

Reflections on the Teaching Practices for the Reduction of Nitroarenes: Updating Methodologies and Considerations of the Mechanism

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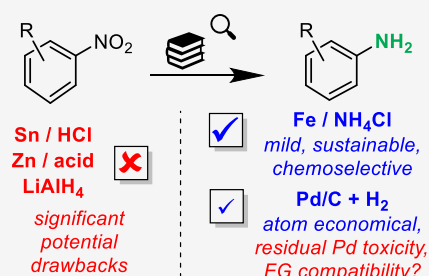
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ABSTRACT: The reduction of nitroarenes to anilines is a key transformation with real-life context, central to the preparation of many important fine chemicals. The importance of this transformation has led to its inclusion in not only university organic chemistry courses but also preuniversity, especially in Europe. A variety of reagent combinations have been developed to achieve this reduction, each with its own merits; we report herein comparison of the most common methods and what and how this transformation is taught to students. Reviewing preuniversity syllabi and a variety of textbooks, we reveal a misalignment between what is taught and the conditions most commonly used in research. Palladium-catalyzed hydrogenation and iron/ammonium chloride are the most popular reaction choices in the literature, yet these methods are often not mentioned, with other, less general, methods being taught, e.g., tin/concentrated hydrochloric acid, zinc/acid, and lithium aluminum hydride. Where multiple methods are taught, the rationale for inclusion of these is often not presented, particularly considering functional group compatibility, ease of purification, safety, or sustainability. Considering the textbooks reviewed, the mechanisms involved in the reduction are generally not discussed. We argue that, despite the perceived complexity of the reaction, coverage of the sequential nature of the reduction is important in aiding students' understanding of this reaction, e.g., to account for the formation of various intermediates and/or byproducts. We present suggestions to enable educators to discuss the processes involved in this important transformation, drawing parallels with the presentation of other frequently taught reaction pathways.

KEYWORDS: Secondary Education, First-Year Undergraduate/General, Second-Year Undergraduate/General, Organic Chemistry, Green Chemistry



INTRODUCTION

Reduction of the nitro group ($-\text{NO}_2$) to the amino functionality ($-\text{NH}_2$) is one of the most important functional group transformations in organic chemistry. Amino-functionalized aromatics (anilines) are particularly important chemical feedstocks, with a plethora of applications, including in polymers (polyurethanes), dyes, photographic materials, pharmaceuticals, explosives, and petroleum refining.¹ As such, the preparation of anilines, particularly in the context of aromatic ring functionalization, is widely introduced at the preuniversity level of study, featuring in all UK A-Level^{2–7} and the international baccalaureate syllabi,⁸ as well as in many introductory university-level organic chemistry courses worldwide. Generally, installation of the nitro functionality is achieved via electrophilic aromatic substitution of a parent arene. This nitroarene can then be reduced to the aniline, and further transformed, for example, via reductive amination, acylation, or diazotization (Figure 1).

LITERATURE METHODS FOR THE REDUCTION

As testament to their importance, myriad reagents and catalysts have been investigated for the reduction of nitroarenes to anilines. The methods can be broadly classified by their mode of

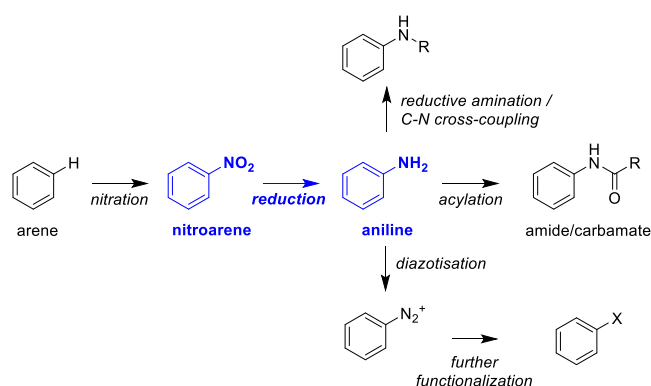


Figure 1. Illustrative preparation of functionalized arenes via the conversion of a nitroarene to an aniline.

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action:⁹ (i) reducing metal reductions (including electrochemical reduction), (ii) metal-catalyzed hydrogenation/transferred hydrogenation, and (iii) hydride transfer (Figure 2).

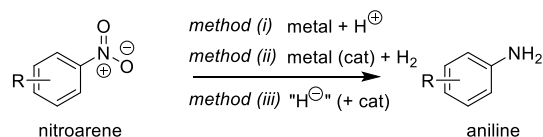


Figure 2. Strategies for conversion of nitroarenes to anilines.

