Algorithms HW

1. Let G be a group, and let $\Gamma^\bullet G$ be its descending central series. Show that:
   - each $\Gamma^i G$ is a normal subgroup of G;
   - each $\Gamma^{i+1}G$ is contained in $\Gamma^i G$; and
   - each $\Gamma^i G/\Gamma^{i+1}G$ is contained in the centre of $G/\Gamma^{i+1}G$.

- We show that $\Gamma^i G \trianglelefteq G$ by induction on i. Since $\Gamma^1 G = G$ our base case is $i = 2$. Recall that $\gamma^2 G$ is generated by commutators $[g, h]$ where $g, h \in G$. Now let $k \in G$ and consider

  $$k[g,h]k^{-1} = kghg^{-1}h^{-1}k^{-1} = (kgk^{-1})(khk^{-1})(kg^{-1}k^{-1})(kh^{-1}k^{-1}) = [kgk^{-1}, khk^{-1}] \in \Gamma^2 G.$$

  And so, $\Gamma^2 G \trianglelefteq G$ by definition.

  Now suppose $\Gamma^i G \trianglelefteq G$ and consider $\Gamma^{i+1}G$, which is generated by elements $[g, h]$ where now $g \in G$ and $h \in \Gamma^i G$. Let $k \in G$ and notice that, since $\Gamma^i G$ is normal by the induction hypothesis, we have $khk^{-1} \in \Gamma^i G$. Thus the above calculation gives that $k[g,h]k^{-1} = [kgk^{-1}, khk^{-1}] \in \Gamma^{i+1}G$. Thus, each $\Gamma^i G \trianglelefteq G$ by induction.

- We show that $\Gamma^{i+1}G \subseteq \Gamma^i G$. Let $[g, h]$ be a generator of $\Gamma^{i+1}G$ so that $g \in G$ and $h \in \Gamma^i G$. Above we showed that $\Gamma^i G \trianglelefteq G$ and so $ghg^{-1} \in \Gamma^i G$. Moreover, $h \in \Gamma^i G$ implies $h^{-1} \in \Gamma^i G$ since $\Gamma^i G$ is a group. Thus

  $$[g,h] = ghg^{-1}h^{-1} = (ghg^{-1})h \in \Gamma^i G.$$

  Then, since each generator of $\Gamma^{i+1}G$ is contained in $\Gamma^i G$, we have $\Gamma^{i+1}G \subseteq \Gamma^i G$.

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2. (CMN Example 2.8) What is the derived series for the dihedral group D_{2n}? What is the descending central series?

I'm sorry I'm going to use D_n to denote the dihedral group which has $2n$ elements. Recall the presentation

$$D_n = \langle r, s : r^n = s^2 = e \quad rs = sr^{-1} \rangle$$

First note that D_1 and D_2 are abelian. We have $D_1 = \{e, s\}$ a single non-trivial element, and so is trivially abelian. Meanwhile $D_2 = \{e, s, r, rs\}$, the relation $rs = sr^{-1}$ becomes $rs = sr$, i.e. $[r, s] = e$. Likewise we have $[r, rs] = r(rs)r(rs)^{-1} = r^2(rs)(rs)^{-1} = e$ and $[s, rs] = s(rs)s(rs)^{-1} = s^2(rs)(rs)^{-1} = e$[1]. Hence, D_2 is also abelian. Question: was it sufficient to show that r, s commute to show that D_n is abelian? And generally speaking, if a group is generated by n elements $g_1, \cdots g_n$ which all commute, is that sufficient to show that the group is abelian? (later), okay I have convinced myself. I think in general showing that all the generators of a finite group commute with each other is enough to show that every commutator of a group is trivial.

It follows that the derived subgroup $G' = \Gamma^2 G$ is trivial for $G = D_1$ or $G = D_2$. Moreover, since $\Gamma^3 G$ is generated by $[g, e] = geg^{-1}e = e$ for each $g \in G$, it follows that $\Gamma^i G$ is trivial for each $i > 1$ for both of these groups.

