Improving Robustness in Social Fabric-based Cultural Algorithms

By

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ABSTRACT

In this thesis, we propose two new approaches which aim at improving robustness in social fabric-based cultural algorithms. Robustness is one of the most significant issues when designing evolutionary algorithms. These algorithms should be capable of adapting themselves to various search landscapes.

In the first proposed approach, we utilize the dynamics of social interactions in solving complex and multi-modal problems. In the literature of Cultural Algorithms, Social fabric has been suggested as a new method to use social phenomena to improve the search process of CAs. In this research, we introduce the Irregular Neighborhood Restructuring as a new adaptive method to allow individuals to rearrange their neighborhoods to avoid local optima or stagnation during the search process.

In the second approach, we apply the concept of Confidence Interval from Inferential Statistics to improve the performance of knowledge sources in the Belief Space. This approach aims at improving the robustness and accuracy of the normative knowledge source. It is supposed to be more stable against sudden changes in the values of incoming solutions.

The IEEE-CEC2015 benchmark optimization functions are used to evaluate our proposed methods against standard versions of CA and Social Fabric. IEEE-CEC2015 is a set of 15 multi-modal and hybrid functions which are used as a standard benchmark to evaluate optimization algorithms. We observed that both of the proposed approaches produce promising results on the majority of benchmark functions. Finally, we state that our proposed strategies enhance the robustness of the social fabric-based CAs against challenges such as multi-modality, copious local optima, and diverse landscapes.

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I believe I know the only cure, which is to make one's centre of life inside of one's self, not selfishly or excludingly, but with a kind of unassailable serenity-to decorate one's inner house so richly that one is content there, glad to welcome any one who wants to come and stay, but happy all the same in the hours when one is inevitably alone.

Edith Wharton

DEDICATION

Just hoping this is useful!

Chapter 1

Introduction

1.1 Evolutionary Algorithms

Evolutionary algorithms take their roots from the evolution theory of Darwin. These algorithms try to mimic the collective behavior of natural systems. Natural processes such as natural selection, survival of the fittest, and reproduction have been subject to inspiration as the fundamental components of evolutionary problem-solving methods. The basic part of all these algorithms is that they start with a randomly generated set of solutions. Then, they try to evolve the solutions through applying a set evolutionary operators such as mutation and crossover.

Evolutionary algorithms are not limited to biological processes. There is another category of evolutionary algorithms known as Swarm Intelligence (SI). These algorithms take inspiration from social behaviors of living colonies such as ants, flocks, schools, and hives. Within these swarms, individuals have relatively simple structures, but their collective behavior usually looks very complex. The complex behavior of a swarm emerges as a result of the interactions between the individuals over time. This complex behavior can not be easily predicted by observing the simple behaviors of the agents separately.

There are some well-known examples categorized as evolutionary algorithms:

1. Genetic Algorithms
2. Cultural Algorithms
3. Prticle Swarm Optimization
4. Ant Colony Optimization
5. Honey Bee Colony

Both categories of evolutionary algorithms share the same idea of evolving some initially generated solutions. However, the difference is in the way that they manipulate and evolve individuals through applying evolutionary operators.

1.2 Robustness in Evolutionary Algorithms

The aim of this research work is to improve robustness in evolutionary algorithms. In this field, robustness means that an algorithm can be used to solve many kinds of problems, with a minimum number of adjustments to address particular problems with special qualities. Also, it can mean the capability of algorithms to deal acceptably with noisy or missing data.

As stated by No Free Lunch(NFL) theorem, there is no algorithm better than others over all cost functions. It means, there is no guarantee for an algorithm to work well for all functions if it shows promising results for a particular category of them. Therefore, robustness has been one of the most desired features which motivates researchers to invent new methods which are less dependent on the kind of a problem than others.

1.3 Research Motivation

abcd

1.4 Thesis Contribution

In the thesis, I am going to improve the robustness of Cultural Algorithms in both components of poplation and belief spaces. In the population space, a new neighborhood restructuring strategy is proposed which works based on a dynamic and irregular topology. In the belief space, a new normative knowledge source is proposed on Confidence Interval inspired form Inferential Statistics. Talk about IEEE-CEC2015 $\cdots$

1.5 Thesis Outline

abcd

Chapter 2

Related Works

Many variants of CAs have been proposed in a vast range of different applications such as single and multi-objective optimization, dynamic problems, social interactions simulation. Here, we are interested in studying socially motivated and multi-population variants as some modern approaches in solving optimization problems.

