

Enhancing Reinforcement Learning for MuJoCo Tasks with Dynamic Memory in Tangled Program Graphs

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ABSTRACT

A clear and well-documented \LaTeX document is presented as an article formatted for publication by ACM in a conference proceedings or journal publication. Based on the “acmart” document class, this article presents and explains many of the common variations, as well as many of the formatting elements an author may use in the preparation of the documentation of their work.

KEYWORDS

Do, Not, Us, This, Code, Put, the, Correct, Terms, for, Your, Paper

ACM Reference Format:

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1 INTRODUCTION

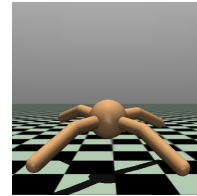
Reinforcement learning (RL) has emerged as a powerful paradigm for training autonomous agents to perform complex tasks. A key challenge in RL is creating agents that can generalize to multiple tasks and environments, a problem known as multi-task learning (MTL). Real-world applications often require agents to adapt to diverse situations, making MTL a critical area of research.

Many existing reinforcement learning algorithms struggle with sample inefficiency, difficulty in handling continuous control, and poor generalization when applied to MuJoCo multi-task learning problems. Deep reinforcement learning methods, while powerful, often require vast amounts of training data and can be computationally expensive [4]. These methods often fail to capture the temporal dependencies and complex dynamics inherent in these environments, leading to sub-optimal performance, especially in partially observable scenarios.

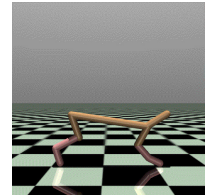
1.1 MuJoCo

A significant domain for RL research, particularly in robotics, is physics simulation. MuJoCo (Multi-Joint dynamics with Contact) is a widely used physics engine, known for its accurate and efficient simulation of complex dynamics, contact forces, and articulated bodies [5]. Its ability to simulate realistic physics and provide diverse, challenging control tasks makes MuJoCo an invaluable tool for developing and evaluating reinforcement learning algorithms

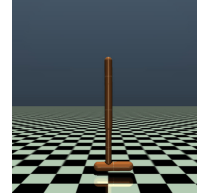
for robotics. The unique MTL and Single-Task Learning (STL) environments formulated in this work includes partially observable versions of the following 6 widely used RL benchmarks found on Gymnasium’s MuJoCo suite [6]: Ant, Half Cheetah, Hopper, Humanoid Standup, Inverted Pendulum, and Inverted Double Pendulum, Figures 1(a) to 1(e).



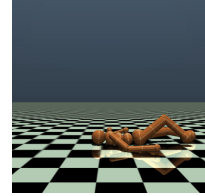
(a) Ant



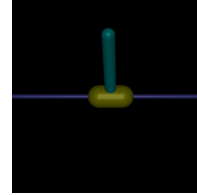
(b) Half Cheetah



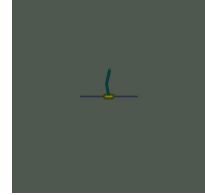
(c) Hopper



(d) Humanoid Standup



(e) Inverted Pendulum



(f) Inverted Double Pendulum

Figure 1: MuJoCo Environments used in this work

1.2 Dynamic memory

Dynamic memory plays a crucial role in evolving program graphs, particularly in multi-task learning (MTL), by providing a flexible and adaptive mechanism for encoding and processing temporal information. Unlike static memory architectures, which impose fixed storage structures, dynamic memory allows each program within an evolving graph to independently adjust its memory representation

based on task demands. This adaptability facilitates more efficient learning and decision-making, ultimately accelerating evolutionary processes.

Dynamic memory within program graphs consists of three primary types:

- **Scalar Memory:** Stores single numerical values, useful for tracking individual state variables.
- **Vector Memory:** Represents data as structured arrays, allowing operations across multiple related values.
- **Matrix Memory:** Enables higher-dimensional representations, which can encode richer state information and facilitate more complex transformations.

Each program selects an appropriate memory type based on its computational needs, and mutations can modify both the type and dimensionality of the memory structures over the course of evolution.

