Reinforcement Learning for Cooperative Multi-Agent Systems

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Abstract

With the advances of robotics, autonomous vehicles, and other notable reinforcement learning (RL) applications in recent years, multi-agent RL (MARL) has reemerged with the advances in single-agent RL. As an interdisciplinary research area that includes learning, game theory, communication, and optimization, there are many technics come with challenges and restrictions in different MARL settings, MARL-related subareas, and theoretical foundation lackings. The centralized traning and decentralized execution (CTDE) paradigm is used to tackle communication problems as it enables agents to share information during training and somehow reduce other concerns on nonstationarity and partial observability. However, as CTDE is under homogeneous settings, this paradigm may be not beneficial in a more general multi-agent setting with heterogeneous agents, which means agents are not the same on capabilities and goals. In this short paper which mainly focuses on cooperative MARL, I will provide problems background, introduce selective current challenges, and propose potential directions for future solutions.

Background

In this section, I will review the theoretical methods from single-agent RL to MARL, especially methods related to cooperative MARL settings.

Markov Decision Process.
For a reinforcement leaning question, we can formulate it as a infinite-horizon discounted Markov Decision Process (MDP). An MDP is defined by a quintuiple $(\mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{R}, \gamma)$, where $\mathcal{S}$ is the set of states; $\mathcal{A}$ is the set of actions; $\mathcal{P} : \mathcal{S} \times \mathcal{A} \to \mathcal{S}$ denotes the set of possibility from a state $s \in \mathcal{S}$ to a state $s' \in \mathcal{S}$, given a action $a \in \mathcal{A}$; $\mathcal{R} : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \to \mathbb{R}$ is the immediate reward function for agents tranfer from (s, a) to s'; $\gamma \in [0, 1)$ is the discount factor.
At time t, the agent in state s_t executes an action a_t by following the policy $\pi : \pi(a|s)$, which is a mapping from states $\mathcal{S}$ to actions $\mathcal{A}$. The system transit from state s_t to the next state $s_{t+1} \sim \mathcal{P}(\cdot|s_t, a_t)$. For MDPs, the goal is to find the optimal policy π to maximize $a_t \sim \pi(\cdot|s_t)$ and the accumulated rewards

$$\mathbb{E}\left[\sum_{t\geq 0}\gamma^t\mathcal{R}(s_t, a_t, s_{t+1})\middle| a_t \sim \pi(\cdot|s_t), s_0\right].$$

Accordingly, given policy π, for any $s \in \mathcal{S}$ and $a \in \mathcal{A}$, we could define the *action-value function* (the Q-function), which is starting from $(s_0, a_0) = (s, a)$, as

$$Q_\pi(s, a) = \mathbb{E}\left[\sum_{t\geq 0}\gamma^t\mathcal{R}(s_t, a_t, s_{t+1})\middle| a_t \sim \pi(\cdot|s_t), a_0 = a, s_0 = s\right],$$

and the *state-value function* (the V-function), starting from $s_0 = s$, as

$$V_\pi(s, a) = \mathbb{E}\left[\sum_{t\geq 0}\gamma^t\mathcal{R}(s_t, a_t, s_{t+1})\middle| a_t \sim \pi(\cdot|s_t), s_0 = s\right]$$

π^* are referred to the optimal policy as the optimal Q-function and V-function respextively. By virtue if the Markov property, the optimal function could be obtained by iteration based on dynamic programming (DP), which is usually required of the complete knowledge of the model.