2.0.1 Heterogeneous Multi-Population Cultural Algorithm

[] proposed a new architecture for cultural algorithms. In this pproach, the whole population is divided into a set of independent sub-populations which work in parallel without direct communication. They referred to the works of [] [] [] []. As their motivation they stated that most of proposed variants of evolutionary algorithms suffers from immature convergence. This occurs because these algorithms can not hold the diversity at a reasonable level. Based on existing research works, they hypothesized that multi-population streategies would be a better choice as they have the potential to perfrom an efficient search on complex landscapes. In their approach, the optimization parameters are divided among some heterogenous sub-populations. the sub-populations are called heterogenous because each sub-population is responsible for optimizing a different subset of parameters. Each sub-population represents

a partial solution instead of a complete solution. To evaluate a partial solution, it gets completed by its complement parameter values from the belief space. The complete solution is evaluated based on a numerical optimization function. Also, to make the convergence process faster a simple local search strategy is incorporated into the proppsed algorithm. The general architecture of their algorithm is presented in figure ???

In the experiments, they considered the whole population size to be 1000 individuals. It is divided into 30 sub-populations. So, the size of each sub-popualtion is 33. The algorithm runs for the maximum of 10000 generations and the local search strategy runs only for 10 iterations. They evaluated HMP-CA on a set of 8 complex optimization functions. It is able to find the minimum value for 7 functions out of 8. However, when the local search strategy is applied to the expriments, the proposed method outperforms all of the functions and it finds the optimum value very quickly. Ultimately, they claimed that their porpsed approach is efficient in both time and space complexity.

2.0.2 The Social Fabric Approach as an Approach to Knowledge Integration in Cultural Algorithms

[] begins with a brief introduction to socially motivated methods to problem solving. It compares qualities of Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Cultural Algorithms (CA) regarding the scale in which the interactions between agents occur. Figure (()) compares PSO, ACO, and CA in terms of the time and space continuum over which the social interactions occur. Individuals in ACO and PSO tend to interact in a reatively limited temporal and spatial scales. It is obvious because the agents in both ant and paricle swarm algorithms exchange information with only other agents in their local neighborhood. On the other hand, cultural algorithms let the individuals interact together using various types of sym-

bolic information emerged from complex cultural systems. In cultural algorithms the interactions among individuals occur indirectly through a shared belief space. So, cultural algorithms allow individuals interact in a global scale.

Then, they asked the essential question of what social structures might emerege alongisde the search process?. To answer such questions, they introduced a new influence function which utilizes the social fabric phenomena. The old influence function assumes no interactions between agents and works based on the simple roulete wheel method. On the other hand, in the new influence function, the individuals are connected through a social network (fabric). Multiple layers of such networks could be employed in a population. The interplay of these network connection forms a social fabric. At each iteration, an individual could specify its controller knowledge source. In this approach, the contoller knowledge source is chosen based on the majority of knowledge sources in the neighborhood of an individual. The neighborhood size of an individual is specified by the topology of the fabric. Inspired by Particle Swarm Optimization literature, different topologies could be taken into consideration to model the relationships among individuals. In their work, they only considered Ring and Square topologies. They stated that, the topology of the social fabric determines the extent to which the influence of knowledge sources could be spread thorugh the network.

DONT FORGET REPAST!!

Here is where you tell me what is the problem you have been working on for the past few months (or years). I want all the details and you should not be timid about being too tutorial, except that you do not want to cross the line towards writing a textbook. However consider carefully that *communication* implies conveying ideas to other people, while *effective communication* occurs when your message is clearly

understood. Remember that your audience must understand your message before they can agree with you.

Ask yourself: *who is your audience?* You might think of your supervisor who knows everything and you want to impress with your knowledge. I think instead of the graduate students who will be reading this thesis which is, after all, a property of the university. It is published as a university technical report so that others may learn by reading it. Then teach them! Be a bit tutorial. Even the expert external examiner will be impressed by your clarity of exposition if he or she does not need to read paragraphs twice in order to understand - something which people with PhDs and big egos find particularly irritating.

