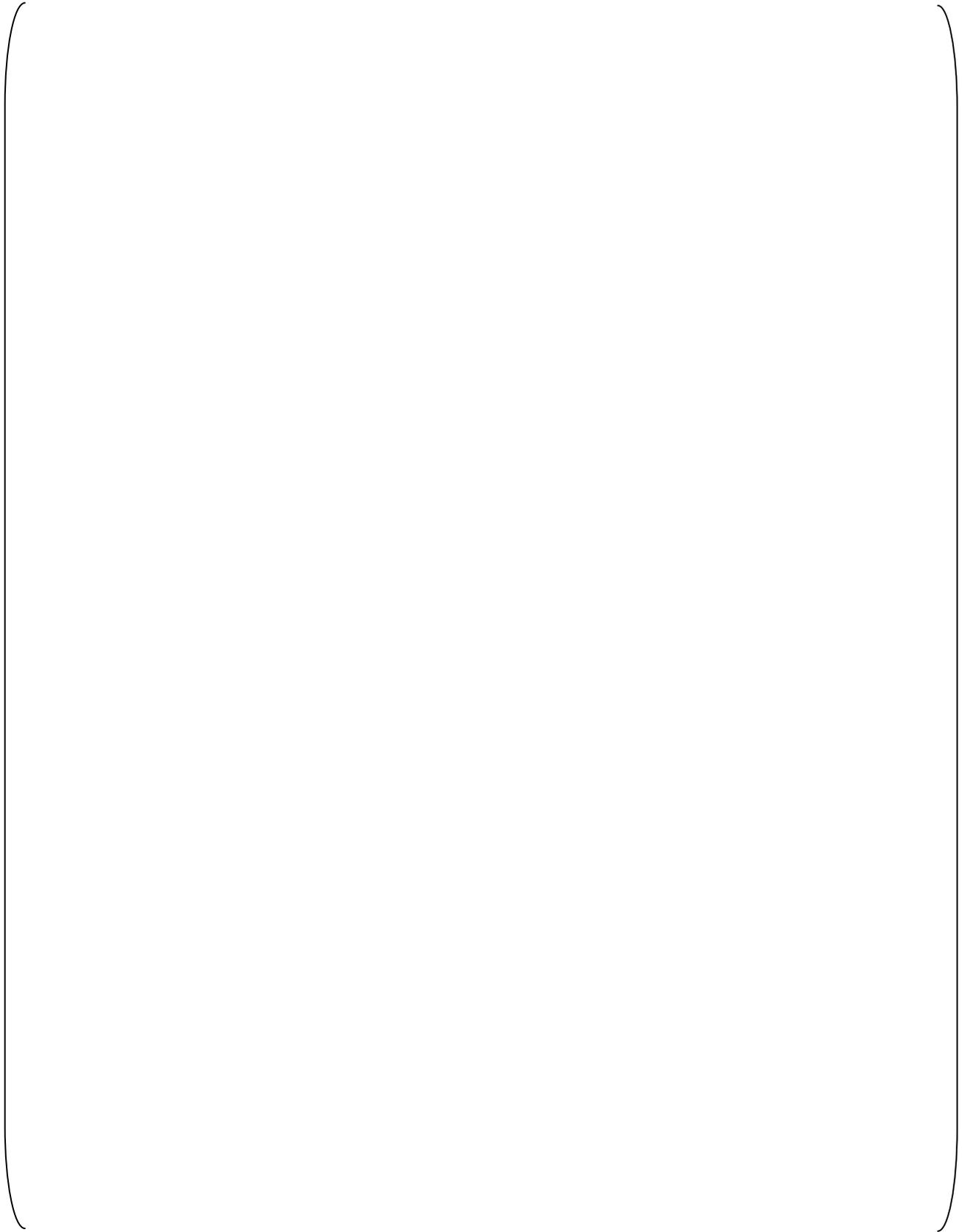


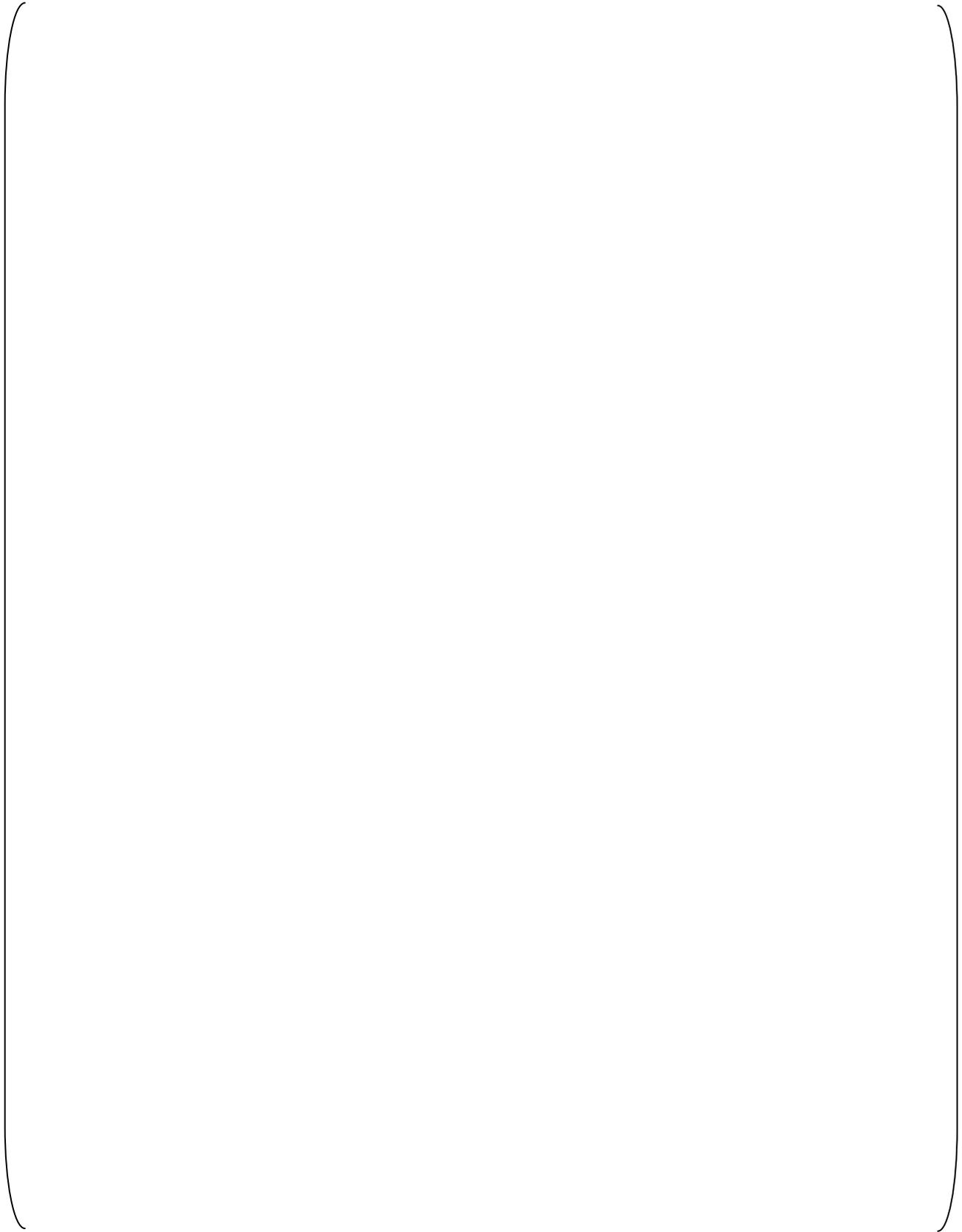