Value-Based Methods.
The value-based methods are mainly to find the estimate of the optimal Q-function Q^*_π. One famous value-based algorithm is Monte-Carlo tree search (MCTS), which is used under the imcomplete environment knowledge. In this method, a monte carlo simulation is executed based on a search tree to estimate the optimal value function.
Temporal-Difference (TD) learning method is a combination of MCTS and DP. It learns the estimates partially based on estimates, which is known as *bootstrapping*. As model free methods, TD methods are implemented more naturally than MCTS and DP with a online and fully incremental way.
Q-learning is one of the most important value-based method, which is actuall an off-policy TD control. The optimal policy can be approximated by taking the greedy action of estimation of the Q-value function $\hat{Q}(s, a)$. The Q-function is updated according to

$$\hat{Q}(s, a) \leftarrow \hat{Q}(s, a) + \alpha\left[r + \gamma\max_{a'}\hat{Q}(s', a') - \hat{Q}(s, a)\right]$$

with the loss funciton

$$\mathcal{L}(s, a, r, s') = (r + \gamma\max_{a'}Q(s', a') - Q(s, a))^2.$$

Policy-Based Methods.
The main idea in policy-based method is to update the parameter by following the gradient direction, which is known as policy gradient (PG). The closed-form of PG is given as

$$\nabla J(\theta) = \mathbb{E}_{a\sim\pi_\theta(\cdot|s),s\sim\eta_{\pi_\theta}(\cdot)}\Big[\mathcal{Q}_{\pi_\theta}(s,a)\nabla log\pi_\theta(a|s)\Big],$$

where $J(\theta)$ and $\mathcal{Q}_\pi$ are the expected reward and Q-function with following policy π_θ, respectively, $\pi_\theta(\cdot|s)$ is the approximation of $\pi(\cdot|s)$, η_{π_θ} is the measurement of state occpancy, and $\nabla log\pi_\theta(a|s)$ is the score of the policy.
Compared with value based methods, policy based one are more powerful with better convergence guarantees with neural networks for function approximation, which is a fashion today with the rise of Deep Learning (DL). And policy-based method are believed to have the ability to handle bigger discrete or even continuous state-action spaces.

Markov Games.
Markov games (MGs), which is also known as stochastic games, is originally a framework for MDP in multi-agent settings. A markov game is defined by a tuple $(\mathcal{N},\mathcal{S},\{\mathcal{A}^i\}_{i\in\mathcal{N}},\mathcal{P},\{\mathcal{R}^i\}_{i\in\mathcal{N}},\gamma)$, where $\mathcal{N}=\{1,\cdots,N\}$ denotes the set of N agents, $\mathcal{S}$ denotes the globally observed state space by the whole system, $\mathcal{A}^i$ denotes the action space of agent i, $\mathcal{P}:\mathcal{S}\times\{\mathcal{A}:=\mathcal{A}^1\times\cdots\times\mathcal{A}^N\}\to\Delta(\mathcal{S})$ denotes the transition probability from any state $s\in\mathcal{S}$ to any state $s'\in\mathcal{S}$ denotes the possibility distribution for mapping from any state $s\in\mathcal{S}$ to any state $s'\in\mathcal{S}$ via any joint action $a\in\mathcal{A}$, $\mathcal{R}^i:\mathcal{S}\times\mathcal{A}\times\mathcal{S}\to\mathbb{R}$ denotes the immediate reward received by agent i via a transition from (s,a) to s', $\gamma\in[0,1)$ denotes the discount factor.
From time t to time $t+1$, agent $i\in\mathcal{N}$ executes action a_t^i, the system will transites from s_t to s_{t+1}, and all agents get immediate reward by $R^i(s_t,a_t,s_{t+1})$. For every individual agent i, the goal is to maximize its own reward in a long finite horizon or infinite horizon by finding the optimal policy $\pi^i:\mathcal{S}\to\Delta(\mathcal{A}^i)$ so that $a_t^i\sim\pi^i(\cdot|s_t)$. The joint policy $\pi:\mathcal{S}\to\Delta(\mathcal{A})$ is $\pi(a|s):=\prod_{i\in\mathcal{N}}\pi^i(a^i|s)$. For any state $s\in\mathcal{S}$ and joint policy π,

$$V^i_{\pi^i,\pi^{-i}}(s) := \mathbb{E}\left[\sum_{t\geq 0}\gamma^t R^i(s_t,a_t,s_{t+1})\middle| a_t^i\sim\pi^i(\cdot|s_t),s_0=s\right],$$