Various metals with acids have been reported to reduce nitroarenes to anilines (see Table 1 for a nonexhaustive list). Chronologically, Hoffman reported the reduction using zinc and either hydrochloric acid or sulfuric acid,¹⁰ then Béchamp reported an alternative using iron and acetic acid which proved higher yielding than the reaction with zinc.¹¹ The superior nature of this process led it to be used industrially for the production of aniline. Subsequently, reports on the use of tin metal and concentrated hydrochloric acid followed from 1865.^{12–14} In 1944, Pfizer Ltd. reported extensions to the reduction using iron (reduced iron powder, iron filings, or chips), using significantly milder acidic conditions of NH_4Cl (the use of CaCl_2 , dilute HCl , or dilute acetic acid in place of NH_4Cl were also described).¹⁵ Subsequently, samarium in methanol,¹⁶ electrochemically generated nickel,¹⁷ indium/dilute HCl ,¹⁸ and cobalt octacarbonyl and water¹⁹ have all been reported as active metals/metal complexes for the reduction.

Catalytic hydrogenation emerged as a method for the reduction in a patent by Bayer in 1920 using palladium and hydrogen gas.²⁰ Other early reports of hydrogenation, for example, in reducing a nitro-tyrosine derivative using platinum black, were described as early as 1923.²¹ The need for activated platinum in the form of platinum black (generated from reduction of PtO_2 by H_2 *in situ*) was a major discovery in the field, as platinum metal often provides unsatisfactory results in the reduction.

Hydride transfer methods have emerged relatively recently. Although there are reports of LiAlH_4 being used to reduce nitroarenes to anilines,^{22,23} LiAlH_4 reductions typically afford azo products rather than anilines.²⁴ Effective new hydride transfer methods have been developed mainly using catalytic activation. Examples include the use of NaBH_4 with charcoal²⁵ or organocatalyst phenyl(2-quinolyl)methanol²⁶ or phenylsilane in the presence of an oxo-rhenium catalyst.²⁷

For most nitroarene to aniline reductions, a sequence of reduction steps are proposed (Figure 3):²⁸ the nitroarene 1 is reduced first to the nitroso intermediate 2, then the hydroxylamine 3, and finally to the aniline 4 through N–O cleavage. The particular details of these processes are often considered beyond the scope of an introductory course, but overlooking the sequential nature of the reduction is problematic, as many reductions either stop at these intermediates or afford products as a result of interception of these species, e.g., the azo compound 6 is often obtained, where the nitroso compound 2 reacts with the aniline 4.

REPORTED OCCURANCES OF DIFFERENT METHODS

To examine the frequency and/or popularity of the available methods, a chemical structure-based search of the reported

Table 1. Comparison of Different Nitroarene to Aniline Reduction Methods

reagent combination (categorization)	advantages	drawbacks
Fe/ NH_4Cl (aq) (reducing metal)	mild reaction conditions chemoselective abundant, cheap metal ease of purification	noncatalytic
Fe/ HCl (aq) or Fe/ AcOH (reducing metal)	chemoselective abundant, cheap metal	highly corrosive reaction medium treatment of product with conc NaOH is necessary prior to isolation of aniline
Zn/ HCl or Zn/ AcOH (reducing metal)	nonhazardous salt waste abundant, cheap metal	highly corrosive reaction medium; serious threat to long-term availability may afford azo or hydroxylamine products
Zn/ NH_4Cl (reducing metal)	mild reaction conditions nonhazardous salt waste abundant, cheap metal	may afford azo or hydroxylamine products serious threat to long-term availability chemoselectivity only reported in ionic liquid solvent ³⁹
Sn/ HCl (aq) (reducing metal)	chemoselective	highly corrosive reaction medium; treatment of product with conc NaOH is necessary prior to isolation of aniline limited resource availability large volume of hazardous tin-salt waste
SnCl_2 (+ HCl) (reducing metal)	chemoselective	treatment of product with conc NaOH is necessary prior to isolation of aniline limited resource availability large volume of hazardous tin-salt waste
Pd/H_2 (catalytic hydrogenation)	atom economical catalytic methodology	highly toxic Pd contamination of product extremely flammable H_2 gas and pyrophoric Pd-hydride species issues of chemoselectivity, e.g., $\text{C}=\text{C}$, $\text{C}-\text{halogen}$, $\text{C}=\text{O}$ limited resource availability
Pt/H_2 (catalytic hydrogenation)	atom economical catalytic methodology	highly toxic Pt contamination of product extremely flammable H_2 gas and pyrophoric Pt-hydride species issues of chemoselectivity, e.g., $\text{C}=\text{C}$, $\text{C}-\text{halogen}$, $\text{C}=\text{O}$ rising concerns on resource availability
Ni/H_2 (catalytic hydrogenation)	atom economical catalytic methodology	highly toxic Ni contamination of product extremely flammable H_2 gas and pyrophoric Ni-hydride species Issues of chemoselectivity, e.g., $\text{C}=\text{C}$, $\text{C}-\text{S}$, $\text{C}-\text{halogen}$, $\text{C}=\text{O}$
LiAlH_4 (hydride)	reactive reagent, especially for hindered nitroarenes	pyrophoric/air-sensitive generally affords others products, e.g., azobenzene use of less renewable solvent (e.g., THF)