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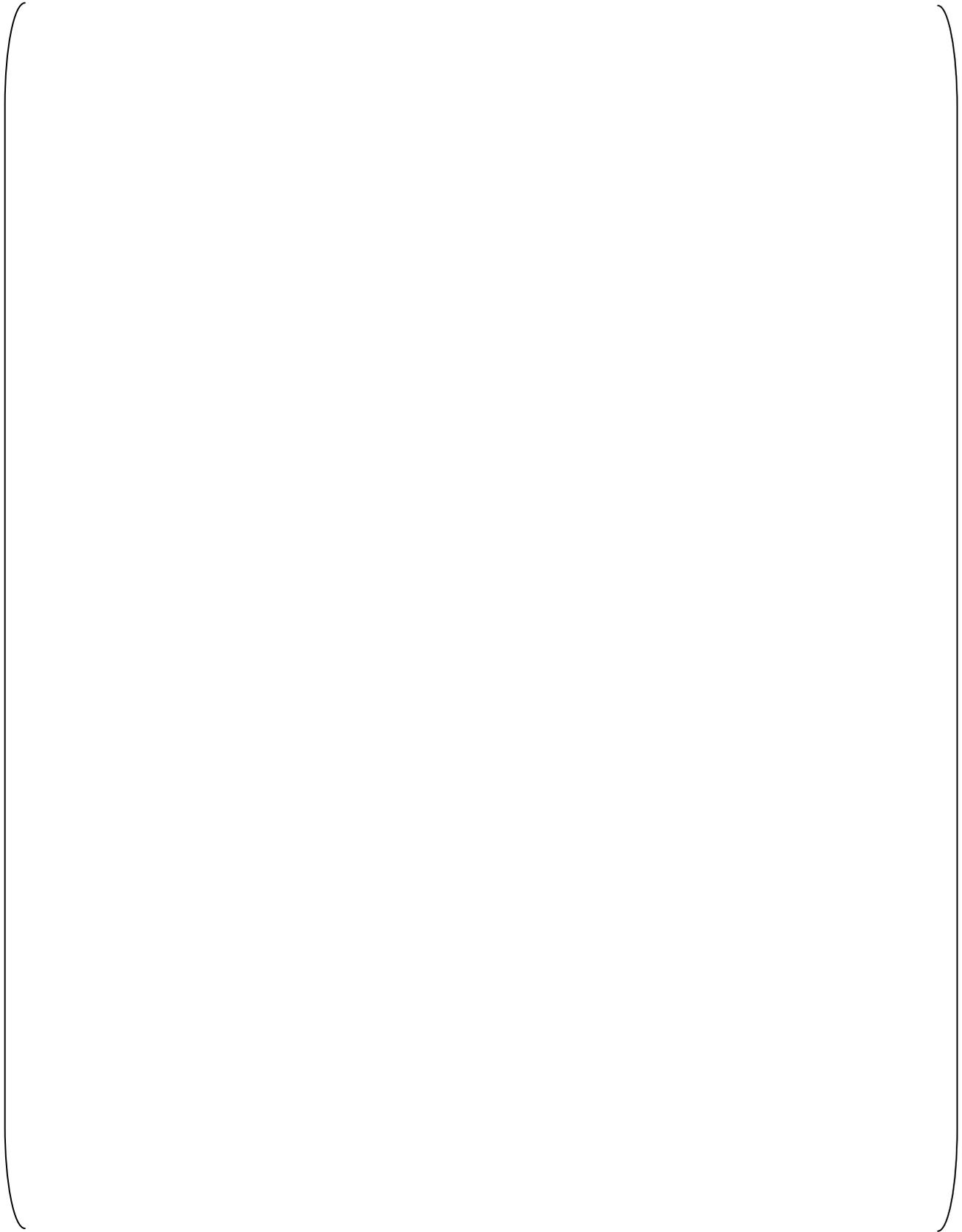