On the other hand, do not go too far and give trivial definitions from concepts learned in a 3rd year undergraduate courses, else you might find yourself in trouble when having to remember the details during an oral examination.

My approach is to put everything necessary to make clarity for the problem the main goal of this chapter, assuming an intelligent and well prepared reader who already has a Bachelor degree in an appropriate subject.

Once I understand the problem clearly and its nuances (it may not be what I expected after all), I also need to know why the problem is important, what its impact is and what its application, if any. Here you are free to elaborate and write as much as you think is necessary to avoid the examination doubt that you have a brilliant new solution to a trivial and unimportant issue.

I suggest reading various books on how to do research and set up problems. The best for me was "The Craft of Research" by Wayne Booth [2], which can be found in the main library at Q180.55 M4B66. From there I have transferred to my writing a fairly simple structure for talking about the topic of the research, with the question to be asked and its motivation and significance. It goes as follows:

1. *I am trying to learn about (working on, studying...)*

2. *because I want to find out....*

3. *in order to understand...*

Another way of looking at this is to ask the *what*, *why* and *where*, starting from a *setting* of the problem with a first point A, stating what the *goal* is at point B and having an *action link* between the two which will encompass your new solution. As surprising as this may be to some of you, I found reading a book from Microsoft very useful: "Beyond Bullet Points: Using Microsoft Office PowerPoint 2007 to Create Presentations That Inform" [1]. The goal of the book is to improve presentations with Power Point, but there is a lot that can be transferred towards *effective communication* for a thesis.

In summary, my view of the second chapter on *"The Problem to be solved"* is as follows:

1. *Not* all the background and definitions (boring!) - use instead just-in-time explanations as needed in every context as it comes up;

2. Motivation in depth;

3. Tutorial high level explanation, where it is important to choose the right pitch: who is the audience? who are you teaching here?

4. Make it exciting, make it current, make it important - why do I want to keep reading?

5. Should you list here the solutions from other researchers? I think not, list instead the different facets of the problems that other researchers have attacked.

6. A taxonomy can be extremely useful to place your problem and its particular special features within the perfect context of the overall area, as you need to make sure that the reader understands perfectly what you are trying to solve.

Chapter 3

The New Approach and Solution

This is where you go all out and tell us all about your new discovery and research related to the problem in the previous chapter. No arrogant sweeping statements which cannot be fully justified, but no false modesty either. You must impress your reader that you have accomplished something.

Simply summarized, this chapter should be comprised of at least two main sections, each with appropriate subsections. The first section should describe:

- what the new approach is;
- what is really totally new;
- what is incrementally new;
- what you built upon.

The second part should describe fully how the new approach works, both with the overall theoretical exposition (e.g. an algorithm) and with as many examples as necessary for clarity. Remember that if the reader does not understand fully, you will get a lot of questions and doubts. Good examples, good figures, good diagrams with super clear tutorial explanations can be a joy to read and make even a small

contribution appear to be more impressive. Are you afraid that if you are too tutorial your work will not seem as deep and difficult? Only shallow people will make such a superficial evaluation, have trust instead in the wisdom of your supervisory committee.

Use at least one good example throughout, and even better if this is one of the examples you used in Chapter 2 to describe the original problem.

By the way, this would be the first chapter I would write. This is what I know best right now, as I just finished working on it. It is clear to me and on the tip of my fingers. Start with your strengths! The second chapter I would write is the next one about the experiments, followed closely by chapter 2 describing the problem. It may not seem intuitive to you, but it works and it is the most productive way I ever found to finish a document.

3.1 Some LaTeX Examples

A Latex document is composed of two parts: the Preamble, and the Document Body. The *Preamble* is the site for inclusion of all document set up commands: definition of new commands, inclusion of prebuilt packages, template declaration, etc. The *Body* is where the document content is placed.

3.1.1 Preamble

The Preamble refers to the input which precedes the documents contents. It is the area where the author determines the general template for the document using the **documentclass**[*options*]{*doc style*} command. For example, \documentclass[11*pt*]{*article*} declares that a document will follow the *article* document class, and have 11pt font.