Now suppose $n \geq 3$ is odd. We show first that $\Gamma^2 G = \langle r \rangle$ by computing all the commutators. Recall that $\Gamma^2 G = G'$ is the subgroup generated by all commutators $[g, h]$ where $g \in G$ and $h \in \Gamma^1 G = G$. We need to compute the following commutators: $[r^k, s], [r, r^k s], [s, r^k s]$ where $k = 1, \cdots, n-1$. First recall the relation $rs = sr^{-1}$ and then consider the following

$$[r^k, s] = r^k s r^{-k} s = r^k r^{-k} s^2 = r^{-2k} \neq e$$

where the last equality follows from the fact that n is odd. In particular $k = 1$ shows that

[1] I later realized that computing $[g, h]$ is enough to determine $[h, g]$. In particular if $[g, h] = x$ for some $x \in G$ then we have $ghg^{-1}h^{-1} = x \implies x^{-1} = hgh^{-1}g^{-1} = [h, g]$. Alas, there is some redundent calculation above.

$r^2 \in \Gamma^2 G$. Very similar calculations give the following

$$[r, r^k s] = r(r^k s)r^{-1}(sr^{-k}) = r^2 \neq e$$
$$[s, r^k s] = s(r^k s)s(sr^{-k}) = r^{-2k} \neq e$$

Then, since we have already shown that $r^2 \in \Gamma^2 G$ we have that $\Gamma^2 G = \langle r^2 \rangle$. The situation is even better than this because for $n \geq 3$ odd we have $\langle r^2 \rangle = \langle r \rangle$. We have $r^2 = r \cdot r \in \langle x \rangle$. Moreover, consider there are n distinct powers of r in $\langle r^2 \rangle$, we have

$$\langle r^2 \rangle = \{r^2, r^4, \cdots, r^{n+1} = r, r^{n+3}, \cdots, r^{2n-2}, e\},$$

since, again, n is odd. That is, we have $r \in \langle r^2 \rangle$ and so indeed we have

$$\Gamma^2 G = \langle r^2 \rangle = \langle r \rangle.$$

Next we show that when $\Gamma^{i-1} G = \langle r \rangle$ then we must have $\Gamma^i G = \langle r \rangle$ for $i = 3, 4, \ldots$ Recall that $\Gamma^i G$ is generated by $[g, h]$ where $g \in G$ and $h \in \Gamma^{i-1} G$. Since $\Gamma^{i-1} G$ is only generated by a single element we only need to compute the following:

$$[r^k, r] = e$$
$$[s, r] = r^{-2}$$
$$[r^k s, r] = r^{-2},$$

following similar calculations to above. That is $\Gamma^i G = \langle r^2 \rangle$ and we still have $\langle r^2 \rangle = \langle r \rangle$, since this was a property of the group D_n for $n \geq 3$ odd. That is, we have shown $\Gamma^i G = \langle r \rangle$ for $i \geq 2$.

Now we consider the case when $n \geq 4$ is even. First notice that we can split this case into two further cases — either $n = 2^k$ for some k or $n = 2^k m$ for some k and some $m \geq 3$ odd. If n is not a power of 2 then its prime factor decomposition is $2^k m$ where m is the product of all of its odd prime factors.

Now first consider the case where $n = 2^k m$. Our above calculation shows that $\Gamma^2 D_{2^k m} = \langle r^2 \rangle$ but now $\langle r^2 \rangle \neq \langle r \rangle$ since r^2 has even order. In particular $\langle r^2 \rangle = \{r^2, r^4, \cdots, r^{2\cdot(2^{k-1} m)} =$

$e\}$. Now we compute $\Gamma^3 G$ via direct computation of the generators $[g,h]$ where $g \in G$ and $h \in \Gamma^2 G = \langle r^2 \rangle$. Following the now usual strategy, we have

$$\begin{aligned}
[r^k, r^2] &= e \\
[s, r^2] &= sr^2sr^{-2} = r^{-4} \\
[r^ks, r^2] &= r^{-4}.
\end{aligned}$$

That is, $\Gamma^3 G = \langle r^4 \rangle$. Essentially the same calculation will give $\Gamma^i G = \langle r^{2^{(i-1)}} \rangle$ for $2 \leq i$. The book claims that this simplifies to $\langle r^{2^k} \rangle$ when $i \geq k+1$, but im having trouble seeing why.