where $-i$ denotes the indices of all other agents in $\mathcal{N}$ except agent i. A nash equilibrium (NE) of a *markov game* $(\mathcal{N},\mathcal{S},\{\mathcal{A}^i\}_{i\in\mathcal{N}},\mathcal{P},\{\mathcal{R}^i\}_{i\in\mathcal{N}},\gamma)$ is a joint policy $\pi^*=(\pi^{1,*},\cdots,\pi^{N,*})$ so that for any $s\in\mathcal{S}$, $i\in\mathcal{N}$, and π^*

$$V^i_{\pi^{i,*},\pi^{-i,*}}(s)\geq V^i_{\pi^i,\pi^{-i,*}}(s)$$

The nash quilibrium point π^* is a fixed point so that all agent won't transite to a better point as there is not any incentive to do so. For any agent $i\in\mathcal{N}$, $\pi^{i,*}$ is the best response to $\pi^{-i,*}$. For MARL settings, finding the NE is a standard learning goal and NE always exists for finite-space infinite-horizon discounted MGs (Filar and Vrieze 2012).

Cooperative Settings.
In this short paper, we only consider cooperative settings which mean all the agents collaborate with each other to achieve shared goal. In a fully cooperative setting, all agents share one reward function $\mathcal{R}^1=\mathcal{R}^2=\cdots=\mathcal{R}^N=\mathcal{R}$. With this model, the Q-function is identical to all agents so that Q-learning updates could be applied with taking the max over the joint action space $a'\in\mathcal{A}$. In a more general cooperative setting, agents have their own reward function and the goal is to optimize the long-term reward for all agents. One common reward model is *team-averager* reward $\bar{R}(s,a,s'):=N^{-1}\cdot\sum_{i\in\mathcal{N}}R^i(s,a,s')$ for any $(s,a,s')\in\mathcal{S}\times\mathcal{A}\times\mathcal{S}$.

Partial Observability.
In multi-agent settings, we can not ignore the influence from the real environment, the noise and limited sensors may prevent the agent from abserving the state of the environment (Oliehoek and Amato 2016). However, MGs can only handle the fully observed environment. In this case, *Partially Observable Markov Decision Process* (POMDP) is more suitable to represent such state uncertainty by incorporating observations and their probability of occurrence conditional on the state of the environment (Kaelbling, Littman, and Cassandra 1998). More generally speaking, this partially observed setting can be modeled by a decentralized POMDP (Dec-POMDP), which shares most of the elements, including the reward function and the trasition model. Based on MGs, a Dec-POMDP is formally defined by the tuple $(\mathcal{N},\mathcal{S},\{\mathcal{A}^i\}_{i\in\mathcal{N}},\mathcal{P},\{\mathcal{R}^i\}_{i\in\mathcal{N}},\mathcal{Z},\mathcal{O},\gamma)$, where $\mathcal{Z}:=\{\mathcal{Z}^1\times\cdots\times\mathcal{Z}^N\}$ denotes the joint abservations, $\mathcal{O}:\mathcal{S}\times\mathcal{A}\to\mathcal{Z}$ denotes the observation probabilities, the others denotation remain the same as MGs. Under this setting. At time t, agent i has its *action-observation* history $\mathcal{H}_i:=[\mathcal{O}_{i,1},\mathcal{A}_{i,1},\cdots\mathcal{O}_{i,t-1},\mathcal{A}_{i,t-1}]$, $\mathcal{H}_i\in\mathcal{H}$, and a stochastic policy for agent i is $\pi^i(\mathcal{A}^i|\mathcal{H}^i)$. Given the history $\mathcal{H}$, the goal for each agent is to maximize its expected discounted rewards in a long term.

Challenges

The challenges in *Cooperative Multi-Agent Reinforcement Learning* (CMARL) not only lie in problems with the models based on MDP but also in the different training schemes and the lacking of theoretical foundations. In this session, I will cover several ones in this research area.