If the document requires support of any library packages they must be included

in the preamble using the **usepackage**{*package name*} command. For example, \usepackage{graphicx} is the command needed to include the graphicx package.

3.1.2 Document Body

The document body is the area which follows the Preamble. It is defined by the **begin**{*document*} and **end**{*document*} commands. The content of a Latex document is declared in the document body. Input which appears after the \end{document} command is ignored.

3.2 How to Number Pages

To number the pages of a document use the **pagenumbering**{*style*} command. Numbering is defined in the documents preamble. There are several different *styles* to choose from.

Numbering Style	**Output**
\pagenumbering{arabic}	1, 2, 3, ...
\pagenumbering{roman}	i, ii, iii, ...
\pagenumbering{alph}	a, b, c, ...
\pagenumbering{Roman}	I, II, III, ...
\pagenumbering{Alph}	A, B, C, ...

Table 3.1: Page Numbering Styles

The numbering of pages for a thesis is, however, much more complex than for an article and, in fact, the *book* class has been adopted. Make changes to those settings only if you are really familiar with LaTeX.

3.3 How to Create a Title Page

A title page can be either on a separate page or integrated directly into the first page of the document. It is defined by three declarations, followed by the **maketitle** command as illustrated below.

```
\title{Title of Paper}
\author{Author(s) of Paper}
\date{Publication Date}
\maketitle
```

The article document class defaults on an integrated title page. To make a separate title page, use the **titlepage** option with the \documentclass[*titlepage*]{*doc style*} command.

For this thesis style the title page has been completely formatted for you. Just insert the various names of people in the supervisory committee, the title, your name and so on in the location where the *dummy* entries exist right now and you will be done. I would suggest to avoid doing any other changes unless you are absolutely sure!

3.4 How to Create an Abstract

To create an abstract, place contents of abstract between the **begin**{*abstract*} and **end**{*abstract*} commands.

3.5 How to Create a Table of Contents

The **tableofcontents** command automatically generates a table of contents from all section headers. The default behavior for the article document class is to produce

an integrated table of contents. However, the document can be altered to generate the table of contents on a separate page using the **newpage** command (see section Formatting Extras).

For this thesis template a special command has been added, namely the **textTOCadd**. You can find it in the file *macros/style.tex*. It has to be explicitly called for an insertion into the Table of Contents and it is already in place appropriately for the existing sections and subsections.

3.6 How to Create Sections

Creating sections, subsections, and subsubsections is completed using the \section{Section Name}, \subsection{Subsection Name} and \subsubsection{Subsubsection Name} commands, respectively. Each sectional division is numerically labeled with respect to it's placement in the section hierarchy. For example, this section was defined with the code:

```
\section{How to Create Sections}
Creating sections, subsections, and ...
```

It is useful to give a label using the **label** command to a section or subsection if a reference to it is made, so that the reference will be automatically updated should the structure of the document change.

3.7 How to Create a List

Lists can be either enumerated, non enumerated, or descriptive. Each element of a list is termed an 'item'.

1. enter the list environment with the \begin{*list style*} command.

loc	Purpose
l	left justified column
r	right justified column
c	centered column
|	vertical rule

Table 3.2: Table Example

2. define each item with the \item command for non\enumerated lists, or \item[*label*] for descriptive lists.

3. terminate list environment with the \end{*list style*} command.

3.8 How to Insert Tables, Figures, Captions, and Footnotes

The table and figure environments contain input blocks which cannot be split across pages. Rather than divide the input of either of these environments, the contents are relocated, or floated, to a location in the document which optimizes page layout with the surrounding document content.

3.8.1 Tables

Tables are created in the tabular environment. A single parameter is used to define the number of columns and item justification pertaining to each column. The single parameter is a combination of the following ones shown in Table 3.2.

\\ and & are used to define rows and columns, respectively. A table can either have the contents of its rows and columns lined or not. Each line used to construct the table must be individually specified, using | and \hline for vertical and horizontal lines, respectively.