nitroarene to aniline reduction literature was conducted (>300,000 hits) (Figure 4, top left). Both hydrogenations (38%) and reducing metal reductions (Fe, SnCl_2 , Zn, and Sn

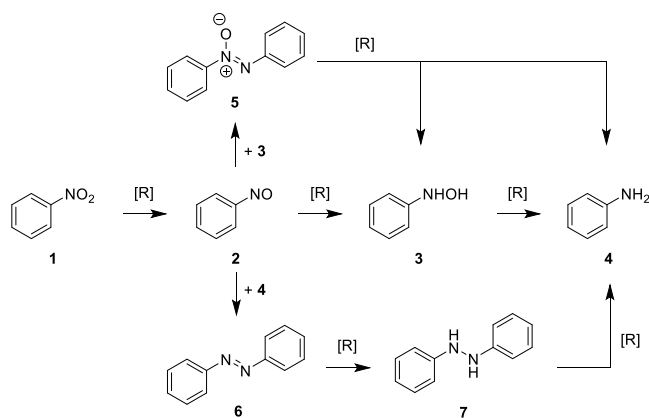


Figure 3. Suggested reduction pathways for conversion of nitrobenzene to aniline.

combined) (38%) are equally represented. Of these methods, palladium-catalyzed hydrogenation and iron-promoted reductions are most prevalent.

When considering the reduction of aliphatic nitro compounds (nitroalkanes) (>21,000 hits), a slightly different reagent preference is observed (Figure 4, top right). Catalytic hydrogenation (using Pd or Ni), reducing metal (Fe or Sn), and hydride methods (LiAlH_4) are all well-employed for the reductions. Of the hydrogenation methods, both Pd/H_2 and Ni/H_2 are used, though Pd/H_2 is more common.

To elucidate if there has been any change in reagent preference over time, refined searches were conducted for the nitroarene to aniline reduction pre-2010 (~120,000 hits) and post-2010 (>180,000 hits) (Figure 4, bottom left, bottom right). Of the more recent literature, reducing metal reductions represent a slightly higher proportion of results (42%) over catalytic hydrogenation (40%). Several reagents have seen a significant decline in use, including Ni/H_2 (10% down to 4%) and tin-based reductions, either with SnCl_2 (14% down to 7%) or Sn/HCl (3% down to 1%). The particular reagent that has seen a significant increase in use is iron, increasing from 11% to 25% of reported reductions; of these, the use of NH_4Cl has emerged as the preferred acid source (3% pre-2010 to 16% post-2010). The use of zinc as a reductant has increased, with both NH_4Cl and AcOH being used as acids more than HCl . It must be noted, however, that reductions with $\text{Zn}/\text{NH}_4\text{Cl}$ can be highly dependent on the stoichiometry of the reagents employed and the conditions used; such reductions can stop at the intermediate stages, affording the nitrosobenzene (2), azobenzene (6),²⁹ hydrazino (7),²⁹ or hydroxylamine (3)³⁰ (see Figure 3); a practical illustration of these processes has been reported in this journal.³¹

With regard to the recent metal-catalyzed hydrogenation (Figure 4, bottom right), there is a clear preference for Pd/C (36%), followed by PtO_2 (1%), Pt (<1%), and then Ni (<1%). As will be discussed later, these reactions do have limitations.