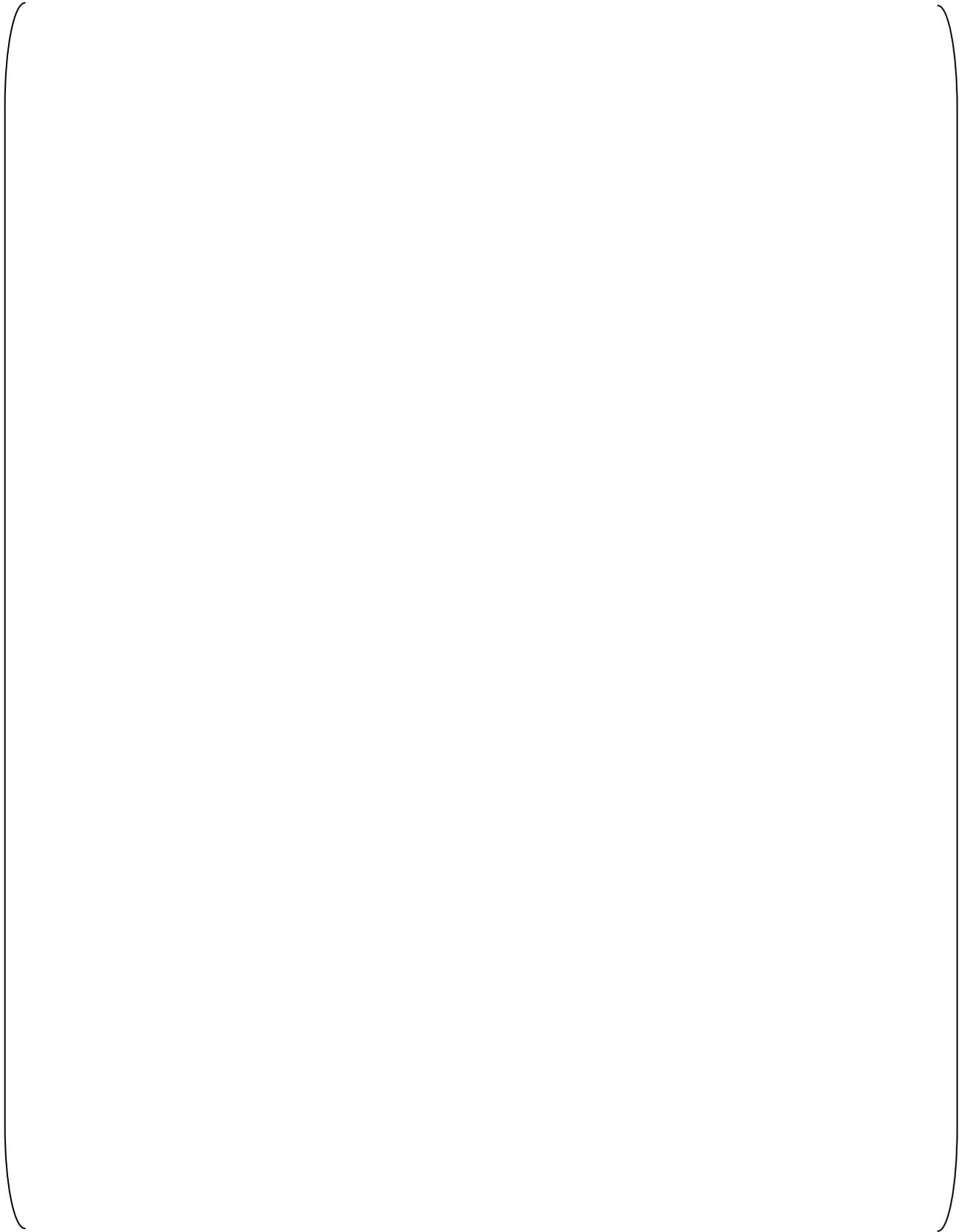


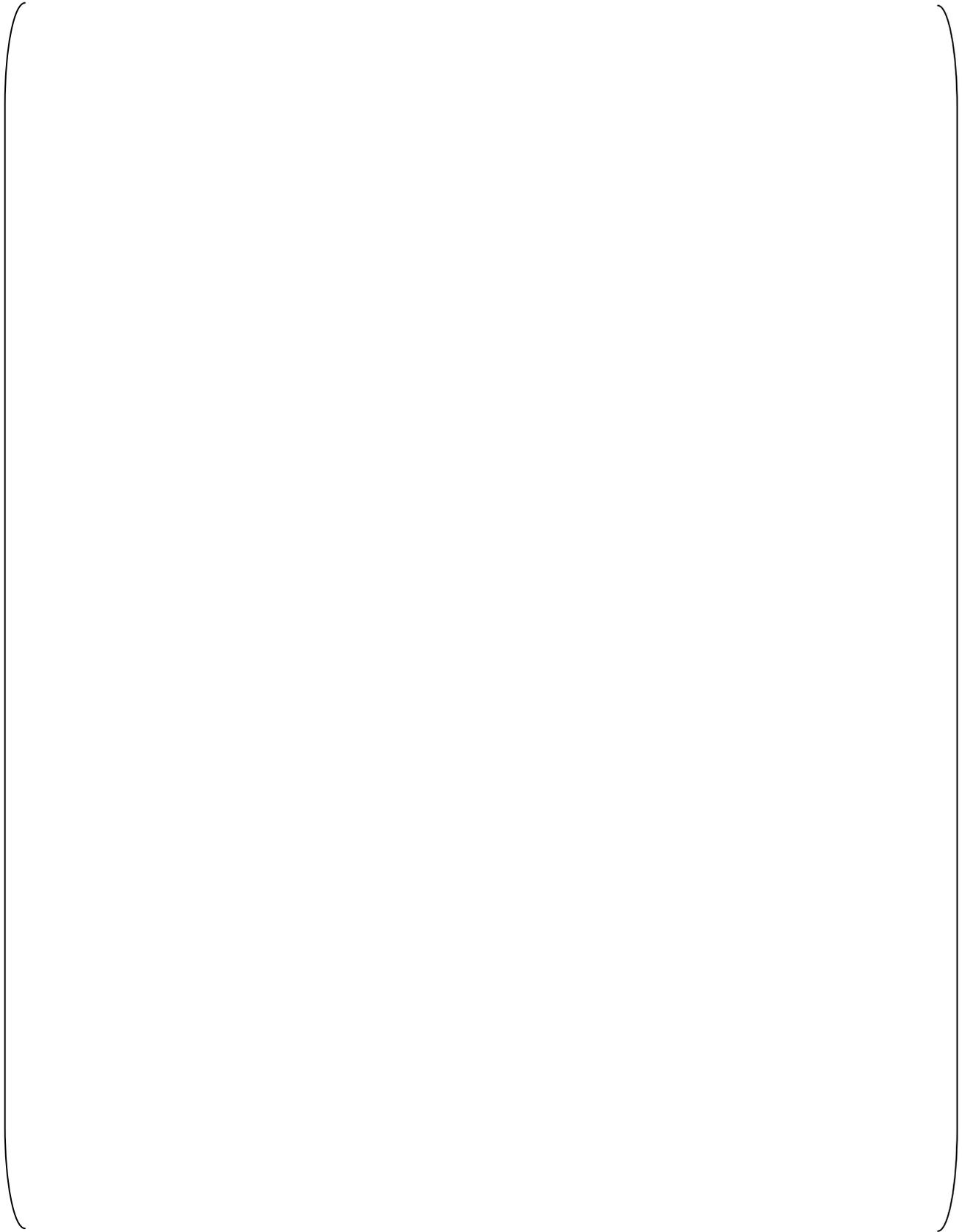