Now suppose $n = 2^k$ for some k. The same computation as above gives $\Gamma^i G = \langle r^{2^{(i-1)}} \rangle$ for $i \geq 2$. However, now when $i \geq k+1$ we have $r^{2^{(i-1)}} = r^{2^{(k+\ell)}} = (r^{2^k})^\ell = e^\ell = e$. And so, when $i \geq k+1$ we have $\Gamma^i G = e$. This last fact also follows since when $i = k+1$ we have $\Gamma^i G = \langle r^{2^k} \rangle = e$ and in question 1 we showed that $\Gamma^i G \subseteq \Gamma^{i-1} G$ and so it would then follow that all $\Gamma^i G = e$ for all $i > k+1$. That is, when $n = 2^k$ we have that D_n is nilpotent, and in particular solvable.

Now we consider the derived series for D_n. Recall that $(D_n)^{(1)} = \Gamma^2 D_n$, and then $(D_n)^{(i)}$ is generated by $[g,h]$ for each $g,h \in (D_n)^{(i-1)}$. For $n = 1,2$ we showed above that D_n is abelian. It follows that all commutators are trivial, i.e., $G^{(1)} = e$ and then $G^{(i)} = 1$ for all $i \geq 1$. For $n \geq 3$ we showed above that the derived subgroup $G' = \langle x \rangle$ is a cyclic subgroup, for either $x = r$ or $x = r^{2k}$. In particular G' is abelian, and so it follows that all commutators $[g,h]$ with $g,h \in G'$ are trivial. And so for $n \geq 3$ we have $(D_n)^{(1)} = \langle x \rangle$ and $(D_n)^{(i)} = e$ for $i > 1$, where x depends on the exact form of n, as discussed above.

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4. Let
$$1 \to N \to G \xrightarrow{\pi} H \to 1$$
be an extension of groups. Show that there is a homomorphism
$$\rho \colon H \to \mathrm{Out}(N)$$
sending an element $h \in H$ to the outer automorphism of N given by conjugation by any $\tilde{h} \in G$ such that $\pi(\tilde{h}) = h$. In the particular case that $G = N \rtimes_\theta H$ is the semidirect product of H by N via θ, show that ρ is equal to the composition
$$H \xrightarrow{\theta} \mathrm{Aut}(N) \to \mathrm{Out}(N)\,.$$

Firstly, we will show that ρ is a well defined map $H \to Out(N)$. Let $h \in H$ and $\tilde{h}_1, \tilde{h}_2 \in G$ such that $\pi(\tilde{h}_1) = \pi(\tilde{h}_2) = h$. We have $\rho(\tilde{h}_1) = f := (n \mapsto \tilde{h}_1 n \tilde{h}_1^{-1})$ and $\rho(\tilde{h}_2) = g := (n \mapsto \tilde{h}_2 n \tilde{h}_2^{-1})$. Note that these are indeed automorphisms of N, as in the previous homework we showed that conjugation by a fixed element is an automorphism. If we show that $\rho(\tilde{h}_1)$ and $\rho(\tilde{h}_2)$ lie in the same coset of $Inn(N)$ then ρ is well-defined. (Note: I believe this map is not well defined as a map $H \to Aut(N)$).

Recall that two elements g, h of a group lie in the same coset of a normal subgroup N if $g^{-1}h \in N$. For our automorphisms f, g we have $g^{-1} = (n \mapsto \tilde{h}_2^{-1} n \tilde{h}_2)$. And so we have $(g^{-1} \circ f)(n) = \tilde{h}_2^{-1} \tilde{h}_1 n \tilde{h}_1^{-1} \tilde{h}_2$. Recall that $N \trianglelefteq G$ and so is closed under conjugation by definition. In particular then $\tilde{h}_1 n \tilde{h}_1^{-1} \in N$ and $\tilde{h}_2^{-1}(\tilde{h}_1 n \tilde{h}_1^{-1})\tilde{h}_2 \in N$ since $\tilde{h}_1, \tilde{h}_2 \in G$. Thus f, g have the same image in $Out(N)$ and so ρ is well defined with respect to the choice of $\tilde{h}$.