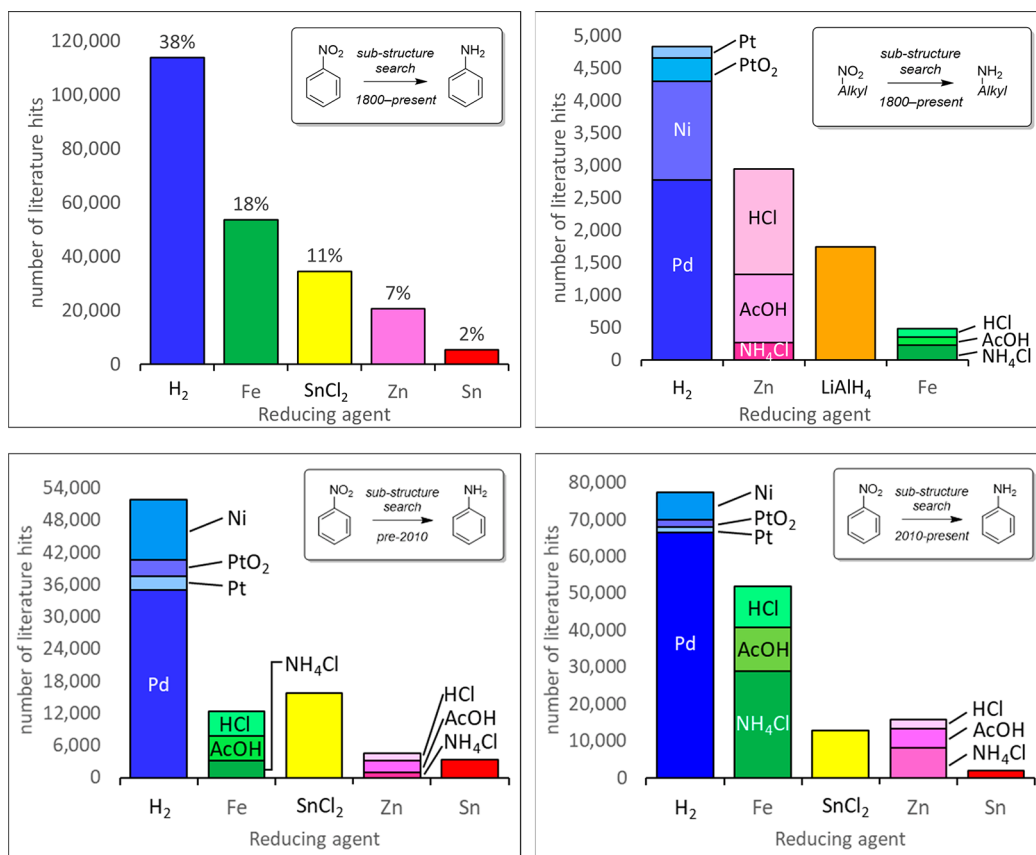


Figure 4. Results of structure-based searches of the chemical literature. (Top left) Instances of different reagents reported in the literature for nitroarene to aniline reduction (all years); (Top right) instances of different reagents reported in the literature for nitroalkane to alkylamine reduction (all years); (Bottom left) instances of reports (pre-2010) for the nitroarene to aniline reduction, broken down by reagent/catalyst; and (Bottom right) instances of recent reports (from 2010-present) for the nitroarene to aniline reduction, broken down by reagent/catalyst.

Lithium aluminum hydride is used infrequently as a hydride source (<1%). Reductions with LiAlH_4 generally result in formation of the azo derivative (6) unless additives such as TiCl_4 are added.³² Where LiAlH_4 has been reported, the systems are often sterically congested with bulky ortho-substituents or where reduction of other functionalities such as amides are sought alongside the nitro reduction. The particular steric and electronic properties of these systems, coupled with the use of excess, LiAlH_4 , may disfavor/discourage formation of the azo compound. As we will discuss later, the disparity between general behavior of nitroarenes and nitroalkanes to reduction with LiAlH_4 may bring misconceptions to the general teaching of this transformation.

■ PROS AND CONS OF THE VARIOUS METHODS

Such a variety of methods and reagents have been developed for this reaction, each with particular strengths and limitations (Table 1). These include, but are not limited to, (i) safety, (ii) atom economy, (iii) reaction efficiency, (iv) functional group tolerance/compatibility, (v) reagent availability, (vi) cost, (vii) operational complexity, (viii) waste generation/products, (ix) use of catalytic methodologies, and (x) use of renewable resources.