Non-Stationarity.
In CMARL, one major issue is that the environment for each agent is non-stationary during the learning process as other agents are learning at the same time. One agent's action influences other agents' reward functions and the transition functions. In single agent RL, the stationarity Markovian property is assumed so that the convergence could be guaranteed. However, in CMARL settings, the agents need to model other agents' behavior and adapt to the *joint behavior*.

Scalability.
In CMARL settings, each agent need to make decision based on *joint action space* which grows rapidly with the increasing number of agents. The curse of dimensionanity

in MARL leads to exponential computaitonal complexity.

Non-Unique Learning Goals.

Heterogeneous Settings.

Related Work

Proposed Methods

Conclusion

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Any credits to a sponsoring agency should appear in the acknowledgments section, unless the agency requires different

placement. If it is necessary to include this information on the front page, use \thanks in either the \author or \title commands. For example:

> \title{Very Important Results in AI\thanks{This work is supported by everybody.}}

Multiple \thanks commands can be given. Each will result in a separate footnote indication in the author or title with the corresponding text at the botton of the first column of the document. Note that the \thanks command is fragile. You will need to use \protect.

Please do not include \pubnote commands in your document.

Abstract

Follow the example commands in this document for creation of your abstract. The command \begin{abstract} will automatically indent the text block. Please do not indent it further. Do not include references in your abstract!

Page Numbers

Do not **ever** print any page numbers on your paper. The use of \pagestyle is forbidden.

Text

The main body of the paper must be formatted in black, ten-point Times Roman with twelve-point leading (line spacing). You may not reduce font size or the linespacing. Commands that alter font size or line spacing (including, but not limited to baselinestretch, baselineshift, linespread, and others) are expressly forbidden. In addition, you may not use color in the text.

Citations

Citations within the text should include the author's last name and year, for example (Newell 1980). Append lowercase letters to the year in cases of ambiguity. Multiple authors should be treated as follows: (Feigenbaum and Engelmore 1988) or (Ford, Hayes, and Glymour 1992). In the case of four or more authors, list only the first author, followed by et al. (Ford et al. 1997).

Extracts

Long quotations and extracts should be indented ten points from the left and right margins.

> This is an example of an extract or quotation. Note the indent on both sides. Quotation marks are not necessary if you offset the text in a block like this, and properly identify and cite the quotation in the text.

Footnotes

Avoid footnotes as much as possible; they interrupt the reading of the text. When essential, they should be consecutively numbered throughout with superscript Arabic numbers. Footnotes should appear at the bottom of the page, separated from the text by a blank line space and a thin, half-point rule.

Headings and Sections

When necessary, headings should be used to separate major sections of your paper. Remember, you are writing a short paper, not a lengthy book! An overabundance of headings will tend to make your paper look more like an outline than a paper. The aaai22.sty package will create headings for you. Do not alter their size nor their spacing above or below.

Section Numbers. The use of section numbers in AAAI Press papers is optional. To use section numbers in LaTeX, uncomment the setcounter line in your document preamble and change the 0 to a 1. Section numbers should not be used in short poster papers and/or extended abstracts.

Section Headings. Sections should be arranged and headed as follows:

1. Main content sections
2. Appendices (optional)
3. Ethical statement (optional, unnumbered)
4. Acknowledgements (optional, unnumbered)
5. References (unnumbered)

Appendices. Any appendices must appear after the main content. If your main sections are numbered, appendix sections must use letters instead of arabic numerals. In LaTeX you can use the `\appendix` command to achieve this effect and then use `\section{Heading}` normally for your appendix sections.

Ethical statement. You can write a statement about the potential ethical impact of your work, including its broad societal implications, both positive and negative. If included, such statement must be written in an unnumbered section titled *Ethical statement*.