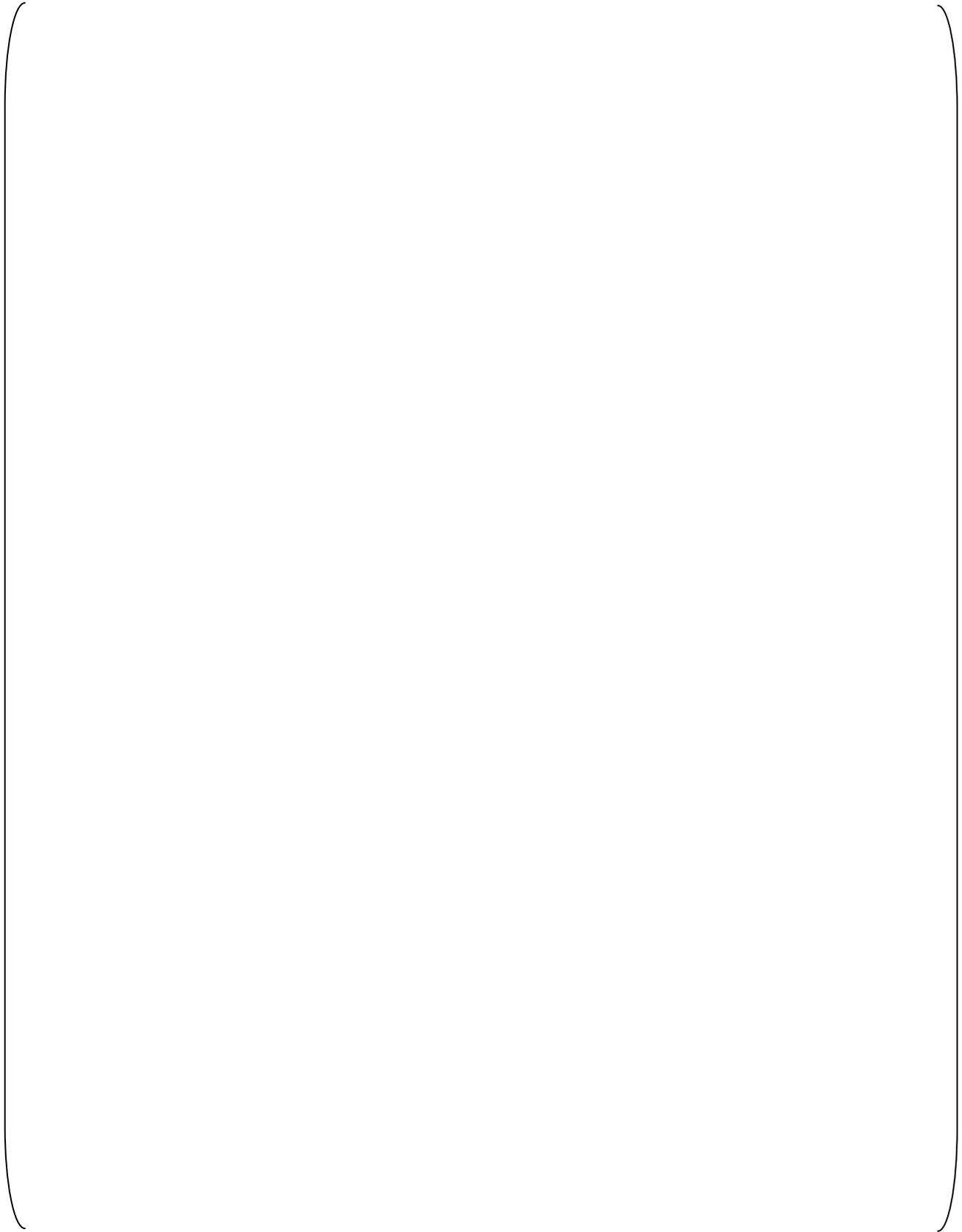


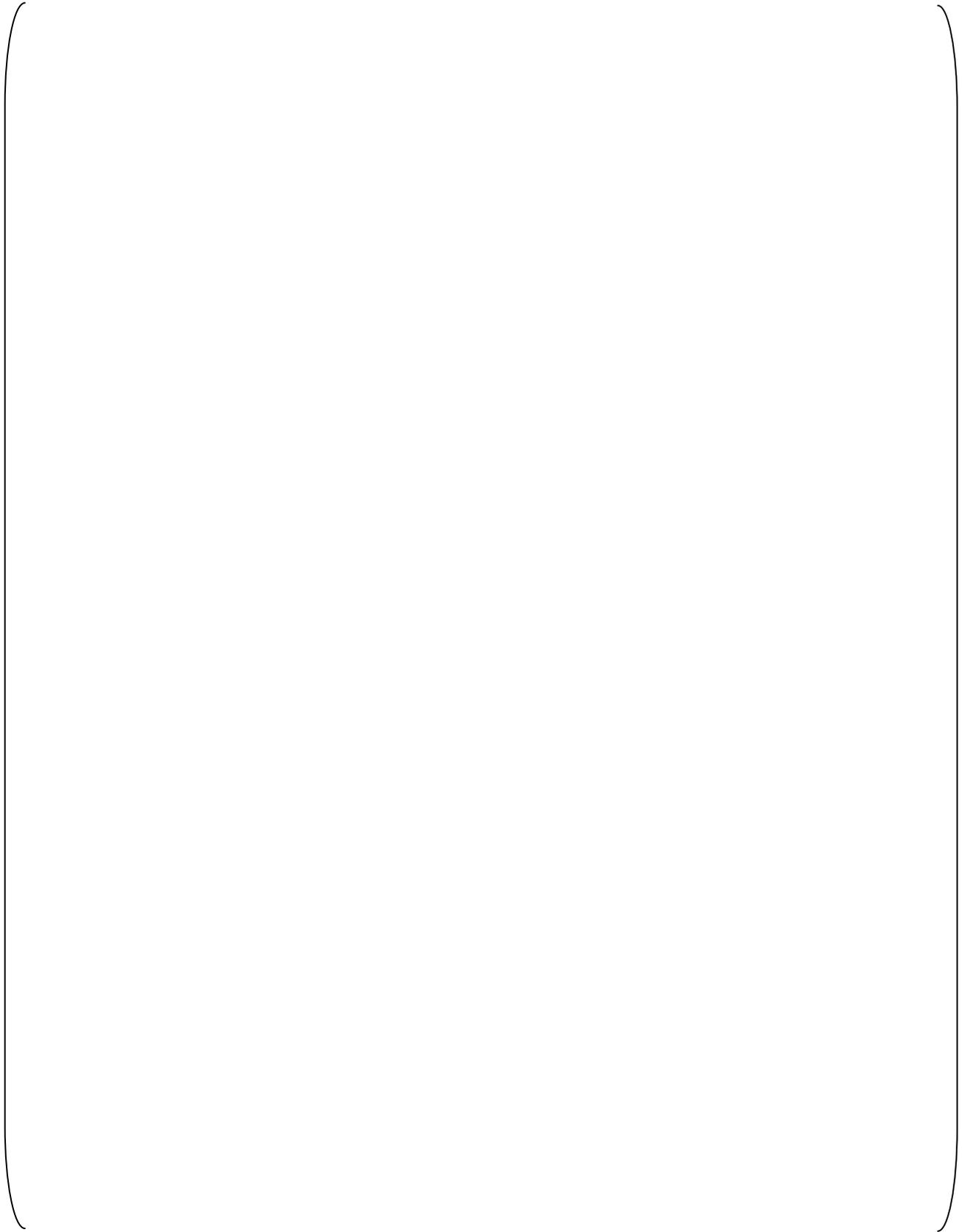


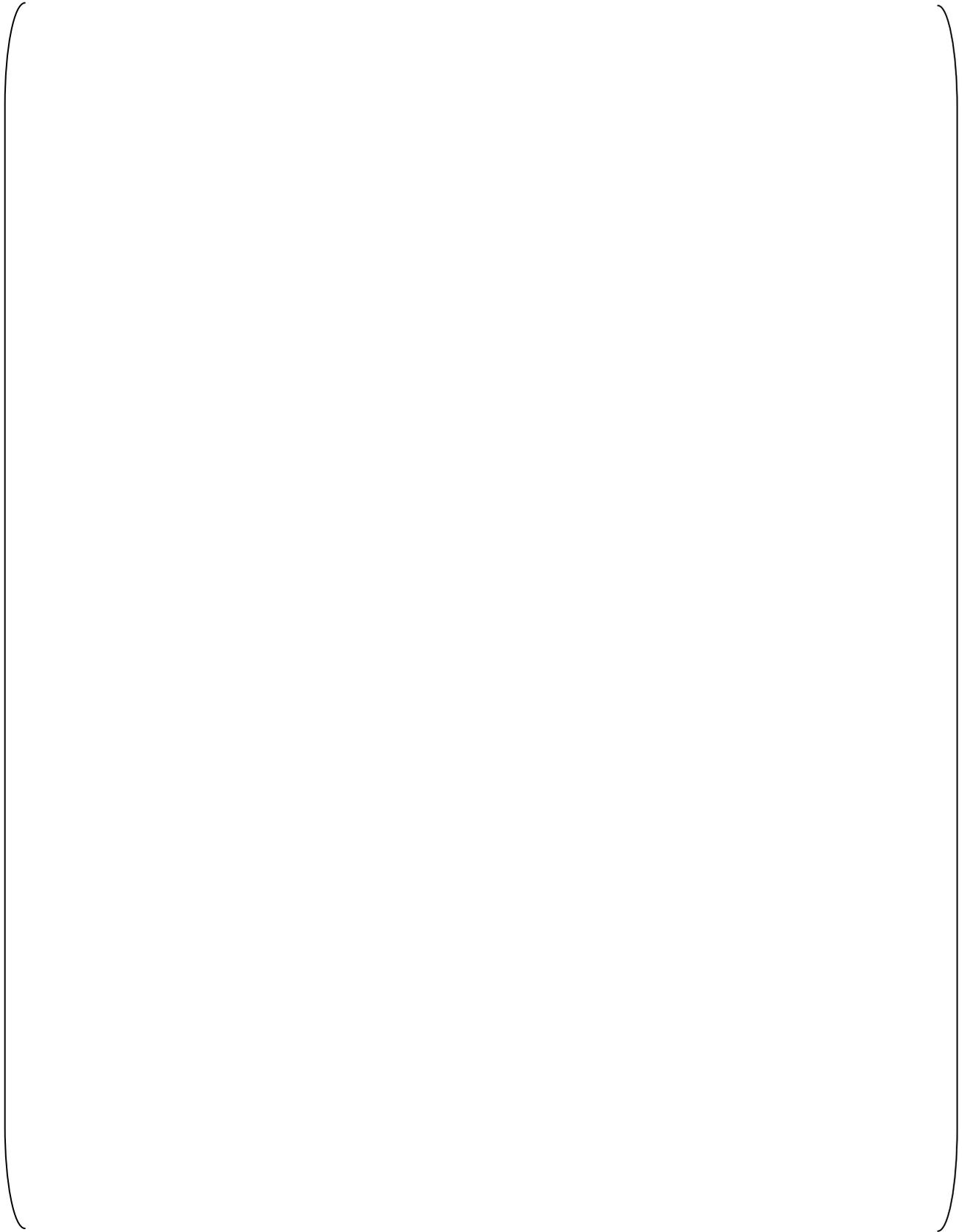