Catalytic hydrogenation represents the most atom-economical means of reduction. Reactions are typically very efficient, generating no significant byproducts (mainly H_2O), and the isolation/purification of the product is facile (simple filtration, followed by removal of solvent is often sufficient to afford sufficiently pure material). There are, however, a number of potential practical issues and considerations associated with the hydrogenation: relatively high cost, low abundance,³³ and long-term availability³⁴ of the noble metal catalyst (Table 2), routes

duced to the reaction. Catalytic hydrogenations also require careful consideration of functional group compatibility, as benzylic alcohols, aldehyde and ketone $\text{C}=\text{O}$ groups, and $\text{C}=\text{C}$ and carbon–halogen bonds are often reduced under the hydrogenation conditions. For example, efforts to reduce 4'-nitroacetophenone chemoselectively under catalytic hydrogenation are reported, including in this journal.^{36,37}

The reducing metal reductions offer advantages over catalytic hydrogenation in terms of functional group compatibility, cost and availability, and safety. The use of concentrated corrosive acids, however, introduces safety and handling issues and leads to protonation of the product aniline (forming the anilinium salt). Treatment of the product with excess NaOH is required to afford the free-based aniline. For reactions employing Sn or SnCl_2 , this step presents significant issues for product isolation, with the formation of large volumes of gelatinous, hazardous tin-salt waste being a major issue. The milder (essentially neutral) $\text{Fe}/\text{NH}_4\text{Cl}$ reaction conditions offer considerable benefits over the other reducing metal/acid options. This includes cost and availability of the metal (Table 2), functional group tolerance, and from a green/sustainability perspective,³⁸ safety considerations, waste generation and handling, and the use of an aqueous or aqueous ethanol renewable solvent.

■ WHAT IS CURRENTLY TAUGHT ABOUT THIS REDUCTION

Noting the different methods and reagents capable of promoting the nitroarene reduction, careful consideration is needed regarding both what material is taught and how the reactions are explained. In Europe, and especially the UK, the nitroarene to aniline reduction is part of A-Level or equivalent syllabi.^{2–8,40} In the US, this topic appears not to be covered preuniversity or in General Chemistry courses but is part of undergraduate Organic Chemistry courses.

Reviewing these preuniversity syllabi, we were surprised to discover that only the reducing metal reduction method is mentioned (Table 3). In all cases, the reagents listed are specifically tin and concentrated hydrochloric acid and only AQA and WJEC examination boards mentioning iron as a possible alternative metal; additionally, some syllabi remark on the need for treatment of the product with concentrated NaOH . This is in contrast to the results of our literature search, where only 2% of all nitroarene to anilines reductions have been reported using tin metal.

Recognizing that prior knowledge plays a significant role in students' future learning and developing misconceptions,⁴¹ introducing the tin-based reduction fails to capture both the importance of the hydrogenation method and the significant improvements that $\text{Fe}/\text{NH}_4\text{Cl}$ provides. Emphasizing the tin-promoted reduction significantly overstates its relevance, even historically. From a pedagogical perspective, discussing the need for treatment with NaOH to free-base the aniline adds complexity to this process, which is alleviated under the mildly acidic conditions using $\text{Fe}/\text{NH}_4\text{Cl}$ (a 0.2 M NH_4Cl (aq) solution has $\text{pH} \sim 5$, readily neutralized with a weak base if necessary). We recommend that European educators, especially those in the secondary education sector, consider updating their curricula to reflect these more contemporary methodologies and sustainability considerations.

To explore if this difference extends to university-level teaching, a survey of international university-level (organic chemistry) textbooks, published between 1985 and 2021, was conducted.^{42–57} Collectively, a similar preference for the use of

Table 2. Cost, Relative Abundance,³³ and Limitations on Supply of Metal Elements³⁴

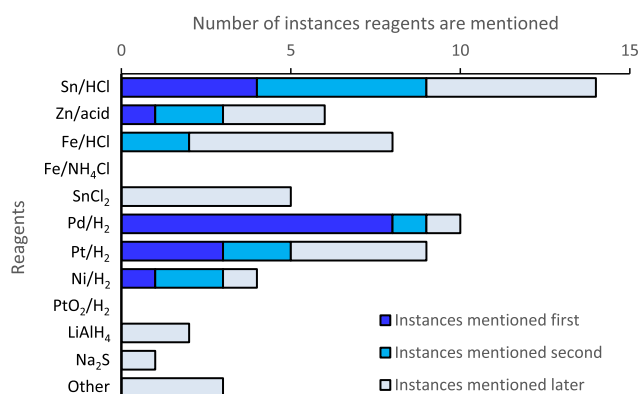
metal	cost (\$/kg)	abundance in Earth's crust and sea (ppm)	endangered status
Fe	0.424	56,300	no current concerns
Zn	2.55	70	serious threat in next 100 years
Ni	13.9	84	limited availability, future risk to supply
Sm	13.9	7.05	no current concerns
Sn	18.7	2.3	limited availability, future risk to supply
Co	32.8	25	limited availability, future risk to supply
In	167	0.25	serious threat in next 100 years
Pd	49,500	0.015	limited availability, future risk to supply
Pt	27,800	0.005	rising threat from increased use