Acknowledgments. The acknowledgments section, if included, appears right before the references and is headed "Acknowledgments". It must not be numbered even if other sections are (use `\section*{Acknowledgements}` in LaTeX). This section includes acknowledgments of help from associates and colleagues, credits to sponsoring agencies, financial support, and permission to publish. Please acknowledge other contributors, grant support, and so forth, in this section. Do not put acknowledgments in a footnote on the first page. If your grant agency requires acknowledgment of the grant on page 1, limit the footnote to the required statement, and put the remaining acknowledgments at the back. Please try to limit acknowledgments to no more than three sentences.

References. The references section should be labeled "References" and must appear at the very end of the paper (don't end the paper with references, and then put a figure by itself on the last page). A sample list of references is given later on in these instructions. Please use a consistent format for references. Poorly prepared or sloppy references reflect badly on the quality of your paper and your research. Please prepare complete and accurate citations.

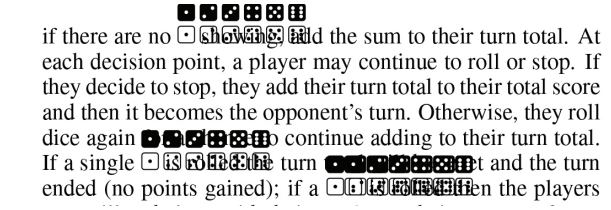

Figure 1: Using the trim and clip commands produces fragile layers that can result in disasters (like this one from an actual paper) when the color space is corrected or the PDF combined with others for the final proceedings. Crop your figures properly in a graphics program – not in LaTeX

.

Illustrations and Figures

Your paper must compile in PDFLaTeX. Consequently, all your figures must be .jpg, .png, or .pdf. You may not use the .gif (the resolution is too low), .ps, or .eps file format for your figures.

Figures, drawings, tables, and photographs should be placed throughout the paper on the page (or the subsequent page) where they are first discussed. Do not group them together at the end of the paper. If placed at the top of the paper, illustrations may run across both columns. Figures must not invade the top, bottom, or side margin areas. Figures must be inserted using the \usepackage{graphicx}. Number figures sequentially, for example, figure 1, and so on. Do not use minipage to group figures.

If you normally create your figures using pgfplots, please create the figures first, and then import them as pdfs with proper bounding boxes, as the bounding and trim boxes created by pfgplots are fragile and not valid.

When you include your figures, you must crop them **outside** of LaTeX. The command \includegraphics*[clip=true, viewport 0 0 10 10]... might result in a PDF that looks great, but the image is **not really cropped.** The full image can reappear (and obscure whatever it is overlapping) when page numbers are applied or color space is standardized. Figures 1, and 2 display some unwanted results that often occur.

If your paper includes illustrations that are not compatible with PDFTeX (such as .eps or .ps documents), you will need to convert them. The epstopdf package will usually work for eps files. You will need to convert your ps files to PDF in either case.

Figure Captions. The illustration number and caption must appear *under* the illustration. Labels and other text with the actual illustration must be at least nine-point type. However, the font and size of figure captions must be 10 point roman. Do not make them smaller, bold, or italic. (Individual words may be italicized if the context requires differentiation.)

Tables

Tables should be presented in 10 point roman type. If necessary, they may be altered to 9 point type. You may not use any commands that further reduce point size below nine points. Tables that do not fit in a single column must be placed across double columns. If your table won't fit within the margins even when spanning both columns, you must split it. Do not use minipage to group tables.

Table Captions. The number and caption for your table must appear *under* (not above) the table. Additionally, the font and size of table captions must be 10 point roman and must be placed beneath the figure. Do not make them smaller, bold, or italic. (Individual words may be italicized if the context requires differentiation.)

Low-Resolution Bitmaps. You may not use low-resolution (such as 72 dpi) screen-dumps and GIF files—these files contain so few pixels that they are always blurry, and illegible when printed. If they are color, they will become an indecipherable mess when converted to black and white. This is always the case with gif files, which should never be used. The resolution of screen dumps can be increased by reducing the print size of the original file while retaining the same number of pixels. You can also enlarge files by manipulating them in software such as PhotoShop. Your figures should be 300 dpi when incorporated into your document.