1.3 Tangled Program Graphs

Tangled Program Graphs (TPG) is an RL framework developed by McMaster University’s Creative Algorithm Lab under the guidance of Dr. Stephen Kelly. It leverages genetic programming principles to evolve agents capable of solving complex tasks in dynamic environments. Traditional RL methods, such as deep reinforcement learning (DRL), often rely on neural networks that require significant computational resources and large datasets for training. [1] In contrast, TPG uses genetic programming to evolve agents that can learn and adapt to their environment through a process of selection, mutation, and crossover. This unique approach allows TPG to achieve competitive performance in RL tasks with better computation efficiency than DRL methods. [1]

TPG revolves around the concept of emergent modularity, where agents are composed of interconnected programs that map environmental states to actions. These programs are organized into hierarchical structures, known as program graphs, that allow agents to break complex tasks into simpler subtasks. [3] To incorporate TPG with multi-task learning, an agent will have to be trained to perform multiple tasks sequentially. This is challenging as the agent must balance different objectives and environments while avoiding catastrophic forgetting (learning a new task causes agent to forget previously learned tasks, effectively wasting progress). [3] TPG’s hierarchical and modular structure however, is able to tackle this challenge by allowing agents to dynamically adapt to different tasks by “recombining specialized behaviors”. [3] TPG has been previously used to evolve agents capable of solving six distinct RL benchmarks from OpenAI’s Classic Control suite, including Cart-Pole, Acrobot, and Pendulum. [3] Currently, TPG is being further developed to gauge its capability of integrating multi-task learning with more complex MuJoCo environments.

2 MOTIVATION

The primary motivation behind this research and development effort is to enhance the performance and efficiency of TPG in complex environments, specifically within the MuJoCo physics simulation framework. MuJoCo environments, such as Ant, Half Cheetah, and Humanoid Standup, present significant challenges due to their high-dimensional state and action spaces, as well as their dynamic nature.

These environments require agents to learn proper control policies that generalize across diverse scenarios, making them ideal benchmarks for evaluating the scalability and adaptability of TPG.

The goal is to both improve performance and increase efficiency. Performance will be measured by the best fitness score achieved by the TPG agent, reflecting its ability to maximize cumulative rewards. Efficiency will be measured by the number of generations required for the agent to converge to an optimal state, which also reflects the time and computational resources needed for training. By integrating dynamic memory and optimizing the evolutionary process, this research aims to reduce the time to learn while maintaining or improving the quality of the learned policies.