for disposal/recovery of the metal, use of specialized reactors (e.g., pressurized steel Parr vessels), safety (reactions under pressure, extremely flammable H_2 gas, generation/handling of pyrophoric metal hydrides, contamination of the product with highly toxic residual $\text{Pd}/\text{Pt}/\text{Ni}$ ³⁵), and the potential for the aniline product to poison the catalyst. These considerations do not necessarily impact teaching the reaction theoretically. However, demonstrating the utility of the reaction in a teaching laboratory setting becomes quite challenging, particularly to preuniversity/early years undergraduate students being intro-

Table 3. Instances of a Particular Reagent Combination for Nitro to Aniline Reduction from Prescribed Syllabi/Specifications

Preuniversity Exam Board	Country	Reducing Metal Reduction	Hydrogenation	Hydride Transfer
Cambridge International	worldwide	Sn/conc HCl then NaOH	×	×
International Baccalaureate	worldwide	Sn/conc HCl then NaOH	×	×
International A-Level, Pearson	worldwide	Sn/conc HCl	×	×
AP	US	×	×	×
SACE South Australia	Australia	×	×	×
AQA	England/Wales	Sn/conc HCl or Fe/conc HCl	×	×
Edexcel Pearson	England/Wales	Sn/conc HCl	×	×
OCR	England/Wales	Sn/conc HCl	×	×
CCEA	Northern Ireland	Sn/conc. HCl then NaOH	×	×
SQA Advanced Higher	Scotland	directs teachers to ChemGuide: Sn/conc HCl then NaOH	×	×
WJEC	Wales	Sn/conc HCl or Fe/conc HCl	×	×

metal/conc HCl is apparent (number of instances: Sn, 14; Fe, 8; Zn, 6), followed by hydrogenation (number of instances: Pd, 10; Pt, 9; Ni, 4) (Figure 5). Sn/conc HCl(aq) features extensively in both the text and in illustrative chemical reaction schemes, and where Fe/conc. HCl is mentioned, it is often placed in a secondary (or later) position; this could, even unconsciously, lead readers to the conclusion that iron is an inferior metal for this transformation.

**Figure 5.** Reported instances of particular reagents for nitroarene to aniline reduction within textbooks.

Newer editions of some textbooks, particularly those used in the US, appear to report both the use of hydrogenation (Pd as the metal) and the reducing metal reduction (often listing Fe as the primary metal). Some textbooks acknowledge the potential for incompatibility of hydrogenations with other functional groups, indicating that “milder” reductions with “active metals” may be more applicable for chemoselective reduction. However, there is no discussion as to which functionalities pose issues under hydrogenation, e.g., C=C systems, benzylic alcohols, etc. Furthermore, the reaction schemes used to illustrate these reductions do not always paint a consistent picture with the supporting text commentary, especially when reading across multiple chapters: the method (or methods) mentioned in one chapter are not necessarily reflected in the chemical schemes or consistent when discussed or illustrated in a subsequent chapter.

Finally, it is noteworthy that lithium aluminum hydride, platinum, and nickel are mentioned for the reduction of nitroarenes, despite being uncommon, especially in the recent chemical literature. While there are limited examples using these reagents, nitroalkanes can be more successfully reduced under these conditions rather than nitroarenes (see Figure 4, bottom left). These inclusions in textbooks may be a historical legacy or

a misconception from considering all nitro reductions under the same umbrella. Additionally, the use of PtO₂ (Adam’s catalyst) is not discussed in any of the surveyed textbooks, despite being used more frequently than Pt metal; although strictly such reductions involve Pt(0), the active platinum black generated in situ is often more effective than Pt metal itself.^{58,59}

CONSIDERATIONS FOR TEACHING OF THE REACTION

The mechanism of the reaction is rarely discussed in textbooks, for any of the three reduction classes (Figure 2). Pedagogically, the nitro reduction is a complex sequence of events, which poses challenges in how to teach the reaction.