Table 3.2 was generated with the following input:

```
\begin{center}
    \begin{tabular}{|l|l|} \hline
    l & left justified column   \\ \hline
    r & right justified column  \\ \hline
    c & centered column         \\ \hline
    $|$ & vertical rule         \\ \hline
 \end{tabular}
 \end{center}
```

You will want to include your table in the "List Of Tables" section at the beginning of your thesis. To do this you enclose the above table inside a table environment like so:

```
\begin{table}
    \begin{center}
    ...
    \end{center}
    \caption{Sentence describing table.}
    \label{unique:label}
\end{table}
```

The caption is the text that appears underneath the table. It should be short and precise. The label is a unique label that you can use to refer to the table within your document. You can use the `\ref{label}` to insert the table number into your text as in Table 3.2. In the example above you would use as in:

```
I am referring to Table \ref{unique:label}.
```

3.8.2 Figures

The first step to including an externally prepared image into a document, is to declare the graphixs package into the documents preamble. Integrating the image can be done using the figure environment. Enter and exit the figure environment with the **begin{figure}**[*loc*] and **end{figure}** commands, respectively. The *loc* dictates the placement of the included image, and can be any of the following:

h here: location in text where the environment appears

t top: top of the page

b bottom: bottom of the page

p page of floats: on a separate page with no text

For organizational purposes, it is best to have keep all figures in a folder together. I usually label the folder as "*Figures*" (with great creativity) and I placed it in the same directory as the topmost main *.tex* file. Include the image into the document with the **includegraphics**[*dim*]{path to image} command. *dim* dictates the magnitude of the `height` or `width`. The image is scaled proportionally. An example and its resulting output follow below.

$$\texttt{\textbackslash begin\{figure\}}[h]$$
$$\texttt{\textbackslash centering}$$
$$\texttt{\textbackslash includegraphics}[height = 1in]\{\texttt{LinuxPenguin.eps}\}$$
$$\texttt{\textbackslash caption\{The Linux Penguin\}}$$
$$\texttt{\textbackslash end\{figure\}}$$

Why is the output for the figure not shown? Because inserting figures into LaTeXis not that simple and it is highly dependent on the system you are using together with the type of figure. This is not the place to dwell upon the inconsistencies which can

make your life difficult. Suffice it to say that the original LaTeXand its tools was geared to accept *.eps* files for figures and it still maintains that expectation if one compiles using a *Latex to dvi to (pdf or ps)* series of commands. On the other hand, if one uses the *Latex to pdf* direct path, then files of other types are perfectly fine (e.g. *pdf, jpg, gif, etc.*).

If you are interested, look at the actual file for this section namely "sec_latexhelp.tex" and consider the set of lines commented out just above this paragraph. There are two examples of insertion of figures, the first with the *.eps* version and the second with the *.pdf* version of the same picture (of a penguin). Delete the comments from one of the two sets and use the appropriate tools.

To refer to a figure, the same approach used for tables should be used, namely a `\ref{label}` command which includes the unique identifier label for that figure, as in:

```
I am referring to Figure \ref{unique:label}.
```

3.8.3 Captions

Captions for tables and figures are created using the **caption**{caption goes here}. Captions are automatically numbered with separate counters for tables and figures. **caption**{caption contents} can only be used in the Figure or Table environment.

3.8.4 Footnotes

Footnotes are inserted with the **footnote**{footnote contents} command. This footnote[1] is generated as follows:

```
...This footnote\footnote{this is a footnote} is generated...
```

[1] this is a footnote

3.9 How to Alter Font

3.9.1 Type Style

Roman Family is the default type style. The types style can be modified using the following commands.

Command	Output
\textit{Italic Characters}	*Italic Characters*
\textsl{Slanted Chartacters}	*Slanted Characters*
\textsc{Small Cap Characters}	Small Cap Characters
\textbf{Boldface characters}	**Boldface characters**
\textsf{Sans Serif Characters}	Sans Serif Characters
\texttt{Typewriter Characters}	`Typewriter Characters`

3.9.2 Type Size

The font size can be modified using the following commands.

Command	Output
\tiny{tiny font}	tiny font
\scriptsize{scriptsize font}	scriptsize font
\small{small font}	small font
\normalsize{normalsize font}	normalsize font
\large{large font}	large font
\Large{Large font}	Large font
\huge{huge font}	huge font
\Huge{Huge font}	Huge font

3.10 Math Mode

To incorperate mathematical content into a document, Latex provides three different environments: Displaymath, Math, and Equation. Brief descriptions for each environment, and environment short cuts are displayed in the table below.