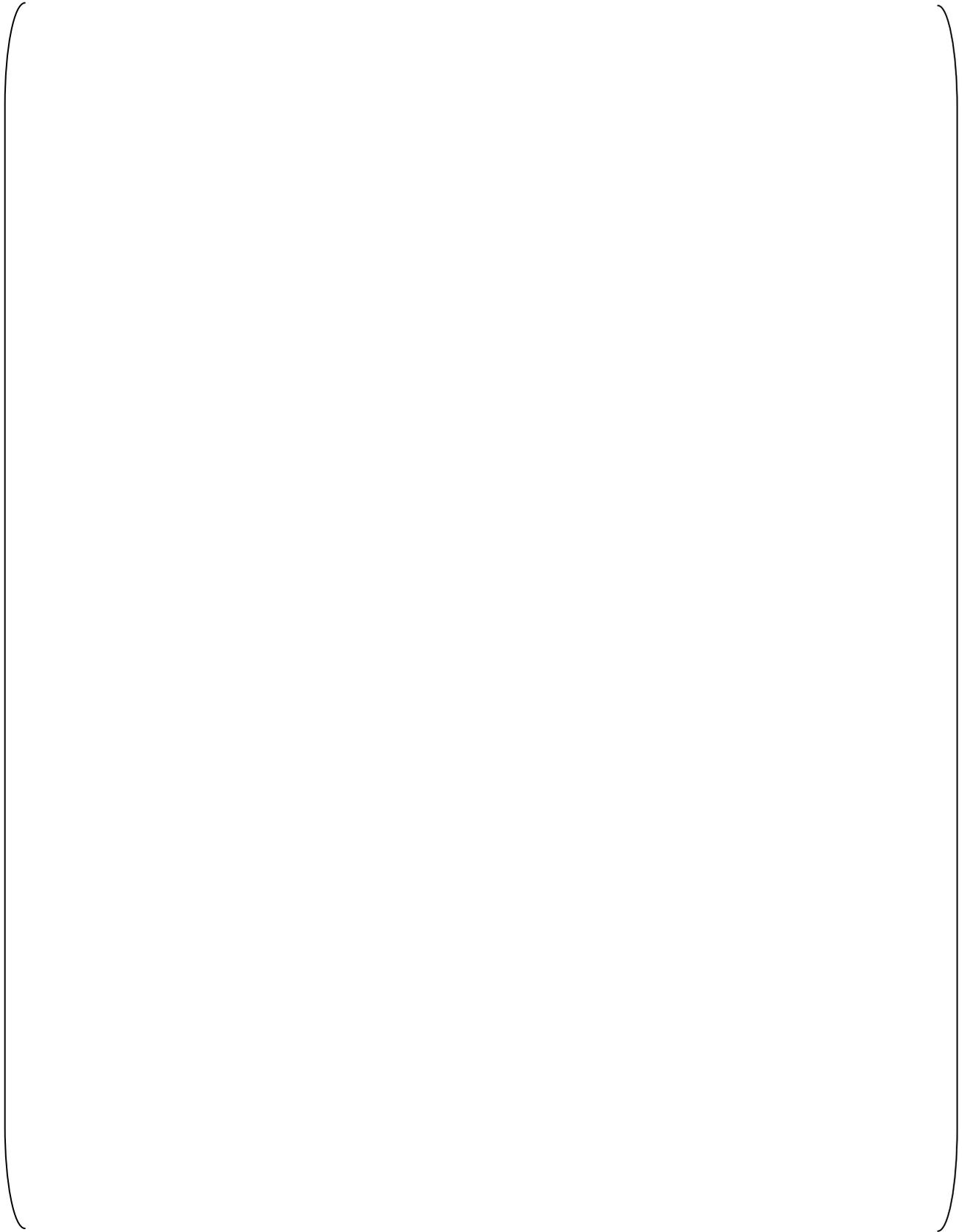


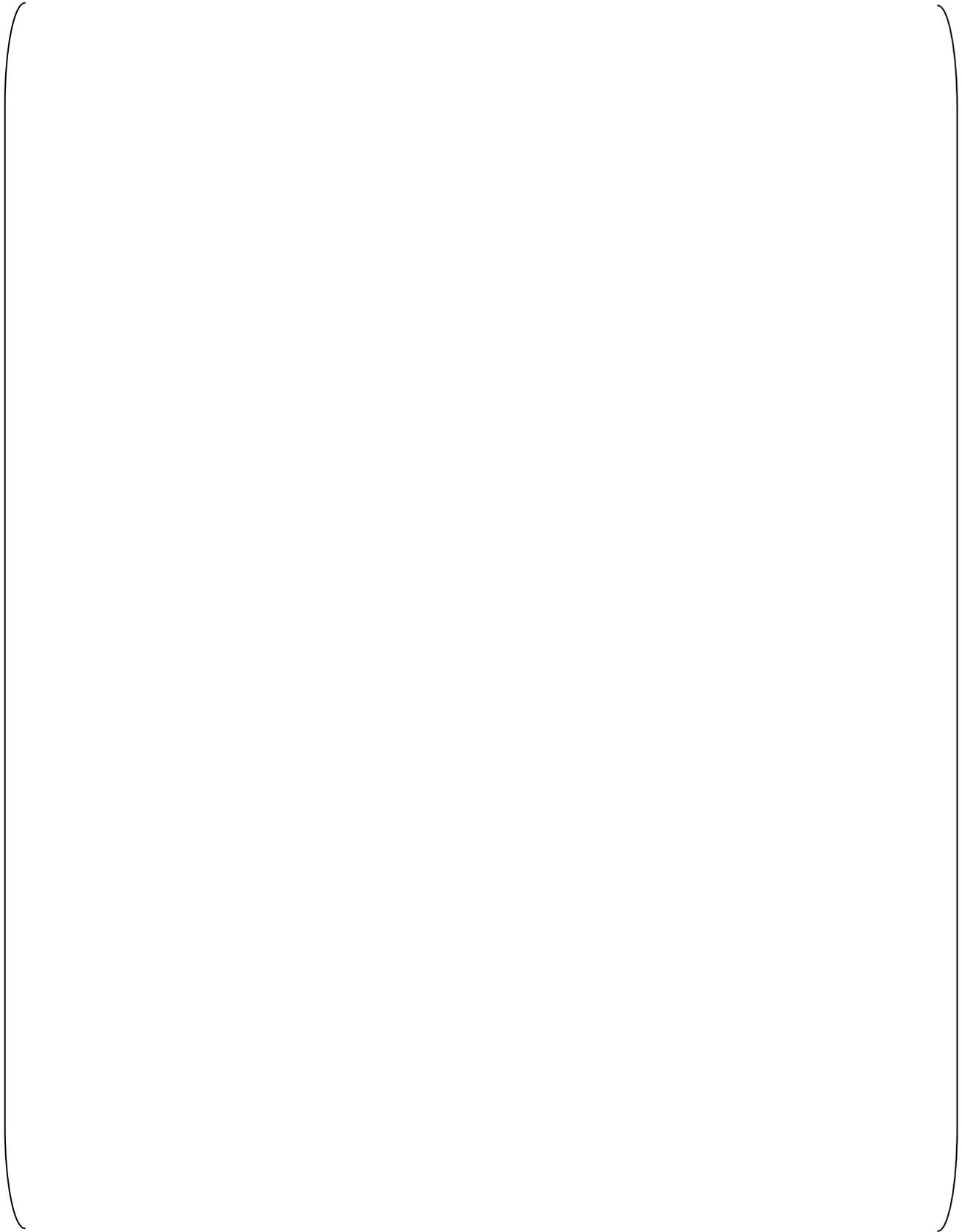