3 RESEARCH QUESTIONS

The primary parameter given to the “acmart” document class is the *template style* which corresponds to the kind of publication or SIG publishing the work. This parameter is enclosed in square brackets and is a part of the `documentclass` command:

```
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```

Journals use one of three template styles. All but three ACM journals use the `acmsmall` template style:

- `acmsmall`: The default journal template style.
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The majority of conference proceedings documentation will use the `acmconf` template style.

- `sigconf`: The default proceedings template style.
- `sigchi`: Used for SIGCHI conference articles.
- `sigplan`: Used for SIGPLAN conference articles.

4 METHODOLOGY

This study evaluates task performance parameters such as generation time and fitness level through experiments conducted in their respective MuJoCo environments (see Figure 1). The methodology follows a two-phase approach: establishing baselines and integrating dynamic memory. We compare between baseline and dynamic memory-enhanced experiments that were conducted using statistical plots and TPG-generated data. All experiments utilized High Performance Parallel Compute (HPPC) resources provided by the Digital Research Alliance of Canada (“The Alliance”). Each experiment was run with three random seeds for a three-hour duration.

4.1 Baseline Experiments

We conducted single-task and multi-task experiments using the following MuJoCo environments: inverted pendulum, inverted double pendulum, and half-cheetah. Single-task experiments used standardized hyperparameters listed in Table 1. Each experiment was assigned a specific `memory_size` parameter value based on the dimensionality of the observation space, detailed in Table 2.

For multi-task experiments, we utilize the same MuJoCo environments. However, the root team size was increased to 3000, and `n_root_gen` was increased to 300 to accommodate the added complexity of multi-task learning. Two multi-task experiments were conducted:

Table 1: Hyperparameters for MuJoCo environments, single-task team population, and program population

MuJoCo parameters		Team population		Program population	
Parameter	Value	Parameter	Value	Parameter	Value
Max timestep	1000	Agent (root team) population size	1000	Initial program size	10
Reward control weight	0.5	Initial team size	1	p_{delete}	0.2
Number of training evaluations	20	Max team size	10	$p_{\text{add}}, p_{\text{swap}}, p_{\text{mutate}}$	0.25
Number of test evaluations	1	$n_{\text{root_gen}}$	100	mem_{min}	2
Number of validation evaluations	0			mem_{max}	32
				p_{mem}	0.0

Note: $n_{\text{root_gen}}$ denotes the number of new root teams to create each generation. p_x in which $x \in \{\text{add}, \text{delete}, \text{swap}, \text{mutate}\}$ are the probabilities of adding, deleting, swapping, or mutating instructions within a program. p_{mem} is the probability of changing the memory size, mem_{size} , within the mem_{min} and mem_{max} interval.

Table 2: Observation and action space sizes for the considered problems [2]

Environment	Obs. \mathcal{O}	Act. \mathcal{A}
Inverted pendulum	\mathbb{R}^4	$[-3, -3]$
Inverted double pendulum	\mathbb{R}^9	$[-1, 1]$
Half cheetah	\mathbb{R}^{17}	$[-1, 1]$

- (1) **Two-environment multi-task:** Inverted pendulum and inverted double pendulum.
- (2) **Three-environment multi-task:** Inverted pendulum, inverted double pendulum, and half cheetah.

The initial mem_{size} parameter was set to 4 for the two-environment multi-task experiment and 17 for the three-environment multi-task experiment.

4.2 Dynamic Memory Experiments

To evaluate the benefits of adaptive memory allocation, we implemented a dynamic memory strategy by increasing the probability of changing memory size, p_{mem} , to 10% (0.1). The effects of this modification were assessed across the same baseline experiments.

- For single-task experiments, the minimum and maximum values for mem_{size} remained fixed at 2 and 32, respectively.
- For multi-task experiments, the minimum and maximum values for mem_{size} were dynamically adjusted based on the smallest and largest observation space dimensions among the participating environments.

4.3 Data Collection

For each experiment, performance metrics were systematically recorded and extracted from the .std output files, then parsed into structured .csv files. These .csv files were categorized into:

- **Timing Metrics:** Measures of computational timing.
- **Selection Metrics:** Data on operations used, fitness level, and instruction count.
- **Replacement Metrics:** Statistics on team and program numbers.

- **Removal Metrics:** Information on program and team deletions.

Key performance indicators analyzed include:

- **Best Fitness Score:** The highest fitness score achieved during execution.
- **Generations to Convergence:** The number of generations required to reach a specified performance threshold.
- **Effective Program Instructions:** The number of program instructions contributing to the final output.

After data collection, comparative analyses were conducted to evaluate the differences between baseline and dynamic memory configurations across both single-task and multi-task experiments. Visualization techniques, including comparative plots, were used to identify performance trends and assess the impact of dynamic memory integration.

5 BASELINE EXPERIMENTS RESULTS

This section presents the performance outcomes of the baseline experiments conducted in the MuJoCo environments, including single-task and multi-task scenarios. The evaluation metrics focus on **Best Fitness Score** and **Effective Program Instruction Count**, as illustrated in Figures 2 and 3, respectively.

5.1 Best Fitness Score Analysis

The **Best Fitness Score** metric, depicted in Figure 2, provides insights into the overall learning progress of the different experiments. The results highlight several key observations:

- **Single-task environments:** The fitness scores for Half Cheetah and Inverted Pendulum show that while both static and dynamic memory setups improve over time, dynamic memory consistently achieves higher fitness scores faster.
- **Multi-task environments:** Dynamic memory demonstrates a clear advantage, particularly in the Two- and Three-task multi-task setups. It outperforms static memory across generations, highlighting its ability to adapt more effectively to increasing task complexity.

5.2 Program Instruction Count Analysis

Figure 3 presents the results of the **Effective Program Instruction Count**, a key metric reflecting the number of active program instructions contributing to task performance.

- **Single-task environments:** Dynamic environments show more fluctuations in active instruction counts, indicating frequent adaptation for optimization. In contrast, static environments stabilize early, limiting flexibility.
- **Multi-task environments:** The Effective Program Instruction Count is significantly higher in dynamic multi-task setups, suggesting better management of complex learning structures. Static environments struggle to scale efficiently.

6 TYPEFACES

The “acmart” document class requires the use of the “Libertine” typeface family. Your \TeX installation should include this set of packages. Please do not substitute other typefaces. The “lmodern” and “ltimes” packages should not be used, as they will override the built-in typeface families.

7 TITLE INFORMATION

The title of your work should use capital letters appropriately - <https://capitalizemytitle.com/> has useful rules for capitalization. Use the `title` command to define the title of your work. If your work has a subtitle, define it with the `subtitle` command. Do not insert line breaks in your title.

If your title is lengthy, you must define a short version to be used in the page headers, to prevent overlapping text. The `title` command has a “short title” parameter:

```
\title[short title]{full title}
```

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Each author must be defined separately for accurate metadata identification. As an exception, multiple authors may share one affiliation. Authors’ names should not be abbreviated; use full first names wherever possible. Include authors’ e-mail addresses whenever possible.

Grouping authors’ names or e-mail addresses, or providing an “e-mail alias,” as shown below, is not acceptable:

```
\author{Brooke Aster, David Mehldau}
\email{dave,judy,steve@university.edu}
\email{firstname.lastname@phillips.org}
```

The `authornote` and `authornotemark` commands allow a note to apply to multiple authors — for example, if the first two authors of an article contributed equally to the work.

If your author list is lengthy, you must define a shortened version of the list of authors to be used in the page headers, to prevent overlapping text. The following command should be placed just after the last `\author{}` definition:

```
\renewcommand{\shortauthors}{McCartney, et al.}
```

Omitting this command will force the use of a concatenated list of all of the authors’ names, which may result in overlapping text in the page headers.

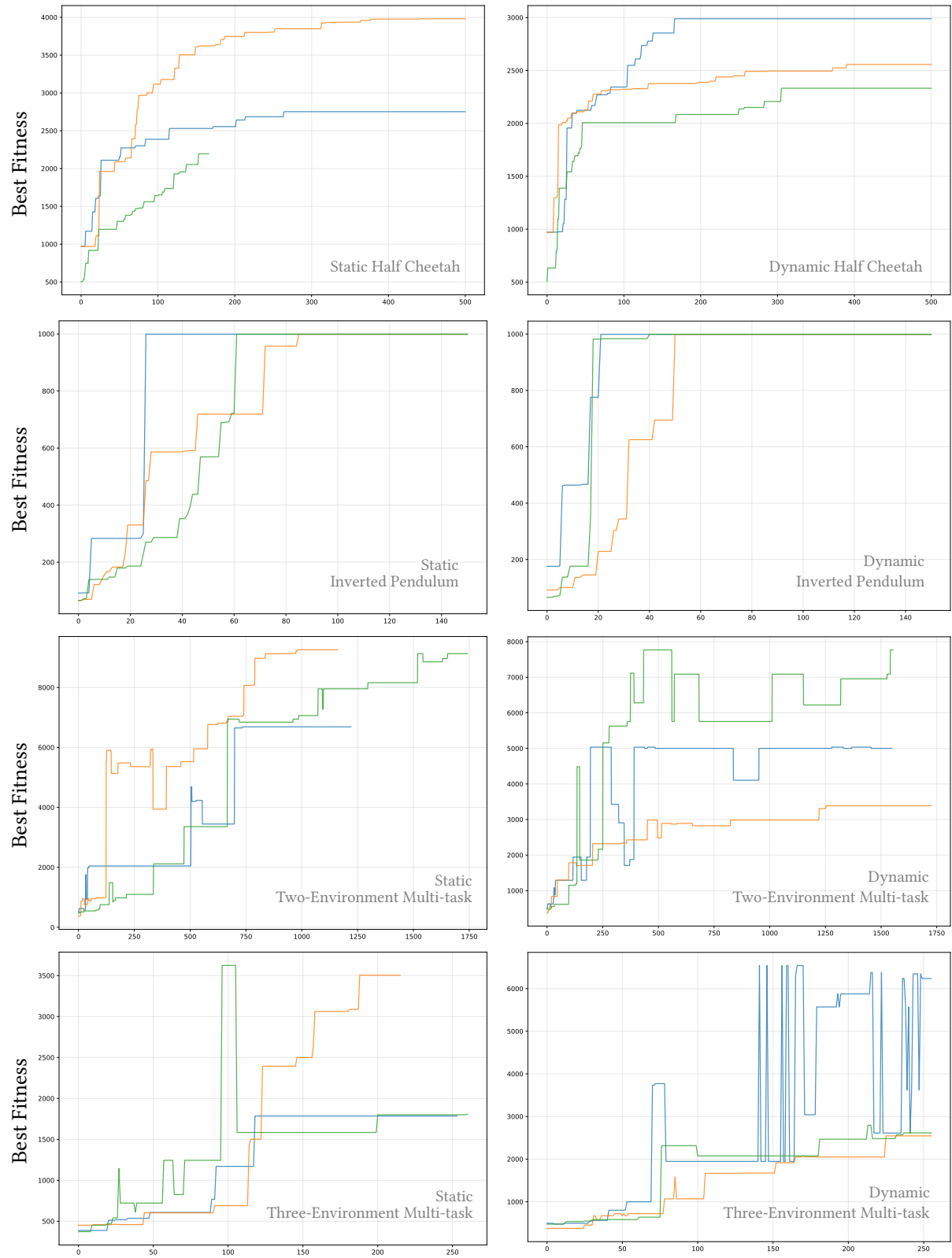


Figure 2: Best Fitness Score results from Single and Multi-task Baseline Experiments

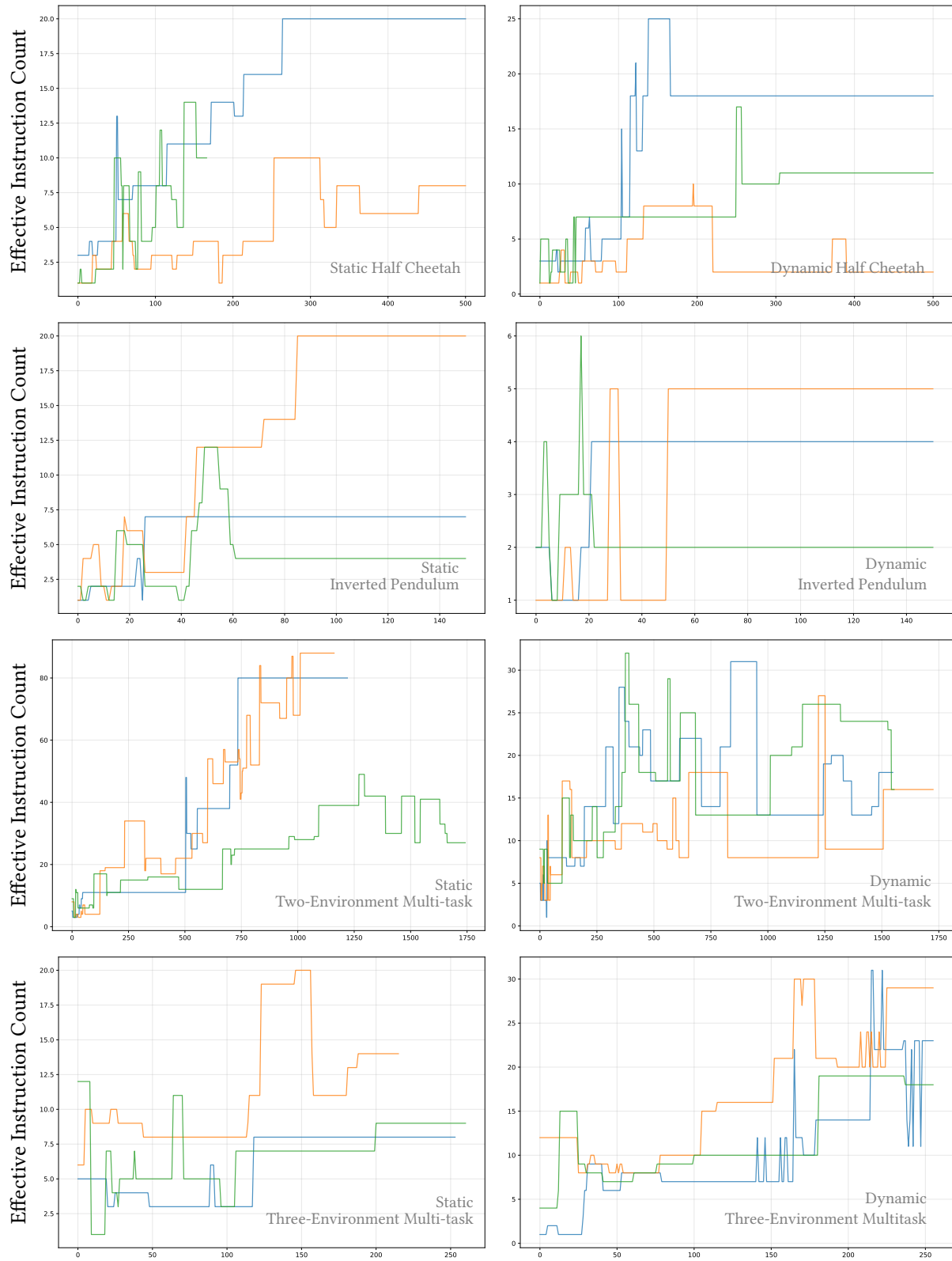


Figure 3: Effective Program Instruction Count results from Single and Multi-task Baseline Experiments

The article template’s documentation, available at <https://www.acm.org/publications/proceedings-template>, has a complete explanation of these commands and tips for their effective use.

Note that authors’ addresses are mandatory for journal articles.

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- the “ACM Reference Format” text on the first page.
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- the conference information in the page header(s).

Rights information is unique to the work; if you are preparing several works for an event, make sure to use the correct set of commands with each of the works.

The ACM Reference Format text is required for all articles over one page in length, and is optional for one-page articles (abstracts).

10 CCS CONCEPTS AND USER-DEFINED KEYWORDS