LaTeX Overflow. LaTeX users please beware: LaTeX will sometimes put portions of the figure or table or an equation in the margin. If this happens, you need to make the figure or table span both columns. If absolutely necessary, you may reduce the figure, or reformat the equation, or reconfigure the table. **Check your log file!** You must fix any overflow into the margin (that means no overfull boxes in LaTeX). **Nothing is permitted to intrude into the margin or gutter.**

Using Color. Use of color is restricted to figures only. It must be WACG 2.0 compliant. (That is, the contrast ratio must be greater than 4.5:1 no matter the font size.) It must be CMYK, NOT RGB. It may never be used for any portion of the text of your paper. The archival version of your paper will be printed in black and white and grayscale. The web version must be readable by persons with disabilities. Consequently, because conversion to grayscale can cause undesirable effects (red changes to black, yellow can disappear, and so forth), we strongly suggest you avoid placing color figures in your document. If you do include color figures, you must (1) use the CMYK (not RGB) colorspace and (2) be mindful of readers who may happen to have trouble distinguishing colors. Your paper must be decipherable without using color for distinction.

Drawings. We suggest you use computer drawing software (such as Adobe Illustrator or, (if unavoidable), the drawing tools in Microsoft Word) to create your illustrations. Do not use Microsoft Publisher. These illustrations will look best if all line widths are uniform (half- to two-point in size), and you do not create labels over shaded areas. Shading should be 133 lines per inch if possible. Use Times Roman or Helvetica for all figure call-outs. **Do not use hairline width lines** — be sure that the stroke width of all lines is at least .5 pt. Zero point lines will print on a laser

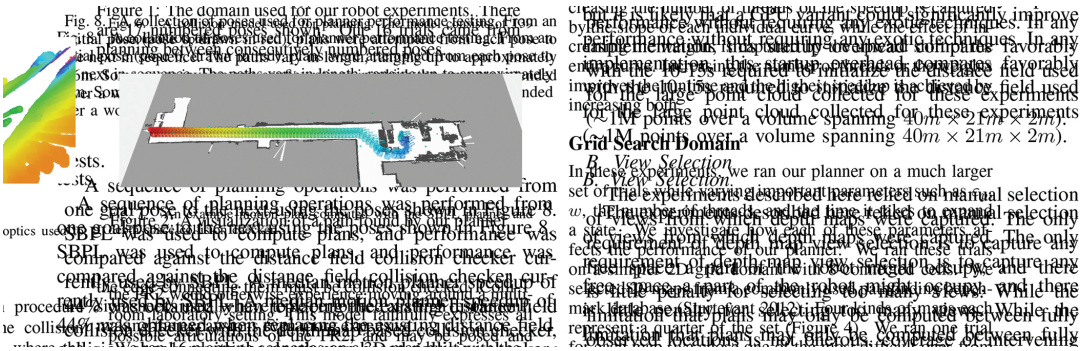

Figure 2: Adjusting the bounding box instead of actually removing the unwanted data resulted multiple layers in this paper. It also needlessly increased the PDF size. In this case, the size of the unwanted layer doubled the paper's size, and produced the following surprising results in final production. Crop your figures properly in a graphics program. Don't just alter the bounding box.

printer, but will completely disappear on the high-resolution devices used by our printers.

Photographs and Images. Photographs and other images should be in grayscale (color photographs will not reproduce well; for example, red tones will reproduce as black, yellow may turn to white, and so forth) and set to a minimum of 300 dpi. Do not prescreen images.

Resizing Graphics. Resize your graphics **before** you include them with LaTeX. You may **not** use trim or clip options as part of your \includegraphics command. Resize the media box of your PDF using a graphics program instead.

Fonts in Your Illustrations. You must embed all fonts in your graphics before including them in your LaTeX document.