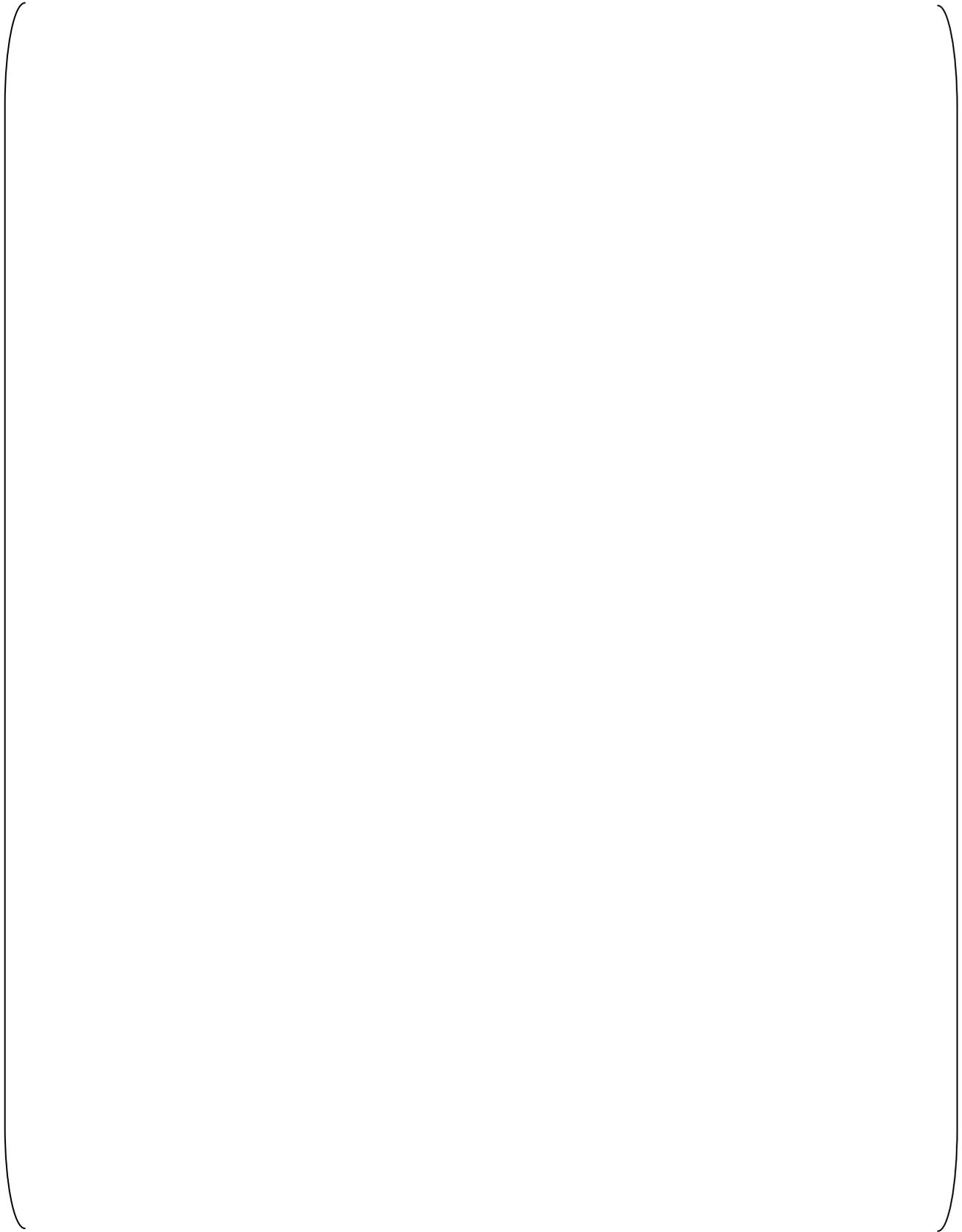


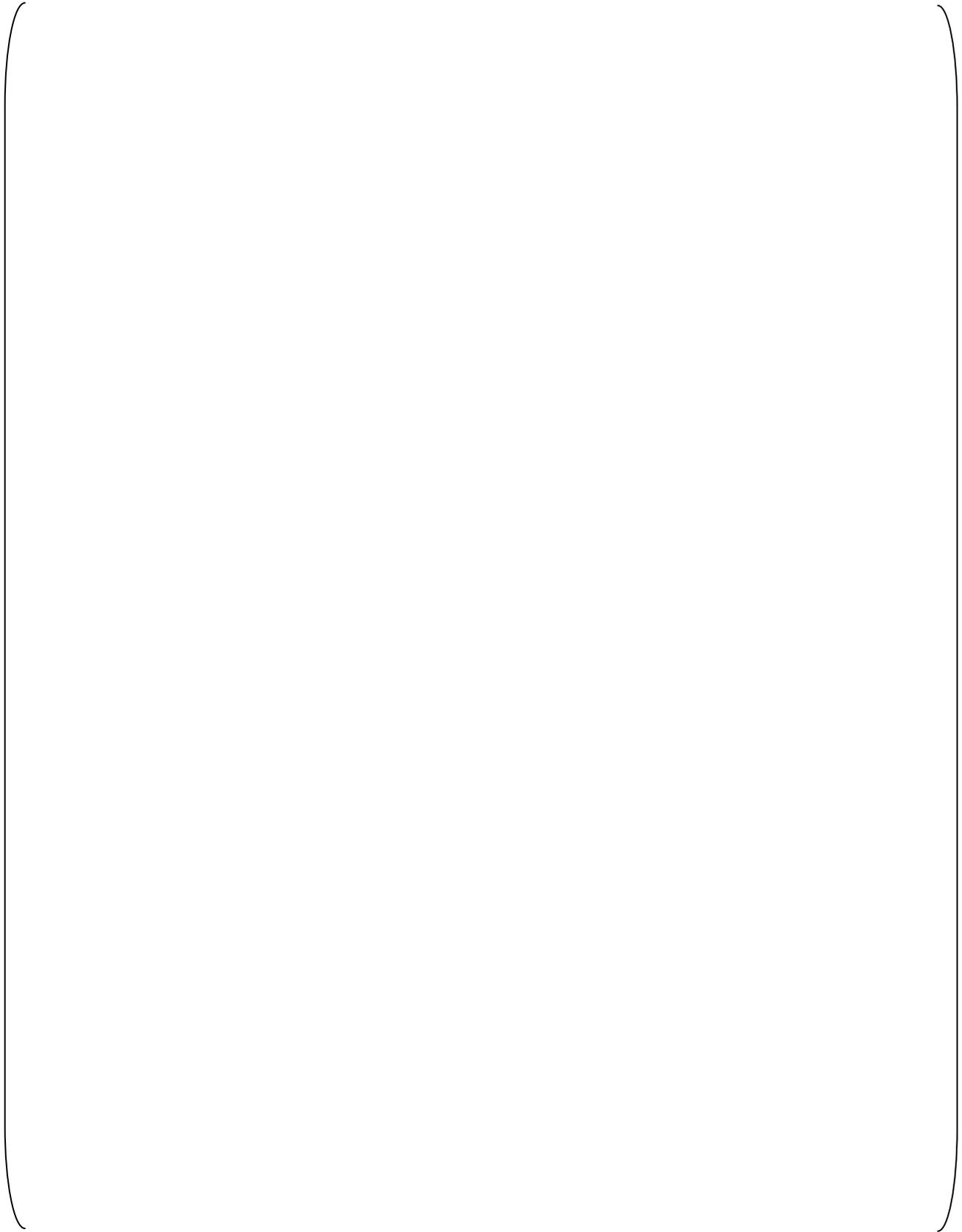