Environment	**Function**	**Shortcut**
`math`	`displays an in-text formula`	`\ ( ...\ )`
`displaymath`	`displays an unnumbered formula`	`\ [ ...\ ]`
`equation`	`displays a numbered formula`	`N/A`

The following examples, using Einstein's famous $e \doteq mc^2$ equation, illustrate how to include a formula into a document.

```
...Einstein's famous \( e \doteq mc^{2} \) equation, illustrate...
```

```
\[e \doteq mc^{2}\]
```

$$e \doteq mc^2$$

```
\begin{equation}
   \doteq mc^{2}
\end{equation}
```

$$e \doteq mc^2 \tag{3.1}$$

3.11 Formatting Extras

The following table illustrates some formatting tips for perfecting the layout of a Latex document.

Command	**Purpose**
\hspace{*len*}	insert a horizontal space of length *len*
\vspace{*len*}	insert a vertical space of length *len*
\mbox{*text*}	ensure that *text* is not split over multiple lines
\\	new line
\newpage	start new page
\pagebreak	insert a page break
%	precedes comments

Chapter 4

Experiments

Assuming you have some experimental results to support your claims this is where all the data is reported. There are a few issues you should consider before dumping a lot of stuff here, or it will lose its effectiveness.

First of all you must describe precisely the experimental setup and the benchmarks you used. In any scientific discipline an experimental result is only good if it is reproducible. To be reproducible then somebody else must have sufficient details of the setup to be able to obtain the same data. Thus the first section in this chapter is a super precise history of the decisions made towards experimentation, including mentions of the paths which became infeasible. The setup must be valid and thus your description of it must prove that it is indeed sound. At times, terrifying times, when writing this section, both supervisor and student realize belatedly that something is missing and more work needs to be done!

The second portion of this chapter is dedicated the the actual results. At least two issues arise here:

1. Should all the data be reported here or should some be placed in the Appendix?

2. Should this be an exposition of the raw facts and data or should it include its analysis and evaluation?

There are no definite answers here, but I follow a few rules.

Should all the data be reported here or should some be placed in the Appendix?

- If there is a large number of tables of data, it might be better to present here only a handful of the most significant ("best") results, leaving all the rest of the data in the Appendix with proper linkages, as it would make the chapter so much more easily readable (not to mention limiting the struggle with a word processor for the proper placement of tables and text).

- Use an example throughout, call it a "case study" to make it sound better, so that all the data and results are somehow linked in their logic, and even better if this is one of the examples you used in Chapter 2 to describe the original problem.

- Highlight in some manner the important new data, for example the column of your execution speed where all the numbers are much smaller. Make the results highly easy to read!

- It is normally expected that data should be presented only in one form and not duplicated, that is, you are not supposed to include both a table of raw numbers and also its graphical representation from some wonderful Excel wizard. I tend to disagree. I would not wish to see every results repeated in this manner, but some crucial ones need to be seen in different manners, even with the same information content, in order to show their impact. One good trick is to place the more boring tables in the Appendix and use wonderful graphs in this chapter.

- This is the one chapter where I would splurge and use colour printing where necessary, as it makes an *enourmous* difference.

Should this be an exposition of the raw facts and data or should it include its analysis and evaluation?

- Is the evaluation of the data really obvious? For example you have 10 tables to show that your chemical process is faster in development and gives purer material - you may simply need to highlight one column in each table and state the obvious.

- Most results are not that obvious even if they appear so. Moreover this is where you are comparing your *new* results to data from other people. I usually describe other people's work at this point and make comparisons. That is why I prefer to talk about the analysis and evaluation of the results in a separate chapter.

- There is absolutely no clear structure here which is best.

Chapter 5

Evaluation, Analysis and Comparisons

For a Master's research this chapter represents the critical part where **you** are truly evaluated to determine whether you should be given your degree. Even more so for a PhD. Consider carefully what the University calendar states regarding the expectations for a master's thesis, paraphrased here.

1. *A Masters thesis is an original lengthy essay.* The main implication here is that the essay is original, that is, it is completely newly written by you and does not contain any writings from others unless precisely quoted. Any paraphrased items must be cited.