At an introductory level, this transformation can be taught to students as a set of reagents suitable to achieve the reaction. Noting that the reaction is a redox process is an important teaching point to be brought out, highlighting that hydrogen is oxidized to water alongside reduction of the nitro group to the amine. In considering which reagents to teach, highlighting H₂/Pd and Fe/NH₄Cl serves the same pedagogical objective as a long list of potential candidates. This is especially true in highlighting why each has particular uses, e.g., atom economy versus functional group compatibility, as well as preventing misconceptions or confusion arising from the use of other reagents that afford other products.

While ensuring the most suitable reagents for the reaction are covered by courses, as argued by Smith, organic chemistry is more than just a series of reactions (or in our case, reagents) to learn and memorize.⁶⁰ Providing even a simplistic mechanistic explanation is valuable to help develop students’ understanding of a reaction; understanding of the conceptual processes and mechanistic sequences of reactions is often linked to development of problem-solving and critical thinking skills,⁶¹ key transferable skills sought of chemistry graduates.

For the nitroarene reduction, a simplistic portrayal of the process is readily achieved as illustrated below, showing the formation of water (though strictly incorrect in mapping where the hydrogens originate in the hydrogenation) (Figure 6). This is a similar approach to the way the formation of an ester **10** from a carboxylic acid **8** and alcohol **9** is initially portrayed to students.

The scheme, however, oversimplifies the reduction sequence, considering the nitro reduction to be a single-step transformation. Describing the multistep reaction sequence, with mechanistic detail, helps students to develop a better understanding of the reaction, including the formation of different products, depending on the particular choice of reagents, stoichiometry in the reaction, or reaction conditions (see Figure 3).

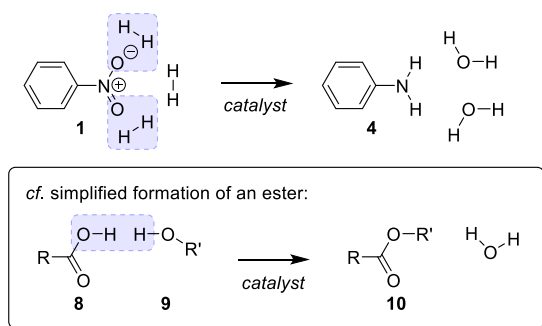


Figure 6. Simplified overview of the reaction “mechanism”, suitable for introductory teaching.

Mechanisms for metal-catalyzed alkene hydrogenation are often covered in courses, generally via adsorption of hydrogen and an olefin to the surface of the metal catalyst (though a more detailed consideration via metal-hydrides may also be considered²⁸). Parallels between the hydrogenation of olefins and nitroarenes are rarely discussed, though there are opportunities to forge useful links between the two reductions (and the further reductions of the nitrosoarene 2) (Figure 7). With the use of this mechanistic explanation, connections to other areas of chemistry can be made: the hydrogenated intermediate 12 can be considered as a hydrated form of the nitrosoarene 2; thus, links to carbonyl compounds and the importance of their hydrate forms 13 can be drawn, i.e., aldehyde-derived hydrates are responsible for (over)oxidation of primary alcohols (or aldehydes) to carboxylic acids using aqueous oxidants, such as Jones' reagent [CrO_3 , $\text{H}_2\text{SO}_4(\text{aq})$].^{45,51,54}

For the reducing metal reduction mechanism (Figure 8), the multistep nature of the process may be considered beyond the scope of many programs. However, there are opportunities here to increase students' exposure to the importance of single-electron reduction processes. These include introduction to nitrogen radical cations, drawing similarities to those encountered in electron-impact mass spectrometry with amines (e.g., R_3N : 17 \rightarrow $\text{R}_3\text{N}^+\bullet$ 18), as well as other functional group transformations using dissolving metal reductions, e.g., con-

version of alkynes to (*E*)-alkenes, Birch reductions, or the directly analogous formation of ketyl radical anions 16 from carbonyl compounds.

CONCLUSION

The reduction of nitroarenes to anilines is an important introductory transformation for students, but the reagents taught, at both secondary-education and higher-education level, may require updating. Two methods for this transformation are particularly prevalent in the literature, accounting for 51% of all reported nitroarene to aniline reductions, namely, catalytic hydrogenation using Pd/C and H_2 and reducing metal reduction with Fe/ NH_4Cl . From the review of textbooks, these reactions are often presented inconsistently, with limited discussion of the suitability of different choices of reagent, and not considered mechanistically. Together, this lack of discussion can hinder student understanding of the reaction, precluding how other reduction products may be formed.