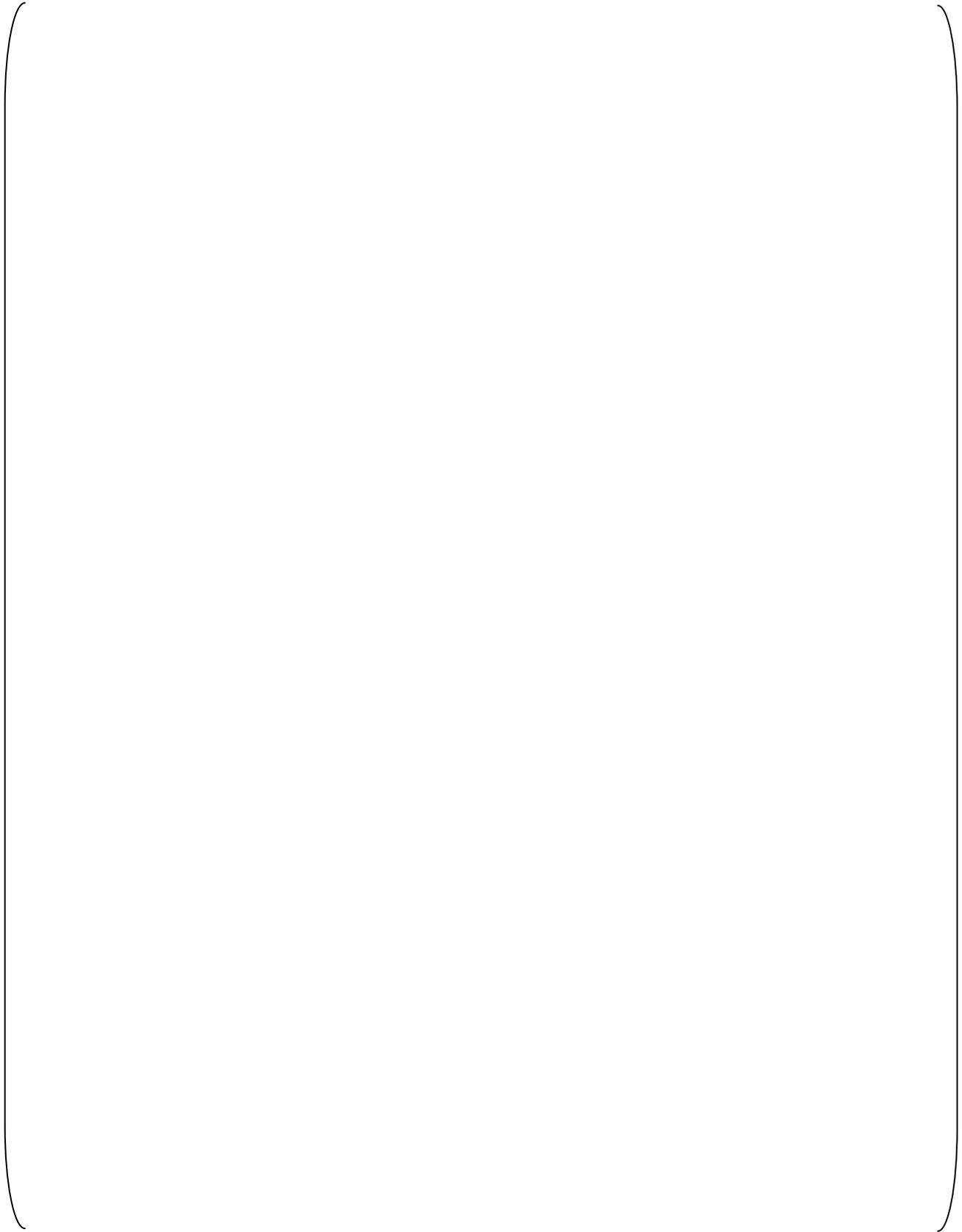


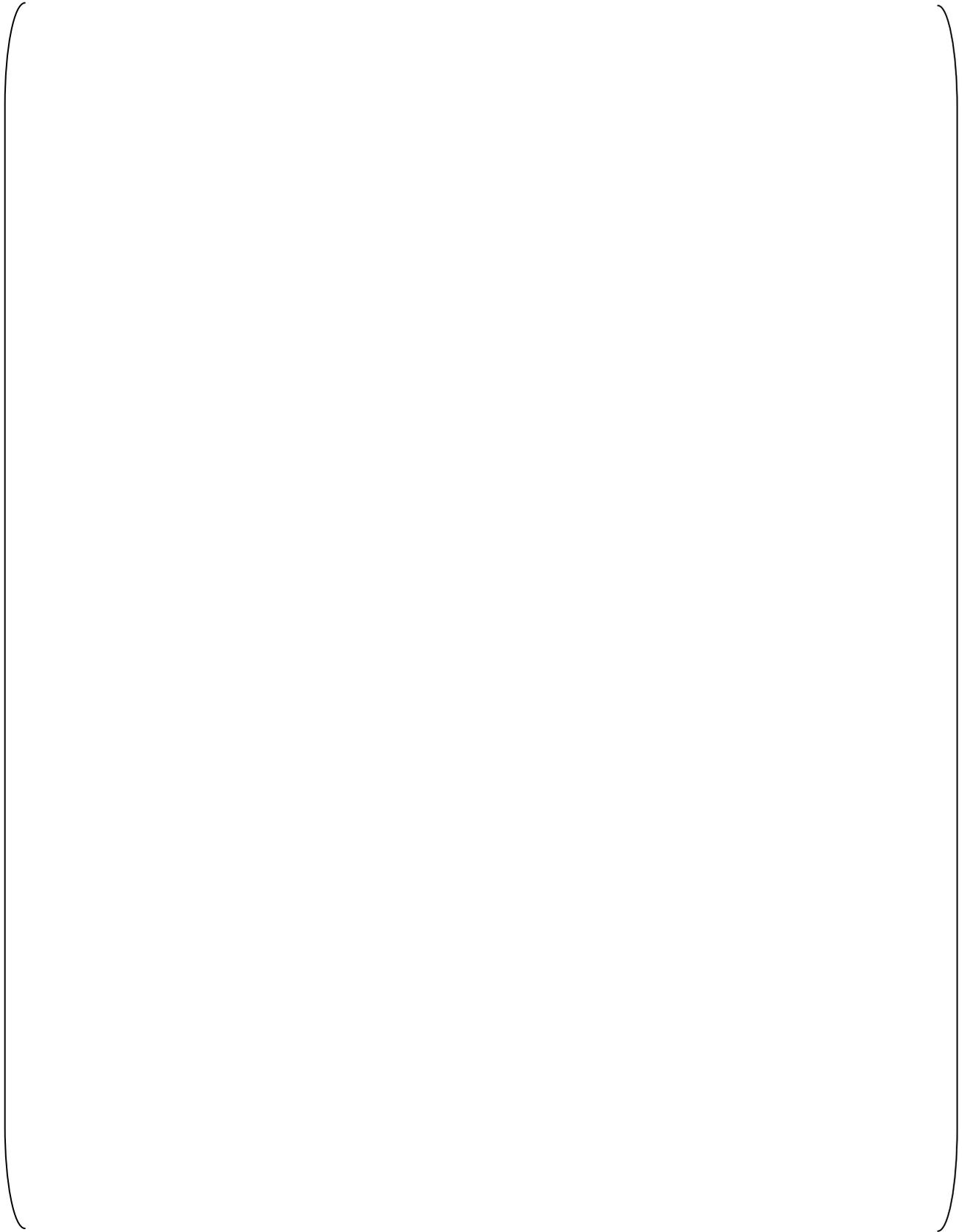