Two elements of the “acmart” document class provide powerful taxonomic tools for you to help readers find your work in an online search.

The ACM Computing Classification System — <https://www.acm.org/publications/class-2012> — is a set of classifiers and concepts that describe the computing discipline. Authors can select entries from this classification system, via <https://dl.acm.org/ccs/ccs.cfm>, and generate the commands to be included in the \LaTeX source.

User-defined keywords are a comma-separated list of words and phrases of the authors’ choosing, providing a more flexible way of describing the research being presented.

CCS concepts and user-defined keywords are required for for all articles over two pages in length, and are optional for one- and two-page articles (or abstracts).

11 SECTIONING COMMANDS

Your work should use standard \LaTeX sectioning commands: `\section`, `\subsection`, `\subsubsection`, `\paragraph`, and `\subparagraph`. The sectioning levels up to `\subsubsection` should be numbered; do not remove the numbering from the commands.

Simulating a sectioning command by setting the first word or words of a paragraph in boldface or italicized text is **not allowed**.

Below are examples of sectioning commands.

11.1 Subsection

This is a subsection.

11.1.1 *Subsubsection*. This is a subsubsection.

Table 3: Frequency of Special Characters

Non-English or Math	Frequency	Comments
Ø	1 in 1,000	For Swedish names
π	1 in 5	Common in math
\$	4 in 5	Used in business
Ψ_1^2	1 in 40,000	Unexplained usage

Paragraph. This is a paragraph.
 Subparagraph This is a subparagraph.

12 TABLES

The “acmart” document class includes the “booktabs” package — <https://ctan.org/pkg/booktabs> — for preparing high-quality tables.

Table captions are placed *above* the table.

Because tables cannot be split across pages, the best placement for them is typically the top of the page nearest their initial cite. To ensure this proper “floating” placement of tables, use the environment **table** to enclose the table’s contents and the table caption. The contents of the table itself must go in the **tabular** environment, to be aligned properly in rows and columns, with the desired horizontal and vertical rules. Again, detailed instructions on **tabular** material are found in the *\LaTeX User’s Guide*.