Algorithms. Algorithms and/or programs are a special kind of figures. Like all illustrations, they should appear floated to the top (preferably) or bottom of the page. However, their caption should appear in the header, left-justified and enclosed between horizontal lines, as shown in Algorithm 1. The algorithm body should be terminated with another horizontal line. It is up to the authors to decide whether to show line numbers or not, how to format comments, etc.

In LaTeX algorithms may be typeset using the `algorithm` and `algorithmic` packages, but you can also use one of the many other packages for the task.

Listings. Listings are much like algorithms and programs. They should also appear floated to the top (preferably) or bottom of the page. Listing captions should appear in the header, left-justified and enclosed between horizontal lines as shown in Listing 1. Terminate the body with another horizontal line and avoid any background color. Line numbers, if included, must appear within the text column.

Algorithm 1: Example algorithm

Input: Your algorithm's input
Parameter: Optional list of parameters
Output: Your algorithm's output

Let $t = 0$.
while condition **do**
  Do some action.
  if conditional **then**
    Perform task A.
  else
    Perform task B.
  end if
end while
return solution

Listing 1: Example listing `quicksort.hs`

```
quicksort :: Ord a => [a] -> [a]
quicksort []     = []
quicksort (p:xs) = (quicksort lesser) ++
      [p] ++ (quicksort greater)
  where
    lesser  = filter (< p) xs
    greater = filter (>= p) xs
```

References

The AAAI style includes a set of definitions for use in formatting references with BibTeX. These definitions make the bibliography style fairly close to the ones specified in the Reference Examples appendix below. To use these definitions, you also need the BibTeX style file "aaai22.bst," available in the AAAI Author Kit on the AAAI web site. Then, at the end of your paper but before \enddocument, you need to put the following lines:

\bibliography{bibfile1,bibfile2,...}

Please note that the aaai22.sty class already sets the bibliographystyle for you, so you do not have to place any \bibliographystyle command in the document yourselves. The aaai22.sty file is incompatible with the hyperref and navigator packages. If you use either, your references will be garbled and your paper will be returned to you.

References may be the same size as surrounding text. However, in this section (only), you may reduce the size to

\small if your paper exceeds the allowable number of pages. Making it any smaller than 9 point with 10 point linespacing, however, is not allowed. A more precise and exact method of reducing the size of your references minimally is by means of the following command:

\fontsize{9.8pt}{10.8pt} \selectfont

You must reduce the size equally for both font size and line spacing, and may not reduce the size beyond {9.0pt}{10.0pt}.

The list of files in the \bibliography command should be the names of your BibTeX source files (that is, the .bib files referenced in your paper).

The following commands are available for your use in citing references:

cite: Cites the given reference(s) with a full citation. This appears as "(Author Year)" for one reference, or "(Author Year; Author Year)" for multiple references.

shortcite: Cites the given reference(s) with just the year. This appears as "(Year)" for one reference, or "(Year; Year)" for multiple references.

citeauthor: Cites the given reference(s) with just the author name(s) and no parentheses.

citeyear: Cites the given reference(s) with just the date(s) and no parentheses.

You may also use any of the *natbib* citation commands.

Proofreading Your PDF

Please check all the pages of your PDF file. The most commonly forgotten element is the acknowledgements — especially the correct grant number. Authors also commonly forget to add the metadata to the source, use the wrong reference style file, or don't follow the capitalization rules or comma placement for their author-title information properly. A final common problem is text (expecially equations) that runs into the margin. You will need to fix these common errors before submitting your file.

Improperly Formatted Files

In the past, AAAI has corrected improperly formatted files submitted by the authors. Unfortunately, this has become an increasingly burdensome expense that we can no longer absorb). Consequently, if your file is improperly formatted, it will be returned to you for correction.

LaTeX 209 Warning

If you use LaTeX 209 your paper will be returned to you unpublished. Convert your paper to LaTeX2e.

Naming Your Electronic File

We require that you name your LaTeX source file with the last name (family name) of the first author so that it can easily be differentiated from other submissions. Complete file-naming instructions will be provided to you in the submission instructions.