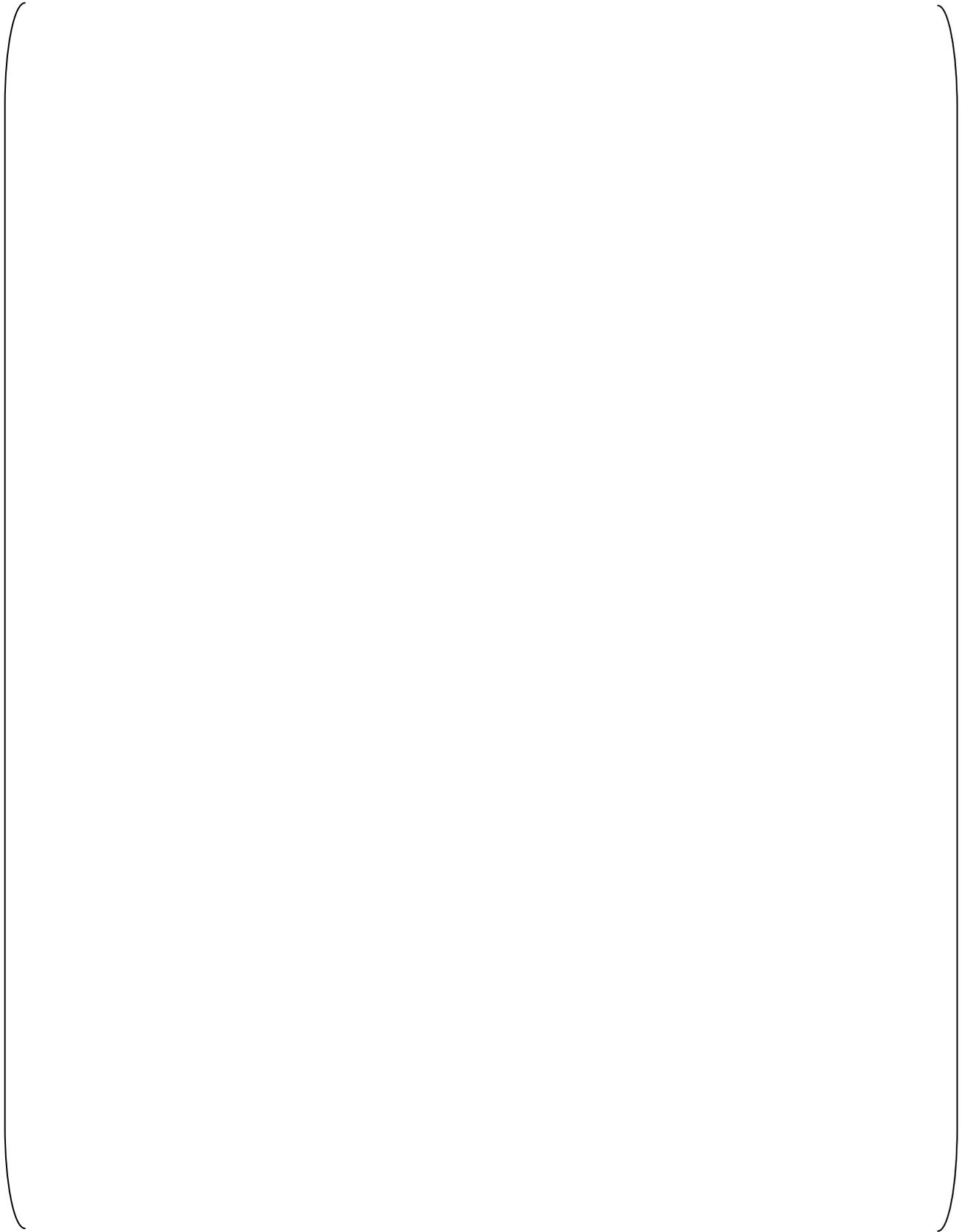


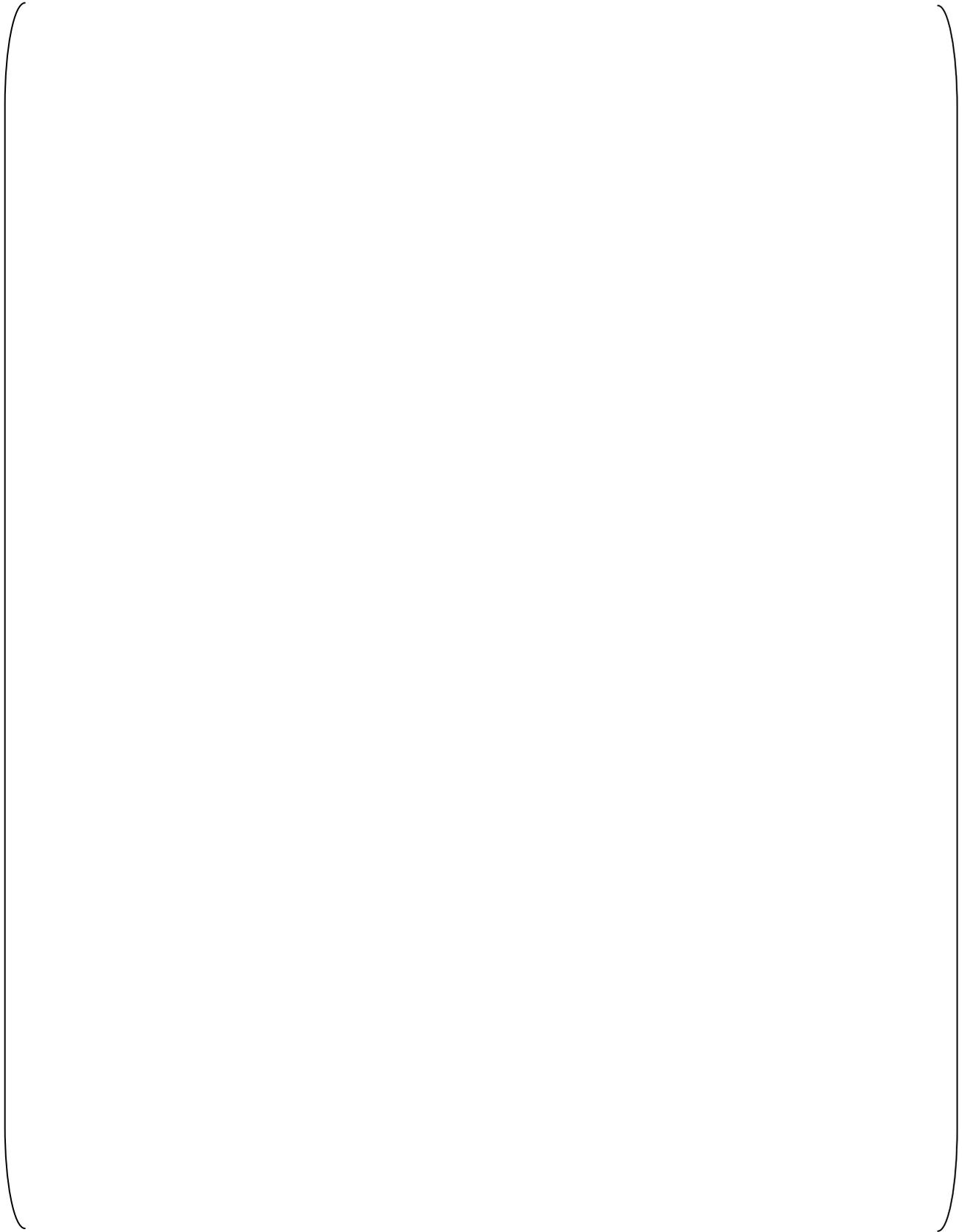












Reference10