2. *It must demonstrate that:*

    - students understand research methods;
    - students are capable to employ research methods;
    - students demonstrate command of the subject.

3. *The work may be based on:*

- original data;
- original exercise from scholarly literature;
- data by others.

4. *The work must show that:*
   - appropriate research methods have been used;
   - appropriate methods of critical analysis supplied.
5. *The work must contain:*
   - evidence of some new contribution;
   - evidence of a new perspective on existing knowledge.

Only the last point uses the attribute *new* and it refers almost entirely to giving a new perspective and analysis, even if based on data from others. This truly implies that this current chapter on evaluation and analysis of results is the most important and must be written with care. You are demonstrating here that, even if given data and methods from others, your skills of critical judgment and analysis are now at the level that you can give professional evaluations.

Things are slightly different for a PhD. According to the Graduate Calendar:
a doctoral dissertation must embody original work and constitute a significant contribution to knowledge in the candidate's field of study. It should contain evidence of broad knowledge of the relevant literature, and should demonstrate a critical understanding of the works of scholars closely related to the subject of the dissertation. Material embodied in the dissertation should, in the opinion of scholars in the field, merit publication.

The general form and style of dissertations may differ from department to department, but all dissertations shall be presented in a form which constitutes an integrated

submission. The dissertation may include materials already published by the candidate, whether alone or in conjunction with others. Previously published materials must be integrated into the dissertation while at the same time distinguishing the student's own work from the work of other researchers. At the final oral examination, the doctoral candidate is responsible for the entire content of the dissertation. This includes those portions of co-authored papers which comprise part of the dissertation.

The second paragraph makes it clear that one must emphasize what is new and different from others, without arrogance, yet without being too subtle either. The first paragraph implies that for a PhD it is required that one approached an important open problem and gave a new solution altogether, making chapters 3, 4, 5 all part of the body of research being evaluated. In fact at times even the problem may be entirely new, thus including chapter 2 in the examination. This is in contrast to a Master's degree where the minimum requirement is for chapter 5 to be original.

Chapter 6

Conclusions

My first rule for this chapter is to avoid finishing it with a section talking about future work. It may seem logical, yet it also appears to give a list of all items which remain undone! It is not the best way psychologically.

This chapter should contain a mirror of the introduction, where a summary of the *extraordinary* new results and their wonderful attributes should be stated first, followed by an executive summary of how this new solution was arrived at. Consider the practical fact that this chapter will be read quickly at the beginning of a review (thus it needs to provide a strong impact) and then again in depth at the very end, perhaps a few days after the details of the previous 3 chapters have been somehow forgotten. Reinforcement of the positive is the key strategy here, without of course blowing hot air.

One other consideration is that some people like to join the chapter containing the analysis with the only with conclusions. This can indeed work very well in certain topics.

Finally, the conclusions do not appear only in this chapter. This sample mini thesis lacks a feature which I regard as absolutely necessary, namely a short paragraph at the end of each chapter giving a brief summary of what was presented together with

a one sentence preview as to what might expect the connection to be with the next chapter(s). You are writing a story, the *story of your wonderful research work*. A story needs a line connecting all its parts and you are responsible for these linkages.

Appendix A

Additional Information

This is a good place to put tables, lots of results, perhaps all the data compiled in the experiments. By avoiding putting all the results inside the chapters themselves, the whole thing may become much more readable and the various tables can be linked to appropriately.

The main purpose of an Appendix however should be to take care of the future readers and researchers. This implies listing all the housekeeping facts needed to continue the research. For example: where is the raw data stored? where is the software used? which version of which operating system or library or experimental equipment was used and where can it be accessed again?

Ask yourself: if you were given this thesis to read with the goal that you will be expanding the research presented here, what would you like to have as housekeeping information and what do you need? Be kind to the future graduate students and to your supervisor who will be the one stuck in the middle trying to find where all the stuff was left!

Bibliography

[1] Cliff Atkinson. *Beyond Bullet Points: Using Microsoft Office PowerPoint 2007 to Create Presentations That Inform.* Microsoft Press, 2008.

[2] Wayne Booth. *The Craft of Research.* University of Chicago Press, 2003.