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Instructions on paper submittal will be provided to you in your acceptance letter.

Inquiries

If you have any questions about the preparation or submission of your paper as instructed in this document, please contact AAAI Press at the address given below. If you have technical questions about implementation of the aaai style file, please contact an expert at your site. We do not provide technical support for LaTeX or any other software package. To avoid problems, please keep your paper simple, and do not incorporate complicated macros and style files.

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Additional Resources

LaTeX is a difficult program to master. If you've used that software, and this document didn't help or some items were not explained clearly, we recommend you read Michael Shell's excellent document (testflow doc.txt V1.0a 2002/08/13) about obtaining correct PS/PDF output on LaTeX systems. (It was written for another purpose, but it has general application as well). It is available at www.ctan.org in the tex-archive.

Reference Examples

Formatted bibliographies should look like the following examples. You should use BibTeX to generate the references. Missing fields are unacceptable when compiling references, and usually indicate that you are using the wrong type of entry (BibTeX class).

Book with multiple authors Use the `@book` class.

.

Journal and magazine articles Use the `@article` class.

.

.

Proceedings paper published by a society, press or publisher Use the `@inproceedings` class. You may abbreviate the *booktitle* field, but make sure that the conference edition is clear.

.

.

University technical report Use the `@techreport` class.

.

Dissertation or thesis Use the `@phdthesis` class.

.

Forthcoming publication Use the `@misc` class with a `note="Forthcoming"` annotation.

```
@misc(key,
  [...]
  note="Forthcoming",
)
```

.

ArXiv paper Fetch the BibTeX entry from the "Export Bibtex Citation" link in the arXiv website. Notice it uses the `@misc` class instead of the `@article` one, and that it includes the `eprint` and `archivePrefix` keys.

```
@misc(key,
  [...]
  eprint="xxxx.yyyy",
  archivePrefix="arXiv",
)
```

.

Website or online resource Use the `@misc` class. Add the url in the `howpublished` field and the date of access in the `note` field:

```
@misc(key,
  [...]
  howpublished="\url{http://...}",
  note="Accessed: YYYY-mm-dd",
)
```

.

For the most up to date version of the AAAI reference style, please consult the *AI Magazine* Author Guidelines at https://aaai.org/ojs/index.php/aimagazine/about/submissions#authorGuidelines

Acknowledgments

AAAI is especially grateful to Peter Patel Schneider for his work in implementing the original aaai.sty file, liberally using the ideas of other style hackers, including Barbara Beeton. We also acknowledge with thanks the work of George Ferguson for his guide to using the style and BibTeX files — which has been incorporated into this document — and Hans Guesgen, who provided several timely modifications, as well as the many others who have, from time to time, sent in suggestions on improvements to the AAAI style. We are especially grateful to Francisco Cruz, Marc Pujol-Gonzalez, and Mico Loretan for the improvements to the BibTEX and LATEX files made in 2020.

The preparation of the LATEX and BibTEX files that implement these instructions was supported by Schlumberger Palo Alto Research, AT&T Bell Laboratories, Morgan Kaufmann Publishers, The Live Oak Press, LLC, and AAAI Press. Bibliography style changes were added by Sunil Issar. \pubnote was added by J. Scott Penberthy. George Ferguson added support for printing the AAAI copyright slug. Additional changes to aaai22.sty and aaai22.bst have been made by Francisco Cruz, Marc Pujol-Gonzalez, and Mico Loretan.

Thank you for reading these instructions carefully. We look forward to receiving your electronic files!

References

Filar, J.; and Vrieze, K. 2012. *Competitive Markov decision processes*. Springer Science & Business Media.

Kaelbling, L. P.; Littman, M. L.; and Cassandra, A. R. 1998. Planning and acting in partially observable stochastic domains. *Artificial intelligence*, 101(1-2): 99–134.

Oliehoek, F. A.; and Amato, C. 2016. *A concise introduction to decentralized POMDPs*. Springer.