We have provided mechanistic suggestions to assist the teaching of these complex reaction processes, highlighting areas where educators can draw parallels with other important reactions.

The use of Fe/ NH_4Cl demonstrates significant advantages in operational suitability over either the tin-mediated reduction or palladium-catalyzed hydrogenation. Without the need for treatment of the product with concentrated base, this becomes a more straightforward transformation for students to understand pedagogically and to carry out practically in the laboratory and features a cheap, readily sourced reagent for the reaction. Thus, the iron-mediated process should feature more prominently within school and university curricula alongside Pd/C and H_2 as primary methods for the reduction of the nitroarenes to anilines. Rather than teaching the need for strongly acidic conditions in the metal reduction, educators should champion the numerous benefits of the Fe/ NH_4Cl combination. This can be compared and contrasted with Pd/ H_2 , particularly regarding chemoselectivity and within the wider arena of sustainability. The currently favored Sn/conc HCl combination can still be discussed, especially given its prevalence in many textbooks, and provides a suitable platform for discussion of environmental impact in chemistry.

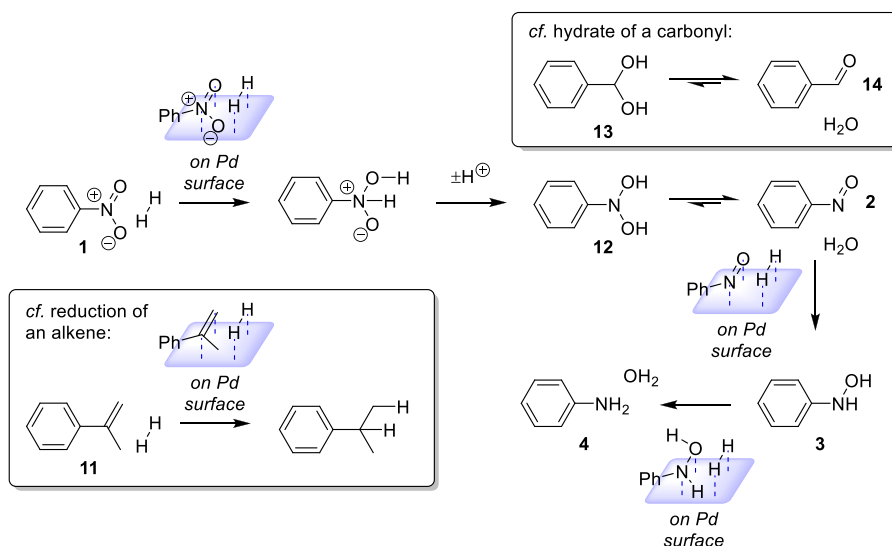


Figure 7. Proposed reduction mechanism via hydrogen adsorption, and analogies with related important processes.

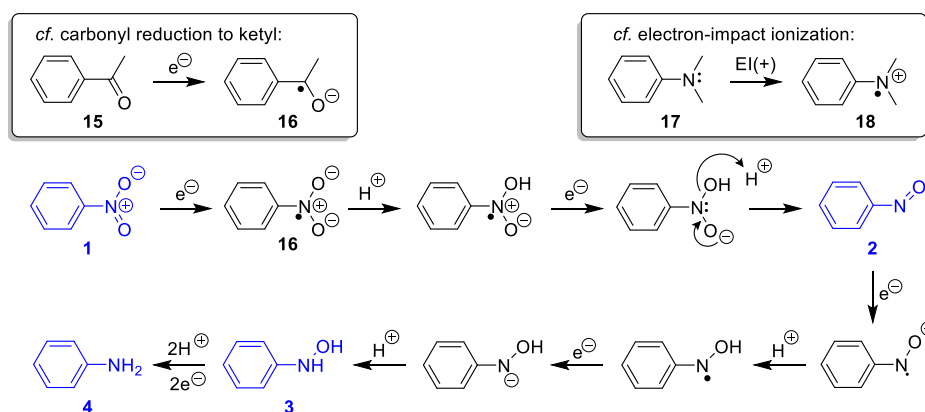


Figure 8. Proposed mechanism of the reduction pathway for conversion of nitrobenzene to aniline.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00283>.

Textbook analysis, literature surveys, and chemical database search data (XLSX)

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Notes

The authors declare no competing financial interest.

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