Next we show that ρ is a group homomorphism. Let $h_1, h_2 \in H$ and $\tilde{h}_1, \tilde{h}_2 \in G$ such that $\pi(\tilde{h}_1) = h_1$ and $\pi(\tilde{h}_2) = h_2$. Moreover, since π is a group homomorphism we have $\pi(\tilde{h}_1 \tilde{h}_2) = \tilde{h}_1 \tilde{h}_2$. Following a similar, calculation to last week's homework, consider the following

$$\begin{aligned}
\rho(h_1h_2) &= \gamma_{\tilde{h}_1\tilde{h}_2} \\
&= (n \mapsto \tilde{h}_1\tilde{h}_2 n(\tilde{h}_1\tilde{h}_2)^{-1}) \\
&= (n \mapsto \tilde{h}_1\tilde{h}_2 n\tilde{h}_2^{-1}\tilde{h}_1^{-1}) \\
&= \gamma_{\tilde{h}_1} \circ \gamma_{\tilde{h}_2} \\
&= \rho(h_1)\rho(h_2).
\end{aligned}$$

Thus, the given ρ is indeed a group homomorphism.

Now suppose $G = N \rtimes_\theta H$. We can state more precisely the outer automorphism given by ρ. Let $h \in H$ and then all lifts are of the form $\tilde{h} = (m, h)$ for some $m \in N$. Then, being explicit about the details of the semidirect product, our map $\rho(h) : \iota(N) \to \iota(N)$ acts as follows

$$\begin{aligned}
\rho_h(n) &= (m,h) \cdot_\theta (n, e_H) \cdot_\theta (m,h)^{-1} \\
&= (m,h)(n,e_H)(\theta_{h^{-1}}(m^{-1}), h^{-1}) \\
&= (m\theta_h(n), h)(\theta_{h^{-1}}(m^{-1}), h^{-1}) \\
&= (m\theta_h(n)(\theta_h \circ \theta_{h^{-1}}(m^{-1}), hh^{-1}) \\
&= (m\theta_h(n)m^{-1}, e_H).
\end{aligned}$$

Which induces the automorphism $f = (n \mapsto m\theta_h(n)m^{-1}) : N \to N$. Note that $(\theta_h\theta_{h^{-1}}) = id_H$ since θ is a group homomorphism $H \to Aut(N)$.

We show that this is the same as the composition $H \to Aut(N) \to Out(N)$. We have $h \mapsto \theta_h \mapsto \overline{\theta_h}$. Notice now that θ_h and f are lie in the same coset of $Inn(N)$. In particular

$$\overline{\theta_h} = \overline{\gamma_m\theta_h} = \overline{f}$$

since $\gamma_m = (n \mapsto mnm^{-1})$ is one of the inner automorphisms of N. Hence, in the case where $G = N \rtimes_\theta H$ we have ρ and $H \to Aut(N) \to Out(N)$ give the same map.

One interpretation of this is that, whilst ρ is a well defined map $H \to Out(N)$, it is not a well defined map $H \to Aut(N)$. However, in the case where G is a semidirect product of

N and H via θ, we have a preferred lift $h \mapsto (e_N, h) \in G$, and in fact there is a well defined map $H \to Aut(N)$, namely θ, whose projection gives the same map as ρ.

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5. (Aluffi Exercise IV.5.15) Let G be a group of order 28.

- Prove that G contains a subgroup of order 4, and a normal subgroup of order 7. Deduce that G is either a split extension of C_4 by C_7, or is a split extension of $C_2 \times C_2$ by C_7.
- Prove that there are only two homomorphisms $C_4 \to \mathrm{Aut}(C_7)$ and only two homomorphisms $C_2 \times C_2 \to \mathrm{Aut}(C_7)$, up to changing the choice of generators for C_4 and $C_2 \times C_2$.
- Deduce that there are exactly four groups of order 28, up to isomorphism.

- Sylow's theorem I gives us that there exists a subgroup of order 7 in G, since $|H| = 7^1 \cdot 4$ and $7 \not| 4$. Alternatively, Cauchy's theorem gives us that there exists an element $g \in G$ with $|g| = 7$, hence we have $|\langle g \rangle| \leq G$. Moreover, Sylow III gives us that there's only a single Sylow 7 group. Consider, if n_7 is the number of Sylow 7 groups in G then Sylow III gives us that $n_7 \equiv 1 \mod 7$ and $n_7|4$. The only integer solving both these conditions is $n_p = 1$. Likewise if we write $|G| = 28 = 2^2 \cdot 7$ and notice $2 \not| 7$ then Sylow I gives us that there exists a subgroup of order $2^2 = 4$.