Immediately following this sentence is the point at which Table 3 is included in the input file; compare the placement of the table here with the table in the printed output of this document.

To set a wider table, which takes up the whole width of the page’s live area, use the environment **table*** to enclose the table’s contents and the table caption. As with a single-column table, this wide table will “float” to a location deemed more desirable. Immediately following this sentence is the point at which Table 4 is included in the input file; again, it is instructive to compare the placement of the table here with the table in the printed output of this document.

Always use `midrule` to separate table header rows from data rows, and use it only for this purpose. This enables assistive technologies to recognise table headers and support their users in navigating tables more easily.

13 MATH EQUATIONS

You may want to display math equations in three distinct styles: inline, numbered or non-numbered display. Each of the three are discussed in the next sections.

13.1 Inline (In-text) Equations

A formula that appears in the running text is called an inline or in-text formula. It is produced by the **math** environment, which can be invoked with the usual `\begin . . . \end` construction or with the short form `$. . . $`. You can use any of the symbols and structures, from α to ω , available in examples of in-text equations in context. Notice how this equation: $\lim_{n \rightarrow \infty} x = 0$, set here in in-line math style, looks slightly different when set in display style. (See next section).

Table 4: Some Typical Commands

Command	A Number	Comments
<code>\author</code>	100	Author
<code>\table</code>	300	For tables
<code>\table*</code>	400	For wider tables

13.2 Display Equations

A numbered display equation—one set off by vertical space from the text and centered horizontally—is produced by the **equation** environment. An unnumbered display equation is produced by the **displaymath** environment.

Again, in either environment, you can use any of the symbols and structures available in \LaTeX ; this section will just give a couple of examples of display equations in context. First, consider the equation, shown as an inline equation above:

$$\lim_{n \rightarrow \infty} x = 0 \quad (1)$$

Notice how it is formatted somewhat differently in the **displaymath** environment. Now, we'll enter an unnumbered equation:

$$\sum_{i=0}^{\infty} x + 1$$

and follow it with another numbered equation:

$$\sum_{i=0}^{\infty} x_i = \int_0^{\pi+2} f \quad (2)$$

just to demonstrate \LaTeX 's able handling of numbering.

14 FIGURES

The “figure” environment should be used for figures. One or more images can be placed within a figure. If your figure contains third-party material, you must clearly identify it as such, as shown in the example below.

Your figures should contain a caption which describes the figure to the reader.

Figure captions are placed *below* the figure.

Every figure should also have a figure description unless it is purely decorative. These descriptions convey what's in the image to someone who cannot see it. They are also used by search engine crawlers for indexing images, and when images cannot be loaded.

A figure description must be unformatted plain text less than 2000 characters long (including spaces). **Figure descriptions should not repeat the figure caption – their purpose is to capture important information that is not already provided in the caption or the main text of the paper.** For figures that convey important and complex new information, a short text description may not be adequate. More complex alternative descriptions can be placed in an appendix and referenced in a short figure description. For example, provide a data table capturing the information in a bar chart, or a structured list representing a graph. For additional information regarding how best to write figure descriptions and why doing this is so important, please see <https://www.acm.org/publications/taps/describing-figures/>.



Figure 4: 1907 Franklin Model D roadster. Photograph by Harris & Ewing, Inc. [Public domain], via Wikimedia Commons. (<https://goo.gl/VLCRBB>).

14.1 The “Teaser Figure”

A “teaser figure” is an image, or set of images in one figure, that are placed after all author and affiliation information, and before the body of the article, spanning the page. If you wish to have such a figure in your article, place the command immediately before the `\maketitle` command:

```
\begin{teaserfigure}
  \includegraphics[width=\textwidth]{sampleteaser}
  \caption{figure caption}
  \Description{figure description}
\end{teaserfigure}
```

15 CITATIONS AND BIBLIOGRAPHIES

The use of Bib \TeX for the preparation and formatting of one's references is strongly recommended. Authors' names should be complete — use full first names (“Donald E. Knuth”) not initials (“D. E. Knuth”) — and the salient identifying features of a reference should be included: title, year, volume, number, pages, article DOI, etc.

The bibliography is included in your source document with these two commands, placed just before the `\end{document}` command:

```
\bibliographystyle{ACM-Reference-Format}
\bibliography{bibfile}
```

where “bibfile” is the name, without the “.bib” suffix, of the Bib \TeX file.

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```
\citestyle{acmauthoryear}
```

16 ACKNOWLEDGMENTS

Identification of funding sources and other support, and thanks to individuals and groups that assisted in the research and the preparation of the work should be included in an acknowledgment section, which is placed just before the reference section in your document.

This section has a special environment:

```
\begin{acks}
...
\end{acks}
```

so that the information contained therein can be more easily collected during the article metadata extraction phase, and to ensure consistency in the spelling of the section heading.

Authors should not prepare this section as a numbered or unnumbered \section; please use the “acks” environment.

17 APPENDICES

If your work needs an appendix, add it before the “\end{document}” command at the conclusion of your source document.

Start the appendix with the “appendix” command:

```
\appendix
```

and note that in the appendix, sections are lettered, not numbered. This document has two appendices, demonstrating the section and subsection identification method.

18 MULTI-LANGUAGE PAPERS

Papers may be written in languages other than English or include titles, subtitles, keywords and abstracts in different languages (as a rule, a paper in a language other than English should include an English title and an English abstract). Use `language=...` for every language used in the paper. The last language indicated is the main language of the paper. For example, a French paper with additional titles and abstracts in English and German may start with the following command

```
\documentclass[sigconf, language=english, language=german,
language=french]{acmart}
```

The title, subtitle, keywords and abstract will be typeset in the main language of the paper. The commands `\translatedXXX`, `XXX` begin title, subtitle and keywords, can be used to set these elements in the other languages. The environment `translatedabstract` is used to set the translation of the abstract. These commands and environment have a mandatory first argument: the language of the second argument. See `sample-sigconf-i13n.tex` file for examples of their usage.

19 SIGCHI EXTENDED ABSTRACTS

The “sigchi-a” template style (available only in \LaTeX and not in Word) produces a landscape-orientation formatted article, with a

wide left margin. Three environments are available for use with the “sigchi-a” template style, and produce formatted output in the margin:

sidebar: Place formatted text in the margin.

marginfigure: Place a figure in the margin.

marginfigure: Place a table in the margin.

ACKNOWLEDGMENTS

To Dr. Stephen Kelly, for guiding us throughout the research process and providing valuable insights and feedback.

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A RESEARCH METHODS

A.1 Part One

Lorem ipsum dolor sit amet, onsectetur adipiscing elit. Morbi malesuada, quam in pulvinar varius, metus nunc fermentum urna, id sollicitudin purus odio sit amet enim. Aliquam ullamcorper eu ipsum vel mollis. Curabitur quis dictum nisl. Phasellus vel semper risus, et lacinia dolor. Integer ultricies commodo sem nec semper.

A.2 Part Two

Etiam commodo feugiat nisl pulvinar pellentesque. Etiam auctor sodales ligula, non varius nibh pulvinar semper. Suspendisse nec lectus non ipsum convallis congue hendrerit vitae sapien. Donec at laoreet eros. Vivamus non purus placerat, scelerisque diam eu, cursus ante. Etiam aliquam tortor auctor efficitur mattis.

B ONLINE RESOURCES

Nam id fermentum dui. Suspendisse sagittis tortor a nulla mollis, in pulvinar ex pretium. Sed interdum orci quis metus euismod, et sagittis enim maximus. Vestibulum gravida massa ut felis suscipit congue. Quisque mattis elit a risus ultrices commodo venenatis eget dui. Etiam sagittis eleifend elementum.

Nam interdum magna at lectus dignissim, ac dignissim lorem rhoncus. Maecenas eu arcu ac neque placerat aliquam. Nunc pulvinar massa et mattis lacinia.

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