  Next we argue that N is normal. If $g \in G$ then recall $\gamma_g = (\ell \mapsto g\ell g^{-1}) \in Aut(G)$. Therefore $|\gamma_g(N)| = |N|$. However, there's a unique subgroup of order 7 in G and so the image $\gamma_g(N) = N$ for all $g \in G$. That is, N is closed under conjugation by elements in G and so N is normal by definition. We have shown that G has a normal subgroup of order 7 and in fact we have found that $N \cong C_7$.

- Recall or perhaps I shall prove that $Aut(N) = Aut(C_7) \cong C_6$. Consider C_4, once we have specified where a generator $\sigma \in C_4$ is mapped to in C_6 then we have determined the homomorphism $C_4 \to C_6$. Since $|\sigma| = 4$ we must have $|\theta(\sigma)| = 4$ or $|\theta(\sigma)| = 2$, for θ non-trivial, since a homomorphism must map an element to an element whose order divides the original order. Notice that there's only a single element of order 2 in C_6. And so there's one trivial map and one non-trivial map $\overline{\theta} : C_4 \to N$. Since $\overline{\theta}(\sigma)$ has order two we can deduce that it is the automorphism which sends each element of C_7 to its inverse. That is $\overline{\theta}(\sigma) = (n \mapsto 7 - n)$. And, of course, the trivial map $\theta_{\text{triv}}(\sigma) = (n \mapsto 0)$ for each $\sigma \in C_4$.

  We use similar reasoning to determine the maps $\theta : C_2 \times C_2 \to Aut(N) \cong C_6$.

One generating set of $C_2 \times C_2$ is $\{(0,1),(1,0)\}$ and again, once we determine where these elements are mapped to by θ we have determine the entire homomorphism $\theta : C_2 \times C_2 \to C_6$. Now each generating element has order two, and so any non-trivial θ maps both the generating elements to the unique element of order 2 in C_6. And so, again, we have one trivial map $\theta_{\text{triv}} : C_2 \times C_2 \to C_6$ and one non-trivial map $\tilde{\theta} : C_2 \times C_2 \to C_6$. The automorphisms $\tilde{\theta}((0,1)) = \tilde{\theta}(1,0)$ are both the same as the one described above — $(n \mapsto 7 - n \equiv -n)$.

- Determining all the possible semi-direct products $C_7 \rtimes H$ with $H = C_4$ or $H = C_2 \times C_2$ will tell us the possible group laws on G. Notice that $N \cap H = \{e\}$ for $H = C_4$ or $C_2 \times C_2$, this follows since every element of $N \cong C_7$ is the identity or is order 7, meanwhile there are no elements of order 7 in either C_4 or $C_2 \times C_2$. We also need to show that $NH = G$. Then it follows that $G \cong N \rtimes_\theta H$ for $H = C_4$ or $H = C_2 \times C_2$ and one of the θ described above.

  With all possible homomorphisms $H \to Aut(N)$ described above, we can determine all the semi-direct products $N \rtimes H$. First suppose $H = C_4$ and $\theta : C_4 \to C_6$ the trivial map. That is $\theta(h) = (n \mapsto n)$ for each $h \in H$. We have the following group product for $N \rtimes_\theta H$:

$$\begin{aligned}(n_1, h_1) \cdot_\theta (n_2, h_2) &= (n_1 \theta_{h_1}(n_2), h_1 h_2) \\ &= (n_1 n_2, h_1 h_2).\end{aligned}$$

  That is, then $N \rtimes_\theta H$ is isomorphic to $C_7 \times C_4 \cong G$. The same calculation will give us that when $H = C_2 \times C_2$ and $\theta : C_2 \times C_2 \to Aut(N)$ is the trivial map, we also have $G \cong C_7 \times C_2 \times C_2$.

  Now we determine the products given by the non-trivial $H \to Aut(N)$.

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